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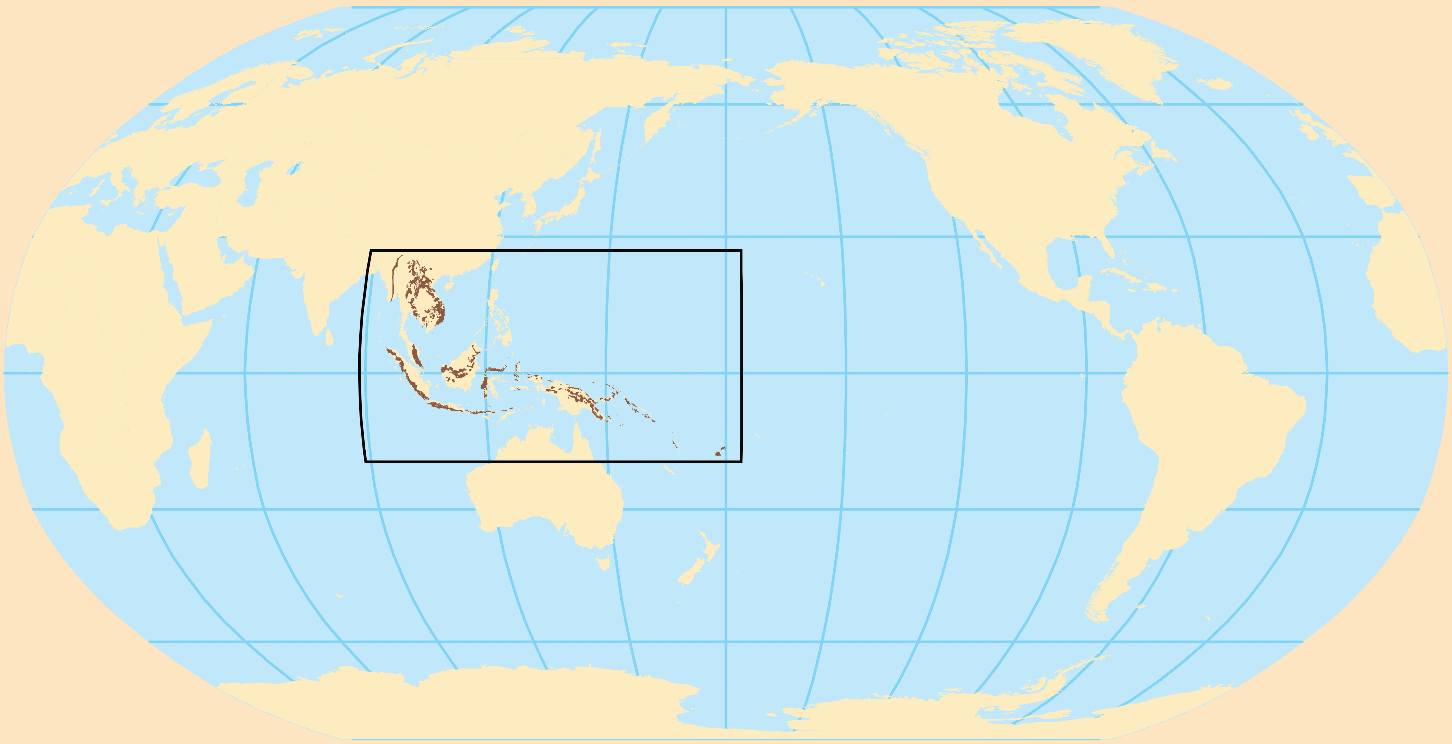
Global Mineral Resource Assessment

Porphyry Copper Assessment of Southeast Asia and Melanesia



Prepared in cooperation with the Coordinating Committee for Geoscience Programmes in East and Southeast Asia

Scientific Investigations Report 2010–5090–D

U.S. Department of the Interior
U.S. Geological Survey

Global Mineral Resource Assessment

Michael L. Zientek, Jane M. Hammarstrom, and Kathleen M. Johnson, editors

Porphyry Copper Assessment of Southeast Asia and Melanesia

By Jane M. Hammarstrom, Arthur A. Bookstrom, Connie L. Dicken, Benjamin J. Drenth, Steve Ludington, Gilpin R. Robinson, Jr., Bambang Tjahjono Setiabudi, Wudhikarn Sukserm, Dwi Nugroho Sunuhadi, Alexander Yan Sze Wah, and Michael L. Zientek, with contributions from Dennis P. Cox, Pairatt Jarnyaharn, Gwaibo Kopi, Nguyen Thi Minh Ngoc, Pichai Otarawanna, Chen Shick Pei, Ung Phany, Nguyen Vay Quy, Takehiro Sakimoto, Dulcie Saroa, Norberta Soares da Costa, Sieng Sotham, I.M. Sim, Nguyen Nhu Trung, Somob Wongsomasak, Boonsong Yokarti, and Khin Zaw

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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Tables

ANOVA	Analysis of variance
GIS	Geographic Information System
g/t	grams per metric ton
kt	thousand metric tons
Ma	million of years before the present
Mt	million metric tons
PGE	platinum-group elements
REE	rare-earth elements
SHRIMP	sensitive high resolution ion microprobe
SSIB	small-scale digital international boundaries
t	metric ton (tonne) or megagram (Mg)
USGS	United States Geological Survey

Conversion Factors

Inch/Pound to SI

	Multiply by	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
Area		
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Mass		
ounce, troy (troy oz)	31.015	gram (g)
ounce, troy (troy oz)	32150.75	megagram (Mg)
ton, short (T) (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

	Multiply by	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
Area		
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Mass		
gram (g)	0.03215	ounce, troy (troy oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
Other conversions used in this report		
metric ton (t)	1	megagram (Mg)
troy ounce per short ton	34.2857	gram per metric ton (g/t)
percent	10,000	parts per million (ppm) or grams per metric ton (g/t)
percent metal	0.01 x ore tonnage, metric tons	metric tons of metal

Porphyry Copper Assessment of Southeast Asia and Melanesia

By Jane M. Hammarstrom[1], Arthur A. Bookstrom[6], Connie L. Dicken[1], Benjamin J. Drenth[8], Steve Ludington[2], Gilpin R. Robinson, Jr.[1], Bambang Tjahjono Setiabudi[3], Wudhikarn Sukserm[4], Dwi Nugroho Sunuhadi[3], Alexander Yan Sze Wah[5], and Michael L. Zientek[6], with contributions from Dennis P. Cox[7], Pairatt Jarnyaharn[4], Gwaibo Kopi[12], Nguyen Thi Minh Ngoc[9], Pichai Otarawanna[4], Chen Shick Pei[10], Ung Phany[11], Nguyen Vay Quy[9], Takehiro Sakimoto[4], Dulcie Saroa[12], Norberta Soares da Costa[13], Sieng Sotham[11], I.M. Sim[11], Nguyen Nhu Trung[4] , Somob Wongsomasak[4], Boonsong Yokarti[4], and Khin Zaw[14]

Abstract

The U.S. Geological Survey collaborated with member countries of the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) on an assessment of the porphyry copper resources of Southeast Asia and Melanesia as part of a global mineral resource assessment. The region hosts world-class porphyry copper deposits and underexplored areas that are likely to contain undiscovered deposits. Examples of known porphyry copper deposits include Batu Hijau and Grasberg in Indonesia; Panguna, Frieda River, and Ok Tedi in Papua New Guinea; and Namosi in Fiji.

This assessment covers the countries of Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Singapore, Thailand, and parts of southeastern China, India, the Solomon Islands, Vanuatu, and Fiji. Twenty-two geographic areas were delineated as tracts that are permissive for porphyry copper deposits in Southeast Asia. Permissive tracts are grouped into four broadly defined geographic/geologic areas, as follows: (1) the Indochina Peninsula area, (2) Indonesian and Malaysian Islands, (3) New Guinea Island and Papuan New Guinea islands, and (4) Melanesia. Individual tracts range from less than 1,000 to more than 350,000 square kilometers in area. Permissive tracts are based on mapped and inferred subsurface (<1 kilometer depth) distributions of igneous rocks of specific age ranges that define magmatic arcs and magmatic belts that are likely to contain porphyry copper deposits. Most of these magmatic arcs are subduction-related, although some have porphyry-style deposits occurring in postcollisional and (or) poorly understood tectonic settings. Although maps at a variety of different scales were used in the compilation, the final tract boundaries are intended for use at a scale of 1:1,000,000.

Global grade and tonnage models for porphyry copper deposits were evaluated. Most of the known deposits are best described as fitting the copper-gold (Cu-Au) subtype of porphyry copper deposit. For some permissive tracts, a general porphyry copper-gold-molybdenum (Cu-Au-Mo) model was used. Assessment participants estimated numbers of undiscovered deposits at different levels of confidence for most of the permissive tracts. These estimates were combined with grade and tonnage models using a Monte Carlo simulation to estimate undiscovered resources. Additional resources in extensions of deposits with identified resources were not evaluated.

Assessment results, presented in tables and graphs, show mean amounts of metal and mineralized rock in undiscovered deposits at different quantile levels, as well as the arithmetic mean for each tract.

This assessment estimated a mean of 89 undiscovered porphyry copper deposits for the assessed permissive tracts in Southeast Asia and Melanesia. About 288 million metric tons (Mt) of copper and 18,000 metric tons (t) of gold, as well as byproduct molybdenum and silver, could be associated with undiscovered deposits. This represents about four times the number of deposits with identified resources (23) already discovered in Southeast Asia; reliable reported identified

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]U.S. Geological Survey, Menlo Park, California, United States.
[3]Geological Agency of Indonesia, Bandung, Indonesia.
[4]Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.
[5]Mineral and Geoscience Department, Sabah, Malaysia.
[6]U.S. Geological Survey, Spokane, Washington, United States.
[7]Palo Alto, California, United States.
[8]U.S. Geological Survey, Denver, Colorado, United States.
[9]Department of Geology and Minerals of Vietnam, Hanoi, Vietnam.
[10]Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) Technical Secretariat, Bangkok, Thailand.
[11]Department of Geology and Mines, Phnom Penh, Cambodia.
[12]Mineral Resources Authority of Papua New Guinea, Port Moresby, Papua New Guinea.
[13]Director of Geology and Mineral Resources, Dili, Timor Leste.
[14]University of Tasmania, Hobart, Australia.

resources for those 23 deposits total 84 Mt of copper and 6,000 t of gold. Eleven permissive tracts have no known porphyry copper deposits with reported resources. Three of those 11 tracts lacked sufficient information for a probabilistic assessment and are discussed in qualitative terms.

On a regional basis, both the Indochina Peninsula area and the Indonesian-Malaysian Islands area are estimated to contain about 10 times as much in place copper in undiscovered porphyry copper deposits as has been identified to date. For the New Guinea Island areas, the ratio of undiscovered to identified copper resources is about 2. Some parts of the region have a long history of porphyry exploration cycles and mine development, interrupted at times by political and social unrest, environmental concerns, and natural disasters. Changes in mining laws within the region and the recent high price of gold on the world market have prompted renewed interest in porphyry copper deposits in Southeast Asia and Melanesia. However, predicted undiscovered deposits may not be found, and if found, may not be developed.

This assessment includes an overview of the assessment results with summary tables. Detailed descriptions of each tract are included in appendixes, with estimates of numbers of undiscovered deposits, and probabilistic estimates of amounts of copper, molybdenum, gold, and silver that could be contained in undiscovered deposits for each permissive tract. A geographic information system (GIS) that accompanies the report includes tract boundaries and a database of known porphyry copper deposits and significant prospects.

Introduction

The Southeast Asia-Melanesia region is one of the world's most productive copper provinces. The region hosts world-class porphyry copper deposits, including the Batu Hijau and Grasberg deposits in Indonesia; the Panguna, Frieda River, and Ok Tedi deposits in Papua New Guinea; and the Namosi deposit in Fiji (fig. 1). Indonesia ranked sixth in world copper production in 2010 (U.S. Geological Survey, 2011). The Grasberg porphyry copper-gold deposit is the world's largest producer of gold. Parts of Southeast Asia remain underexplored. In recent years, new target areas have been recognized, historical mining districts continue to be explored, and new deposits continue to be discovered through greenfields exploration. Most of the copper production in Southeast Asia comes from porphyry copper deposits. Porphyry copper deposits provide approximately 60 percent of the world′s discovered copper (Singer, 1995). The most common ore minerals in porphyry copper deposits are chalcopyrite ($CuFeS_2$) and bornite (Cu_5FeS_4), distributed in stockwork veinlets and disseminations in hydrothermally altered intrusions and adjacent wallrock. Secondary copper minerals, such as chalcocite (Cu_2S), in oxidized, supergene enrichment zones comprise a major part or all of the ore in some deposits. Molybdenum, silver, and gold are important coproducts or byproducts in many deposits.

A probabilistic mineral resource assessment of undiscovered resources in porphyry copper deposits in Southeast Asia and Melanesia was undertaken as part of a global mineral resource assessment (Schulz and Briskey, 2003). The purpose of the assessment was to (1) delineate permissive areas (tracts) for undiscovered porphyry copper deposits at a scale of 1:1,000,000, (2) provide a database of known porphyry copper deposits and significant prospects, (3) estimate numbers of undiscovered deposits within those permissive tracts, and (4) provide probabilistic estimates of amounts of copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag) that could be contained in undiscovered deposits for each permissive tract. The U.S. Geological Survey (USGS) collaborated with the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) on the joint assessment project for Southeast Asia.

CCOP is an intergovernmental organization founded to facilitate and coordinate applied geoscience projects (http://www.ccop.or.th/). The CCOP's mission is to contribute to economic development and improve the quality of life in the region. The CCOP has eleven member countries—Cambodia, China, Indonesia, Japan, Malaysia, Papua New Guinea, Philippines, Singapore, South Korea, Thailand, and Vietnam. Fourteen other countries, including the United States, participate in CCOP activities as cooperating countries.

This assessment report covers parts of the CCOP-member countries that contain known porphyry copper deposits, as well as areas that may contain undiscovered deposits, based on available geologic information. The region was divided into four broadly defined geographic/geologic areas for the assessment. These areas are (1) the Indochina Peninsula area, (2) Indonesian and Malaysian Islands, (3) New Guinea Island and Papuan New Guinea islands, and (4) Melanesia (fig. 1). On the basis of available information, some CCOP member countries have little or no recognized potential for porphyry copper deposits (Timor Leste) although these countries have known deposits and potential for undiscovered deposits of other types. The porphyry copper assessments for other CCOP-member countries (the Philippines, China, Japan, and South Korea) are in separate reports. This assessment report covers the countries of Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Singapore, Thailand, parts of India, and the Melanesian nations of the Solomon Islands, Vanuatu, and Fiji (fig. 1).

The assessment of undiscovered porphyry copper deposits in Southeast Asia and Melanesia was done using the three-part form of mineral resource assessment based on mineral deposit models (Singer 1993, 2007a, b; Singer and Berger, 2007; Singer and Menzie, 2010). In applying the three-part form of mineral resource assessment, geographic areas (permissive tracts) are delineated using geologic, geochemical, and geophysical features typically associated with the type of deposit under consideration. The amount of metal contained in undiscovered deposits is estimated by using grade and tonnage models. Grade and tonnage models are frequency distributions of tonnages and grades of thoroughly explored deposits, based on total production, reserves, and resources at the lowest available cutoff grade. For porphyry copper deposit models, a spatial rule is used to group grade and tonnage information to represent deposits as geologic entities: all mineralized rock or alteration within 2 kilometers (km) is combined as one deposit for model construction (Singer and others, 2008). Data for deposits within the permissive tracts are compared with global grade and tonnage models using statistical tests, along with other geologic information, to select an appropriate model for assessment.

Estimates of numbers of undiscovered deposits in each permissive tract are made at different confidence levels using a variety of estimation strategies to express the degree of belief that some fixed but unknown number of deposits exists within the tract. These estimates represent a measure of the favorability of the tract and the estimator's uncertainty about what may exist (Singer, 2007a). The Monte Carlo simulation that is used to combine deposit number estimates with grade and tonnage models to produce a probabilistic estimate of undiscovered resources is the EMINERS program (Bawiec and Spanski, 2012; Duval, 2012), based on the algorithms described by Root and others (1992).

The assessment data and results for each permissive tract are presented in a standardized format in appendixes A through V of this report. Each permissive tract is assigned a unique identifier (Coded_Id), as well as a geographic/geologic name. Identifiers are based on United Nations regions (142 for Asia, 009 for Oceania), deposit type (pCu), and a 4-digit number. Permissive-tract boundaries and point locations of deposits and significant prospects are included as shapefiles in a geographic information system (GIS) format that accompanies this report (appendix W). Political boundaries are based on data maintained by the U.S. Department of State (2009).

Southeast Asia and Melanesia are areas of active exploration. This report reflects the porphyry copper projects known to the assessment team as of March 2011. Many active exploration projects focus on large concessions that attracted attention owing to reported gold associated with historical workings. Epithermal gold deposits are the initial targets of many projects, owing to the current (2011) high price of gold. Company reports mention porphyry systems associated with some of these targets, and the association of these deposit types is well known in Southeast Asia (for example, Cooke and others, 1998); however, delineation of a porphyry copper deposit, if present, awaits further exploration in most cases.

Terminology

The terminology used in this study follows the definitions used in the 1998 assessment of undiscovered deposits of gold, silver, copper, lead, and zinc in the United States (U.S. Geological Survey National Mineral Resource Assessment Team, 2000; U.S. Bureau of Mines and U.S. Geological Survey, 1976; Bates and Jackson, 1997). The terminology is intended to represent standard definitions and general usage by the minerals industry and the resource-assessment community. Some countries in the world recently have adopted more rigorous definitions of terms for estimating mineral resources and mineral reserves and for reporting exploration information to comply with legal mandates (Committee for Mineral Reserves International Reporting Standards, 2006).

Mineral deposit. A mineral concentration of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have potential for economic development.

Undiscovered mineral deposit. A mineral deposit believed to exist 1 km or less below the surface of the ground, or an incompletely explored mineral occurrence or prospect that could have sufficient size and grade to be classified as a deposit.

Descriptive mineral deposit model. A set of data in a convenient, standardized form that describes a group of mineral deposits having similar characteristics.

Grade and tonnage model. Frequency distributions of the grades and sizes of thoroughly explored, and (or) completely mined out, individual mineral deposits that are classified by a descriptive mineral deposit model.

Permissive tract. The surface projection of a volume of rock where the geology permits the existence of a mineral deposit of a specified type. The probability of deposits of the type being studied occurring outside the tract is negligible.

Resource. A mineral concentration of sufficient size and grade, and in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Identified resources. Resources whose location, grade, quality, and quantity are known or can be estimated from specific geologic evidence. For this assessment, identified resources are the deposits that constitute the grade and tonnage models used in the assessment (which can include measured, indicated, and inferred mineral resources at the lowest available cutoff grade). In addition, deposits that are not included in the models used for the assessment may be considered as identified resources if they are characterized well enough by deposit type, grade, and tonnage to meet U.S. Securities and Exchange Commission or CRIRSCO[15] reporting guidelines.

[15] Committee for Mineral Reserves International Reporting Standards (2006) (http://www.crirsco.com/welcome.asp).

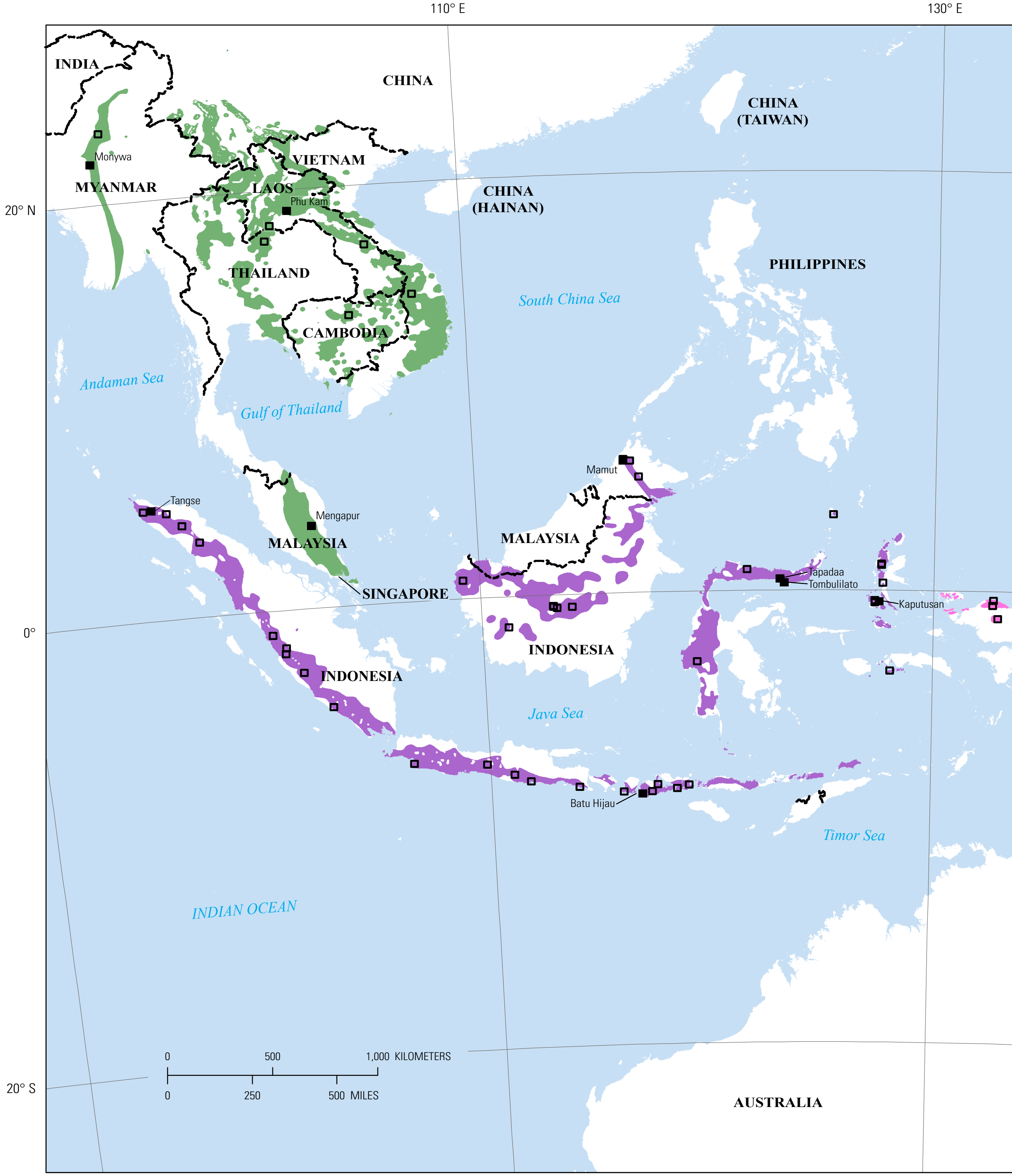
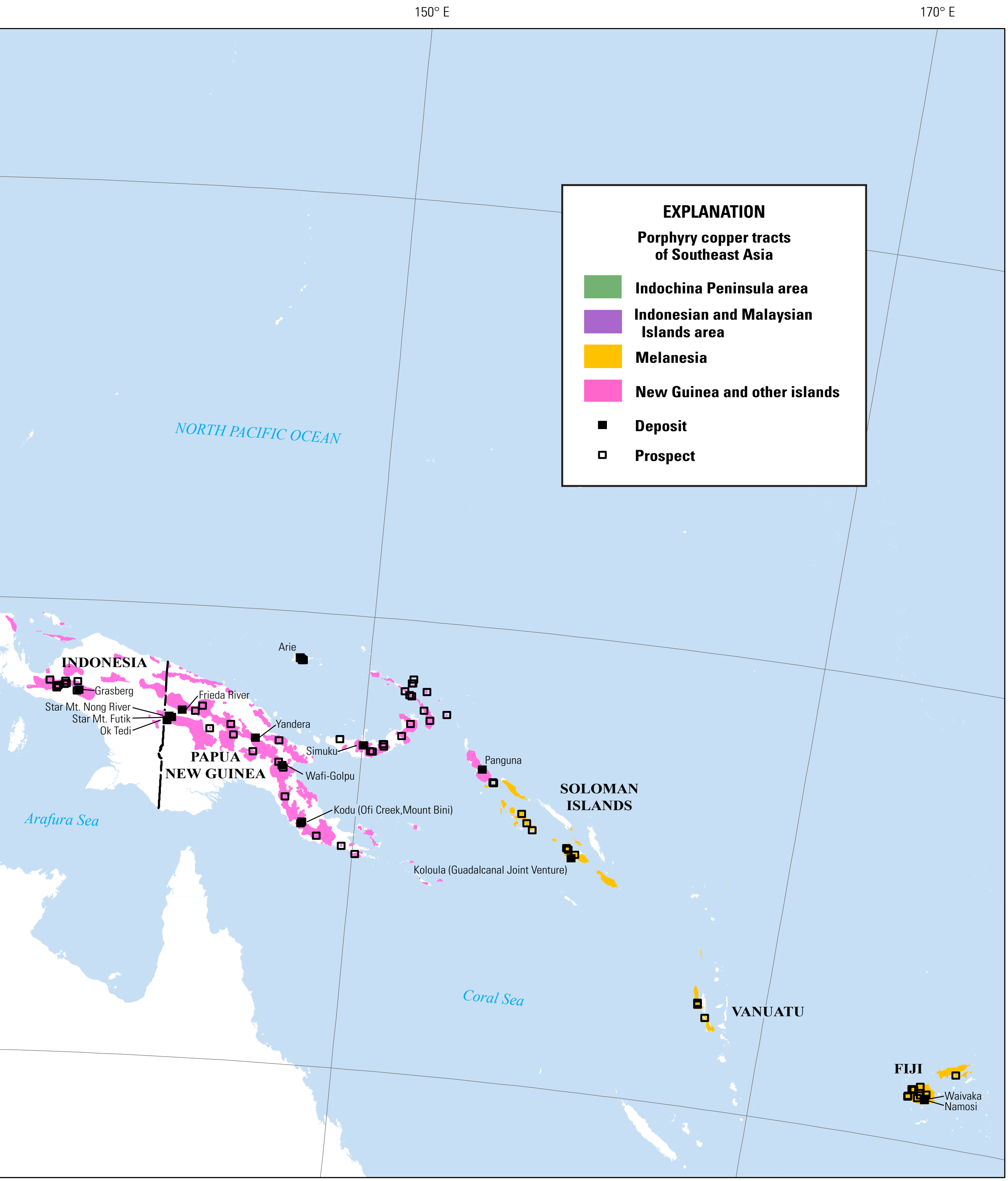


Figure 1. Map showing permissive tracts for porphyry copper deposits in Southeast Asia and Melanesia, grouped by geographic areas. Porphyry copper deposits (filled squares) and significant prospects (open squares) are shown; deposits mentioned in the text are labeled.


150° E
170° E
EXPLANATION
Porphyry copper tracts of Southeast Asia
Indochina Peninsula area
Indonesian and Malaysian Islands area
Melanesia
New Guinea and other islands
Deposit
Prospect
NORTH PACIFIC OCEAN
INDONESIA
Arie
Grasberg
Frieda River
Star Mt. Nong River
Star Mt. Futik
Ok Tedi
Yandera
Simuku
PAPUA NEW GUINEA
Wafi-Golpu
Panguna
SOLOMAN ISLANDS
Kodu (Ofi Creek,Mount Bini)
Arafura Sea
Koloula (Guadalcanal Joint Venture)
Coral Sea
VANUATU
FIJI
Waivaka
Namosi

Undiscovered resources. Resources in undiscovered mineral deposits whose existence is postulated on the basis of indirect geologic evidence. These include undiscovered resources in known types of mineral deposits postulated to exist in permissive geologic settings. Undiscovered resources may include active mines if the resource is delineated incompletely. For example, a deposit that is explored only partially and reported as "open to the west or open at depth" could be counted as an undiscovered deposit. Undiscovered resources in extensions to identified resources are not addressed explicitly in the assessment process.

Calc-alkaline, calc-alkalic; alkaline, alkalic. These terms are used in a general, non-rigorous manner to refer to plutonic igneous rocks of granitoid composition (calc-alkaline or calc-alkalic) and of syenitoid through dioritoid to gabbroid composition (alkaline or alkalic) and their volcanic equivalents (see Le Maitre and others, 2002, provisional field classifications, figures 2.10 and 2.19). In the igneous literature, the terms "-alkaline" and "-alkalic" are defined and used in multiple and inconsistent ways (see Arculus, 2003). For this assessment, the term calc-alkalic is used synonymously for calc-alkaline, and alkalic is used synonymously for alkaline, as well as for their associated deposits, which are classified as calc-alkaline (or calc-alkalic) Cu±Mo±Au or alkaline (or alkalic) porphyry copper subtypes.

Porphyry Copper Assessment of Southeast Asia and Melanesia

Porphyry copper deposits typically form in magmatic arcs, primarily in subduction-related tectonic settings. Postsubduction, collisional, and extensional back-arc settings also are recognized as permissive environments for the formation of porphyry copper-gold deposits, where processes such as postsubduction lithosphere thickening or extension, delamination, slab rollback, and asthenospheric upwelling may have facilitated remelting of lithosphere (Richards, 2009). Postsubduction porphyry copper-gold deposits typically are associated with mildly alkaline, rather than calc-alkaline, magmas, and may form isolated complexes in contrast to volcanoplutonic arcs (Richards, 2009). Molybdenum-rich porphyry copper deposits tend to be associated with calc-alkalic rocks in continental arcs, and gold-rich porphyry copper deposits tend to be associated with diorites or alkaline igneous complexes in island arcs, back-arc basins, or extensional settings. However, both molybdenum- and gold-rich deposits can occur within the same tectonic setting.

Porphyry Copper Models

Cox and Singer (1986) included a general descriptive mineral-deposit model for porphyry copper deposits, as well as separate descriptive models for Cu-Au and Cu-Mo subtypes (Cox, 1986a,b,c). However, recent descriptive models have not identified sufficient geologic criteria to justify division of a general geologic model for porphyry copper deposits into subtypes (Singer and others, 2008; Berger and others, 2008; John and others, 2010). Grade and tonnage distinctions of subtypes are discussed in the "Grade and Tonnage Models" section of this report.

Porphyry copper mineral deposit models used for the assessment include Singer and others (2008), Cox (1986a, b), Berger and others (2008), and John and others (2010). Porphyry copper characteristics and classification schemes discussed by Seedorff and others (2005) and the porphyry copper-gold model compiled by Geoscience Australia (2010) also were considered. In addition, porphyry copper models for Australia and western Pacific porphyry copper-gold deposits apply (Cooke and others, 1998; Sillitoe, 1997). These latter models are appropriate for many of the tectonic settings of Southeast Asia, where most porphyry copper deposits are Cenozoic, island-arc-related, copper-gold deposits unlike the copper-molybdenum-gold deposits in the southwestern United States or the Andes of South America. Conceptual exploration models for southwest Pacific Rim gold-copper systems, including porphyry copper deposits, are included in Corbett and Leach (1998).

For western Pacific porphyry deposits, copper-gold deposits typically are related to island arcs whereas copper-molybdenum deposits typically are related to continental margin arcs or cratons (Cooke and others, 1998). Intrusive rocks associated with many Cenozoic western Pacific porphyry deposits commonly have calc-alkaline to shoshonitic compositions, were emplaced at shallow (1 to 2 km) depths, have distinctive steep-sided, cylindrical form ("pencil porphyries"), and are spatially associated with diatremes, epithermal gold deposits, and if carbonate rocks are present, skarn deposits (fig. 2, table 1). As a result of the rapid uplift and high rates of erosion (tropical climate) in southeast Asia, coeval volcanic rocks and advanced argillic lithocaps are not always preserved. In southeast Asia, supergene enrichment zones tend to be absent or poorly developed compared with the deposits of the Andes and southwestern North America (Cooke and others, 1998). Supergene zones can develop depending on local topography, climate, and hydrology; the best example known in the study area is the oxide zone at the OK Tedi porphyry copper deposit in Papua New Guinea, which contains a 19 million metric tons (Mt) resource at 1.74 percent copper and 1.34 grams per ton (g/t) gold (Rogerson and McKee, 1990).

Gold-rich porphyry copper deposits associated with alkaline (high-K) rocks, typically syenites, also are present in Southeast Asia. Characteristic settings for these deposits include emplacement in subduction-related oceanic arcs within, or along, calderas. Many deposits are localized at fault intersections. Associated rocks typically have elevated K_2O contents, are enriched in chlorine, fluorine, and light rare-earth elements, and have oxidized, magnetite-bearing magma sources (Müller and Groves, 1999). Gold-rich porphyry copper deposits typically have abundant hydrothermal magnetite in copper- and gold-bearing potassic alteration zones; magnetite can be sufficiently abundant to cause "bull's eye" magnetic-high anomalies (Sillitoe, 1997).

Fundamental Basis for Porphyry Copper Assessment

The fundamental geologic feature (unit) for delineation of a permissive tract for porphyry copper deposits, as derived from deposit models, is defined as a subduction-related magmatic arc or a postsubduction or collisional magmatic belt of a given age. Porphyry copper deposits form in hydrothermal systems that are spatially and temporally associated with apical, generally porphyro-aphanitic parts of felsic to intermediate stocks that were emplaced at shallow depths, typically less than 1 to 4 km.

Permissive tracts for porphyry copper deposits are delineated as geographic areas that include volcanic and intrusive rocks of a specified age range that typically can be related to a particular tectonic setting (such as a subduction-boundary zone). Tracts are based primarily on geologic map units that define the magmatic arc or belt. As a framework for the description of permissive tracts identified for the assessment of Southeast Asia, we briefly describe the tectonic setting of the major magmatic arcs and belts of the region.

Tectonic Setting

Southeast Asia and Melanesia host a variety of porphyry copper deposits, including world-class deposits, and deposits that principally are exploited for gold. Both subduction and postsubduction settings for porphyry deposits are recognized. The major magmatic arcs and magmatic belts that form the basis of this assessment are shown in figure 3 and listed in table 2. A complex series of both continental and island arcs developed in response to subduction and plate reorganization related to the geodynamic evolution of the borders of the Eurasian and Indian-Australian continents, the life cycle of seas in the region, and the movement of the Pacific Plate. This complex tectonic evolution has led to the development of a myriad of arc fragments, microcontinents, accreted terranes, and sea basins, many of which are of uncertain origin. Porphyry copper deposits and prospects in the study area range from Permian to Quaternary in age; most of the preserved porphyry copper mineralized systems are Miocene-Pliocene in age (fig. 4).

Pre-Cenozoic Settings.—The Indochina Peninsula is an assembly of micro-continental fragments that were sequentially accreted to Eurasia by the end of Mesozoic time. Metcalfe (2009) provides a particularly thorough discussion of the pre-Cenozoic evolution of Southeast Asia. We refer the reader to that paper and the figures therein for details. The continental terranes that make up today's Indochina and South China originated as blocks that were rifted and dispersed from Gondwana (fig. 5*A*). This dispersion, as three elongate continental slivers, took place at three times, in the Devonian, in the Permian, and near the Triassic-Jurassic boundary. These rifting events marked, successively, the birth of the Paleo-Tethyan, Meso-Tethyan, and Ceno-Tethyan oceans. Igneous rocks were generated by subduction beneath and collision between all these continental fragments; the most important pre-Cenozoic arcs in Southeast Asia are the Sukhothai island-arc system and the Loei and Truong Son magmatic belts (fig. 3), all of which show evidence of porphyry copper-style mineralization and host porphyry copper deposits.

These pre-Cenozoic terranes have been translated, rotated, and deformed by the collision of the Indian subcontinent with Asia, beginning in earliest Cenozoic time and continuing to the Holocene (Metcalfe, 1999). This deformation has been largely accommodated by a giant dextral megashear zone (Ailoshan-Red River Fault Zone) that today forms the boundary between South China and Indochina (fig. 5*A*).

Cenozoic Settings.—Building on the work of Hamilton (1979) and Mitchell and Leach (1991), Garwin and others (2005) described the tectonic setting, geology and gold and copper deposits associated with 20 major Cenozoic magmatic arcs that form a >17,000 km-long volcano-plutonic chain extending from Japan southward to New Guinea, and west-northwest through Indonesia to Myanmar. The porphyry-copper-bearing magmatic arcs described by Garwin and others (2005) provided the geologic framework for most of the Cenozoic assessment areas.

Indochina Peninsula Area

Carboniferous and Permo-Triassic Arcs

Widespread Carboniferous through Late Triassic magmatic rocks in Southeast Asia have been assigned to a variety of named arcs. They are all related to the amalgamation of microcontinents that were rifted from Gondwana and drifted north due to subduction of the Paleotethyan ocean (Wakita and Metcalfe, 2005). We recognize three named arcs or belts that are described below.

Sukhothai Island-Arc System

The Sukhothai island-arc system (no. 3, fig. 3), as defined by Sone and Metcalfe (2008), is a single island arc, nearly 3,000 km long, that developed along the western margin of the Indochina terrane (fig. 5*A*) and was active from latest Carboniferous time through the Permian until the final amalgamation of Indochina in the Late Triassic (the Indosinian Orogeny). Today, it extends from southern Yunnan south through northern Lao People's Democratic Republic[16] and Thailand, where it disappears beneath the Gulf of Thailand

[16] The country commonly referred to as "Laos" is officially known as the Lao People's Democratic Republic. Laos is used on figures in this report.

near the Thai-Cambodia border. It likely is present below this shallow sea as it reappears in southernmost Thailand and Malaysia before disappearing once again into the Karimata Strait. Volcanic rocks of this arc mostly are andesitic in composition and the presence of volcanogenic massive sulfide deposits suggests that much of the volcanism was submarine. Some volcanic suites show chemical affinities with continental-arc rocks and the youngest rocks in the arc probably were emplaced on continental crust (Sone and Metcalfe, 2008).

Loei Magmatic Belt

To the east of the Sukhotai Arc system, the Loei magmatic belt (no. 1, fig. 3) has been defined by a 500-km-long varied suite of Permian and Triassic intrusive and volcanic rocks in northwestern Lao People's Democratic Republic and northern Thailand (Royal Thai Government Department of Mineral Resources, 2010). It is known for hosting base-metal deposits, including the Phu Thong Daeng and Phu Hin Lek Fai porphyry copper deposits and the Phu Lon copper-gold skarn deposit in Thailand (fig. 1).

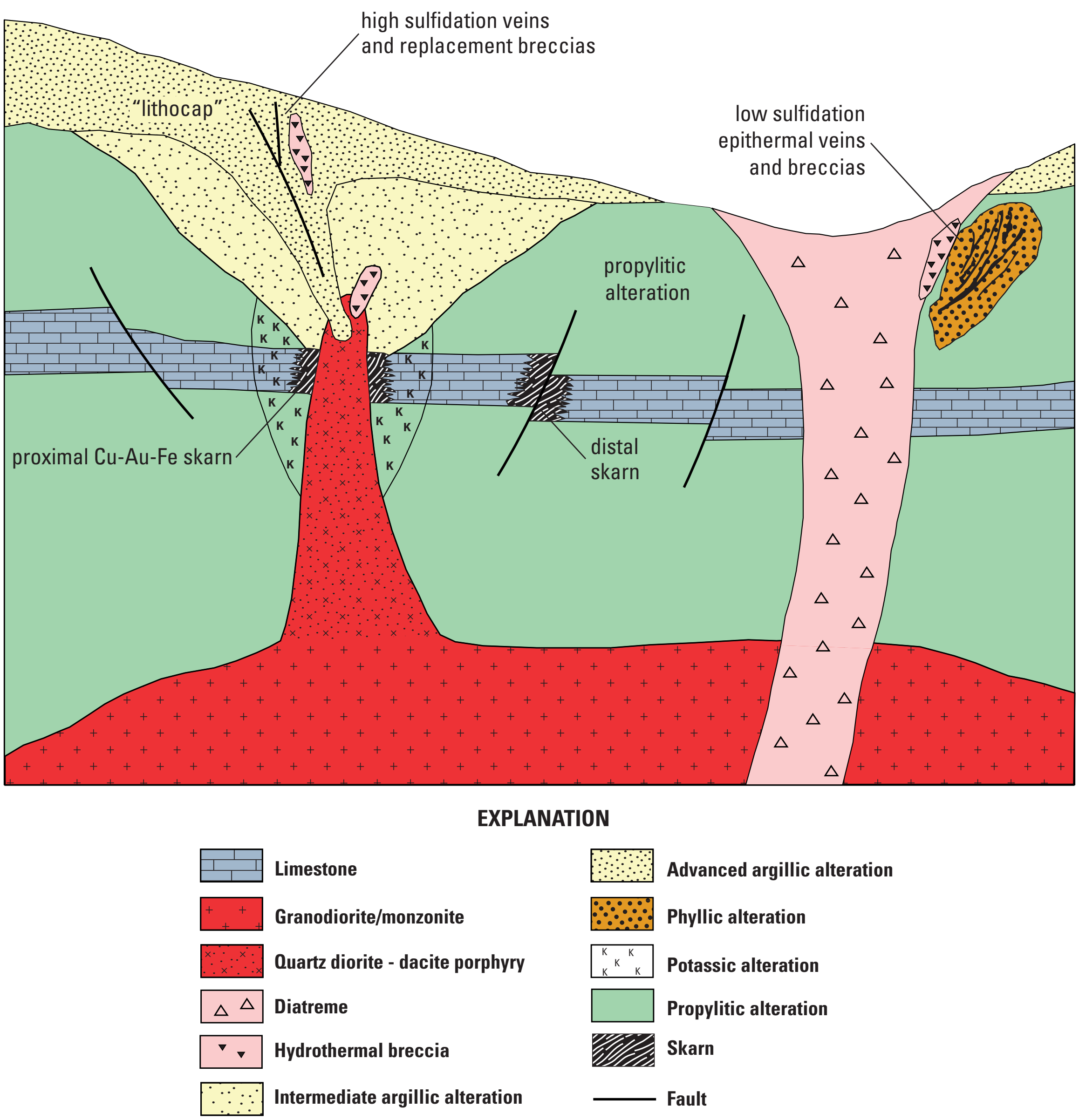


Figure 2. Generalized model of western Pacific porphyry copper-gold deposits (based on Cooke and others, 1998). See table 1 for explanation of terms.

Table 1. General characteristics of porphyry copper deposits in Southeast Asia.

[Based on Cooke and others (1998), Corbett and Leach (1998), and Johnand others (2010)]

Regional-scale features	Deposits tend to occur in belts and clusters
	Proximity to known deposits is a good exploration guide
	Coeval volcanic and intrusive rocks indicate appropriate levels of exposure
	Unmetamorphosed host rock
	Cu-Au deposits in island arcs after arc reversals; postcollisional settings
	Associated with oxidized, I-type, magnetite series, subvolcanic intrusions
	Arc-parallel and arc-oblique fault intersections
Local-scale features	Small (<1 km^2), steep-sided, cylindrical, vertically extensive stocks; margins of batholiths
	Proximity to intrusions with phaneritic textures (<4 km)
	Porphyritic diorite to quartz diorite to monzonite stocks
	Hypabyssal intrusions in andesitic volcanic rocks
	Roots of eroded stratovolcanoes
	Association with skarns and epithermal deposits
	Telescoped epithermal systems over porphyries
	Diatreme breccias; intramineral intrusions
	Significant structural control on magma emplacement and mineralization
	Typically shallow (1–2 km) depth of emplacement
Alteration	K-silicate (biotite, magnetite, orthoclase, quartz, anyhydrite, chalcopyrite, actinolite)
	Propylitic (chlorite, epidote, calcite, pyrite, albite)
	Intermediate argillic [SCC] (sericite, chlorite, kaolinite or illite, pyrite, calcite)
	Phyllic (sericite, quartz, pyrite)
	Advanced argillic (alunite, kaolinite, pyrophyllite, quartz, dickite, gibbsite, pyrite, enargite, covellite)
	Tourmaline absent
	Supergene zone typically <60 m thick due to climate controls; best preserved along ridge crests; may be well-developed (as much as 600 m thick) depending on local topography and hydrology
Geochemical guides	Calc-alkaline to high-K calc-alkaline to shoshonitic volcanic sequences
	Magmatic $\delta^{34}S$ (~-3 to +1‰; magmatic $\delta^{18}O$ (~+4 to +10‰) to meteoric with alteration
	Stream sediment and soil sampling: anomalous concentrations of Cu, Au, Mo, Ag, Zn, Pb, As, Sb, Hg, Te, Sn, S
Associated deposit types	Skarns (Cu, Au, Fe)
	High-sulfidation epithermal gold; "lithocaps" (masses of pyrite and vuggy silica in advanced argillic alteration zones above subvolcanic intrusions)
	Low-sulfidation epithermal gold-silver

Truong Son Magmatic Belt

Farther east, Permian to Triassic intermediate to felsic magmatism characterizes the Truong Son magmatic belt in the Lao People's Democratic Republic and Vietnam (no. 2, fig. 3; Hoa and others, 2008). It is a 1,000-km-long continental-margin arc, characterized by calc-alkaline volcano-plutonic complexes that formed primarily between 270 and 250 Ma and by post-collision alkaline felsic volcano-plutonic complexes that formed primarily after 245 Ma. There are also a few peraluminous granites with ages between 260 and 245 Ma that are interpreted to mark the collision of Indochina with the South China-Vietnam block.

Jurassic and Cretaceous Arcs

In southernmost Vietnam and southeastern Cambodia, I-type Jurassic and Cretaceous magmatic rocks formed as a result of northwest-directed subduction of the Pacific Plate beneath Indochina (no. 4, fig. 3; Taylor and Hayes, 1983). The rocks have not been studied extensively, although Thuy and others (2004) report that the rocks in Vietnam are metaluminous I-type granitoids that vary in composition from about 56 to 76 percent silica. This area is part of the larger Pacific margin arc of southeastern China.

Tertiary Arcs

Wuntho-Popa Arc

The Pliocene to Quaternary Wuntho-Popa magmatic arc (no. 5, fig. 3) includes an onshore portion that extends for 1,200 km from Wuntho State in northern Myanmar through Mount Popa in southern Myanmar, and a southward offshore extension along a chain of islands in the Andaman Sea (figs. 3 and 5). This magmatic arc is a northern extension of the Sunda Arc, but the Wuntho-Popa Arc separated from it by strike-slip displacement and subsequent extension beneath the Andaman Sea. The Wuntho-Popa magmatic arc is related to northeast-directed oblique subduction of the Indian subcontinent and the Indian Ocean Plate beneath Indochina along the Sunda Trench (Mitchell, 1993; Curray, 2005; Chandrasekharam and others, 2009). Today, this relative movement is largely accommodated by the dextral strike-slip Sagaing Fault system (fig. 5*A*) that marks the boundary between the West Burma continental block to the west and the Sibumasu terrane (see Sone and Metcalfe, 2008, fig. 3; Hutchison, 1989). The onshore portion of the arc is primarily mafic calc-alkaline (Mitchell and others, 2008) to high-K calc-alkaline rocks (Maury and others, 2004), while the offshore subsea portion is mostly tholeiitic (Hutchison, 1989). A few alkaline to shoshonitic rocks occur about 100 km to the east of the calc-alkaline arc along the east side of the Sagaing Fault.

Western Indonesian Islands Area

Tertiary Arcs

Sunda-Banda Arc

The Eocene to Holocene Sunda-Banda Arc (no. 6, fig.3) that extends 4,000 km from northwestern Sumatra to Java through the Banda Island group of eastern Indonesia is related to subduction of oceanic crust along the Sunda-Banda Trench system (fig. 5*B,C*). The basement to the arc varies from Eurasian continental crust with Mesozoic to late Paleozoic platform sedimentary rocks intruded by Cretaceous two-mica granites in Sumatra in the eastern segment of the arc, Cretaceous to Cenozoic melange and ophiolite in Java in the central portion of the arc, to oceanic crust in the western Banda Arc portion of the arc (Hamilton, 1979). Porphyry copper mineralization in the Sunda-Banda Arc, mostly late Eocene to Pliocene age, generally is associated with bodies of andesite porphyry, dacite porphyry, and tonalite porphyry. This calc-alkaline magmatism declined in the early Miocene, followed by erosion and widespread deposition of sedimentary rocks. In the late Miocene to Pliocene, collision of the Australian continent with the western segment of the Sunda-Banda Arc shut off subduction along the Timor Trench and initiated a polarity shift to southward subduction of oceanic crust of the marginal Banda Sea beneath the arc (Garwin and others, 2005).

Ambon Arc

The Pliocene-Quaternary Ambon Arc in the Moluccan Islands (no. 9, fig. 3), extends from Ambelau Island across western Seram and Ambon Island (fig 5*C*) to the small islands of the Banda Archipelago. The Ambon Arc and the Moluccan Islands are located east of Sulawesi, west of New Guinea, and north of Timor, near the intersection of the Indo-Australian, Pacific, and Eurasian Plates (fig. 5*B*). Collision of the Australian continent with the western segment of the Sunda-Banda Arc in the late Miocene to Pliocene shut off subduction along the Timor Trench, initiating plate reorganization and southward subduction of Irian Jaya continental crust beneath Seram along the Seram Trough (McCaffrey, 1988). Honthaas and others (1999) separate the Ambon Arc from the Sunda-Banda Arc based on geochemical differences in their Pliocene and younger volcanic rocks and differences in the subduction settings of the arcs. The Ambon Arc consists of two suites of island-arc magmas. These are (1) Pliocene low-K calc-alkaline volcanic rocks (basalts, andesites, dacites, rhyolites) related to mantle melting above the subducting Irian Jaya Plate; and (2) Pleistocene high-K calc-alkaline andesite, dacites, rhyolites, and granites formed by assimilation of continental crust (Whitford and Kezek, 1979).

Halmahera Arc

The Miocene to Holocene Halmahera Arc (no. 10, fig. 3) sweeps north across the western arm of the Halmahera Islands and includes Morotai, Halmahera, Bacan, and Obi Islands (fig 5*C*). The arc system extends 400 km from near the Philippine Trench to the western extension of the Sorong Fault (fig. 5*B*). The basement to the arc consists primarily of Cretaceous-Paleocene ophiolite in Halmahera, Bacan, and Obi (Hall and others, 1991), although there

Table 2. Principal magmatic arcs of Southeast Asia and Melanesia.

[Map key for figure 3; arcs and belts based primarily on Garwin and others (2005); *, Inner Melanesian arc extended across northern New Guinea Island to include accreted terranes; km, kilometers]

Map key	Magmatic arcs and belts	Age range	Arc Length in km	Arc /crust type	Key reference
1	Loei magmatic belt	Permian to Triassic	900	oceanic and continental	Boonsoong and others (2011)
2	Truong Son magmatic belt	Permian to Triassic	1,000	oceanic and continental	Hoa and others (2008)
3	Sukhothai Arc system	Carboniferous to Triassic	1,700	oceanic and continental	Sone and Metcalfe (2008)
4	South Indochina Arcs	Jurassic to Cretaceous	700	continental	Mitchell and others (2008)
5	Wuntho-Popa Arc	Miocene to Holocene	1,200	continental	Garwin and others (2005)
6	Sunda-Banda Arc	Eocene to Holocene	3,800	oceanic (E); continental (W)	Garwin and others (2005)
7	Central Kalimantan magmatic belt	Eocene(?) to Miocene	1,200	continental	Garwin and others (2005)
8	Sulawesi-Sangihe Arc	Miocene to Pliocene	1,200	oceanic (NE); continental (SW)	Garwin and others (2005)
9	Ambon Arc	Pliocene to Quaternary	300	oceanic	Honthaas and others (1999)
10	Halmahera Arc	Neogene to Holocene	400	oceanic (N); continental (S)	Garwin and others (2005)
11	Maramuni Arc	Miocene	1,000	continental and accreted oceanic	Garwin and others (2005)
12	Moon-Utawa Arc	Miocene	200	continental?	Carlile and Mitchell (1994)
13	Medial New Guinea magmatic belt	Late Miocene to Pliocene-Pleistocene	1,800	continental; postcollisional	Garwin and others (2005)
14	Inner Melanesian Arc*	Late Oligocene to Holocene	1,000	oceanic	Garwin and others (2005)
15	Outer Melanesian Arc	Eocene to Holocene; Pliocene to Holocene	>800	oceanic	Garwin and others (2005)
16	Sulu-Zamboanga Arc	Miocene to Holocene	400	oceanic (NE); continental (SW)	Garwin and others (2005)

are Mesozoic and probable Precambrian gneiss and schist exposed on Bacan Island (Hamilton, 1979; Malaihollo and Hall, 1996). The Halmahera Island region has a long history of magmatic activity. The ophiolitic basement was formed in an intra-oceanic arc (Ballantyne, 1992) and it is overlain in Halmahera and Obi Islands by products of a Late Cretaceous arc and in Halmahera, Bacan, and Obi by an Eocene to Oligocene arc (Hall and others, 1988a,b; Ali and Hall, 1995; Malaihollo and Hall, 1996). These arcs formed as the result of subduction at the margin of the Philippine Sea Plate in an intra-oceanic setting. Arc magmatism was terminated between the late Oligocene and early Miocene by collision with the north Australian margin (Hall, 1996). During the middle Miocene, there was little or no magmatic activity and marine platform carbonates were deposited over a large area. Arc magmatism resumed in the late middle Miocene. All these rocks form the basement to the Neogene Halmahera Arc, which has been active since about 11 Ma between Obi in the south and Morotai at the north end of the island chain (Baker and Malaihollo, 1996). The active arc rocks have geochemical data indicating a oceanic-arc chemistry in north and central Halmahera (Morris and others, 1983); continental crust contribution is present in the Neogene lavas on Bacan (Hakimand and Hall, 1991). These data are consistent with movement of Australian continental fragments along strands of the Sorong Fault, as first suggested by Hamilton (1979).

Sulawesi-Sangihe Arc

The Miocene to Holocene Sulawesi-Sangihe magmatic arc (no. 8, fig. 3) extends more than 1,200 km from north of Sangihe Island southward through the northern arm of Sulawesi, west along the neck of Sulawesi, and continues south along the west arm of Sulawesi, ending in small volcanic islands north of Flores (fig. 5*B*).

The western portion of the arc overlies Sundaland (Eurasian) continental crust (fig. 5*B*) and Cretaceous to Eocene metamorphic rocks, which are intruded by late Miocene to Pliocene granitoids (Kavalieris and others, 1992). These rocks are overlain unconformably by Eocene to Oligocene submarine basalt, andesite, and sedimentary rocks that form part of an oceanic arc extending east along the North Arm of Sulawesi (Carlile and others, 1990; Kavalieris and others, 1992). Geochemical and isotopic data from northwestern Sulawesi support the inferred transition from continental- to oceanic-arc settings from west to east and indicate the presence of an underthrust fragment of the Australian continent that extends from the western edge of North Sulawesi through the northern and central parts of west Sulawesi (Elburg and others, 2003). The early to middle Miocene portion of the arc consists of andesitic to dacitic volcanic and volcaniclastic rocks and sedimentary rocks intruded by diorite, quartz diorite, granodiorite, and

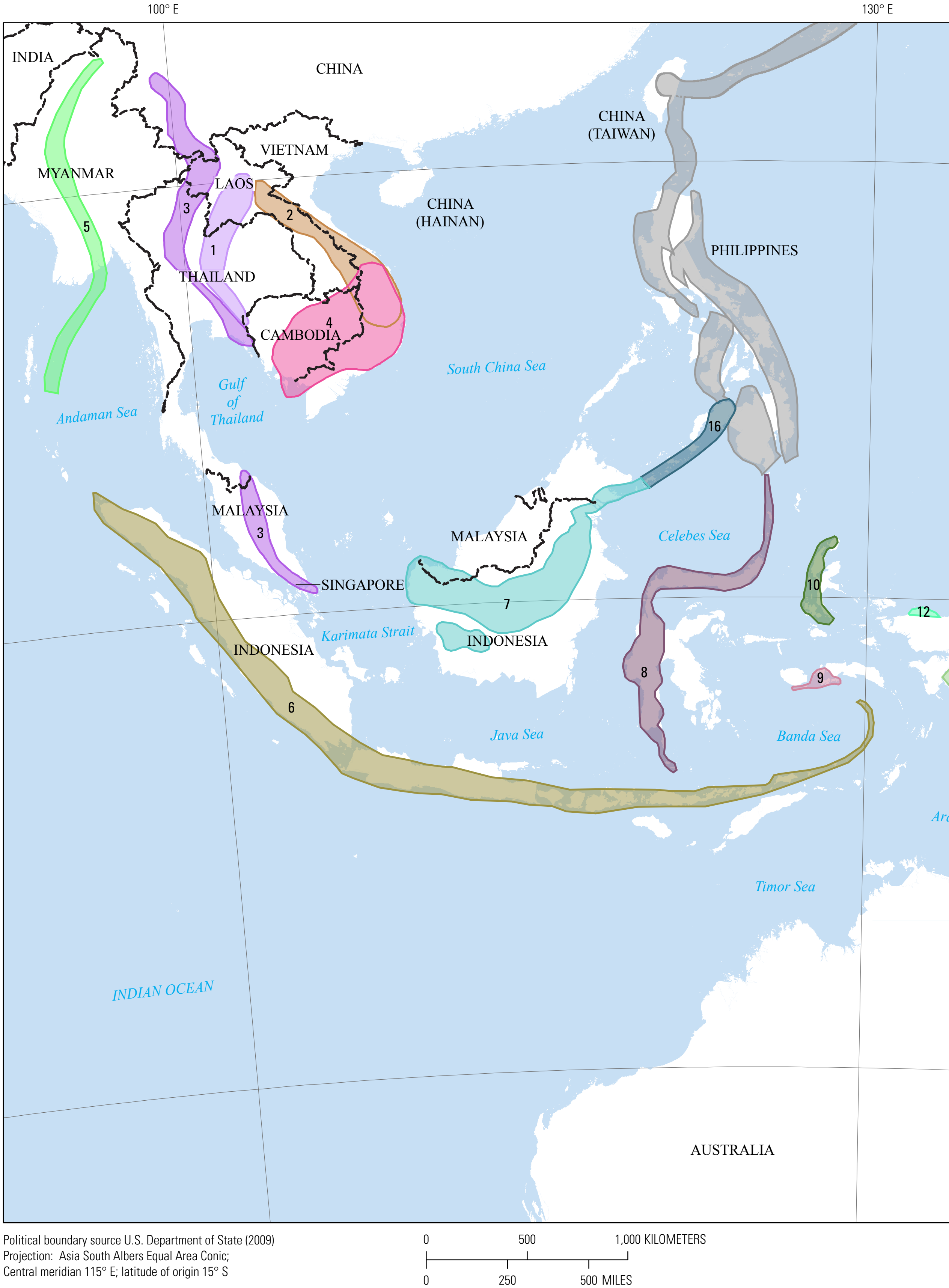
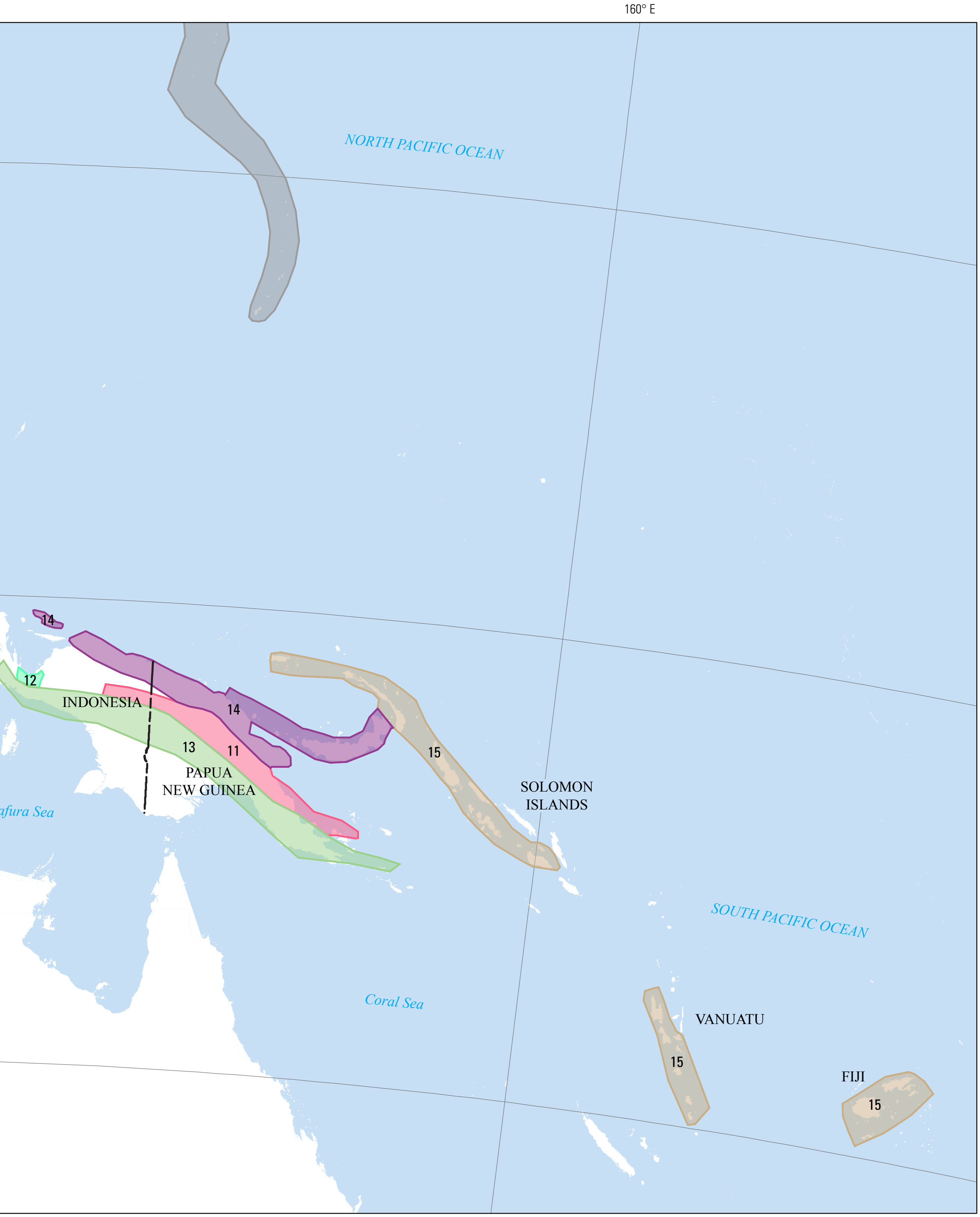


Figure 3. Map of the principal magmatic arcs of Southeast Asia and Melanesia. Arcs that continue north into the Philippines are shown in gray. See table 2 for map key and references.


160° E
NORTH PACIFIC OCEAN
14
12
INDONESIA
14
13
11
PAPUA
NEW GUINEA
15
SOLOMON
ISLANDS
afura Sea
SOUTH PACIFIC OCEAN
Coral Sea
VANUATU
15
FIJI
15

their subvolcanic porphyritic equivalents (Carlile and others, 1990; Kavalieris and others, 1992). Quaternary andesitic stratovolcanoes define the arc from north Sulawesi through Sangihe Island (fig. 5*B*). Major northwest-striking faults influenced the distribution of volcanic and sedimentary rock successions in north Sulawesi. The movement along these faults is oblique-slip, with arc-parallel extension indicated by the progressive down-to-the north movement of the fault blocks in north Sulawesi (Carlile and others, 1990).

Central Kalimantan Magmatic Belt

The Late Oligocene to Pliocene Central Kalimantan magmatic belt (no. 7, fig. 3; Carlile and Mitchell, 1994) extends approximately 1,200 km from western Sarawak, northeast through central Kalimantan, into Sabah where it merges to the northeast with the western onshore extension of the Neogene Sulu-Zamboanga Arc of the Philippines (no. 16, fig. 3) in the Semporna peninsula of Sabah (fig. 5*B*). The arc is defined by the discontinuous distribution of calc-alkaline andesitic, trachyandesitic, and dacitic volcano-plutonic centers, mapped as the Sintang intrusive suite in western Kalimantan and the Long Lai intrusive suite in northeastern Kalimantan (Carlile and Mitchell, 1994).

The continental basement to the arc consists of Paleozoic metasedimentary rocks intruded by Triassic to Carboniferous and Cretaceous (Schwaner Massif) granites in western Kalimantan (Hamilton, 1979; Hutchison, 1989); Late Cretaceous to Paleogene ophiolite, metasedimentary, and volcanic rocks comprise the basement to the arc in eastern Kalimantan and Sabah. The northwest-striking arc-transverse Kinabalu Fault system (fig. 5*B*), that parallels the Late Cretaceous to Paleogene ophiolite belt in Sabah, has localized intrusive centers and dikes of the magmatic arc.

The late Oligocene to Pliocene igneous rocks in the belt overlap and postdate folding, thrusting, uplift, and erosion of pre-Miocene rocks and continental basement in Kalimantan (Hutchison, 2005; Moss and others, 1998). This tectonic-magmatic event resulted in about 1–2 km of exhumation from 25 to 23 Ma, an eastward shift of basin sedimentation (Moss and others, 1998), and a northeastward shift in magmatic activity. This deformation, uplift, and rapid erosion is interpreted to record a collision between the extended passive continental margin of South China that underthrust the northern part of the Eurasian Sundaland continental margin in Borneo and ended Cretaceous to Paleogene subduction of the proto-South China Sea (Hutchison, 2005; Hall and Wilson, 2000). The relationship of this late Oligocene to Pliocene magmatic arc to subduction is unclear, but the arc may be related to tectonic reactivation of melting in the Cretaceous-Paleogene subducted slab. The tectonic setting for the porphyry copper deposits that occur in this tract is consistent with the postsubduction porphyry copper-gold model described by Richards (2009).

New Guinea Island, Indonesia and Papua New Guinea

The eastern half of the island of New Guinea is the independent country of Papua New Guinea. The western half of the island includes the Indonesian provinces of Papua and West Papua, formerly known as Irian Jaya. The regional tectonic setting of the island is shown in figure 6. The shape of the island, that of a westward-flying bird, is used to describe various parts of the island (Quarles van Offord and Cloos, 2005). The Bird’s Head forms the northwesternmost promontory of the island (fig. 7). The southeasternmost part of the island, the Papuan New Guinea Peninsula, is called the Bird’s Tail. The present-day island formed as a result of complex island arc-continent collisions during the Cenozoic. Four major east-west-trending structural belts define the central part of the island known as the Bird’s Body. These belts originally were defined by Dow (1977) and Hamilton (1979), refined by various workers, and summarized in Hill and Hall (2003) and Quarles van Ufford and Cloos (2005). The belts (fig. 7), from north to south, are (1) Paleogene accreted island arcs and oceanic terranes; (2) the Mobile Belt, which includes Miocene intrusive and volcanic rocks; (3) the Fold Belt, Australian continental crust that was deformed during from late Miocene to the Holocene after the late Oligocene-Miocene continent-arc collision; and (4) the Stable Platform (Fly platform), underlain by Australian continental crust (Hill and Hall, 2003).

Paleogene Arcs

Inner Melanesian Arc

Southwestward subduction of the Pacific Plate in the Eocene to early Oligocene formed the Inner Melanesian calc-alkaline arc (no. 14, fig. 3). Segments of the arc that extends for more than 1,000 km include accreted Paleogene island arcs preserved along northern New Guinea Island in the Gauttier terrane, Cyclops Mountains, Bewani-Torricelli Mountains, and Adelbert and Finisterre Ranges (fig. 7), as well as Eocene to early Oligocene igneous rocks on New Britain Island (fig. 7). Late Oligocene to early Miocene plate reorganization occurred about 25 Ma, when New Britain was situated at the intersection of the South Caroline and Melanesian Arcs (Garwin and others, 2005). The accreted arcs on New Guinea Island are poorly understood but may represent remnants of the Philippine Sea Plate that were fragmented by strike-slip faulting since 25 Ma (Ali and Hall, 1995). During the mid- to late Miocene, jamming of the Melanesian Trench by collision of the Cretaceous Ontong Java oceanic plateau[17] (fig. 6) led to a cessation of arc magmatism and changes in subduction polarity.

The Inner Melanesian Arc hosts porphyry copper deposits on New Britain, but no deposits are known in the accreted

[17] The 1,900,000 square kilometer (km^2) Ontong Java Plateau, which represents the largest and thickest oceanic plateau on Earth, is interpreted as the surface location of the head of a mantle plume (Mann and Taira, 2004).

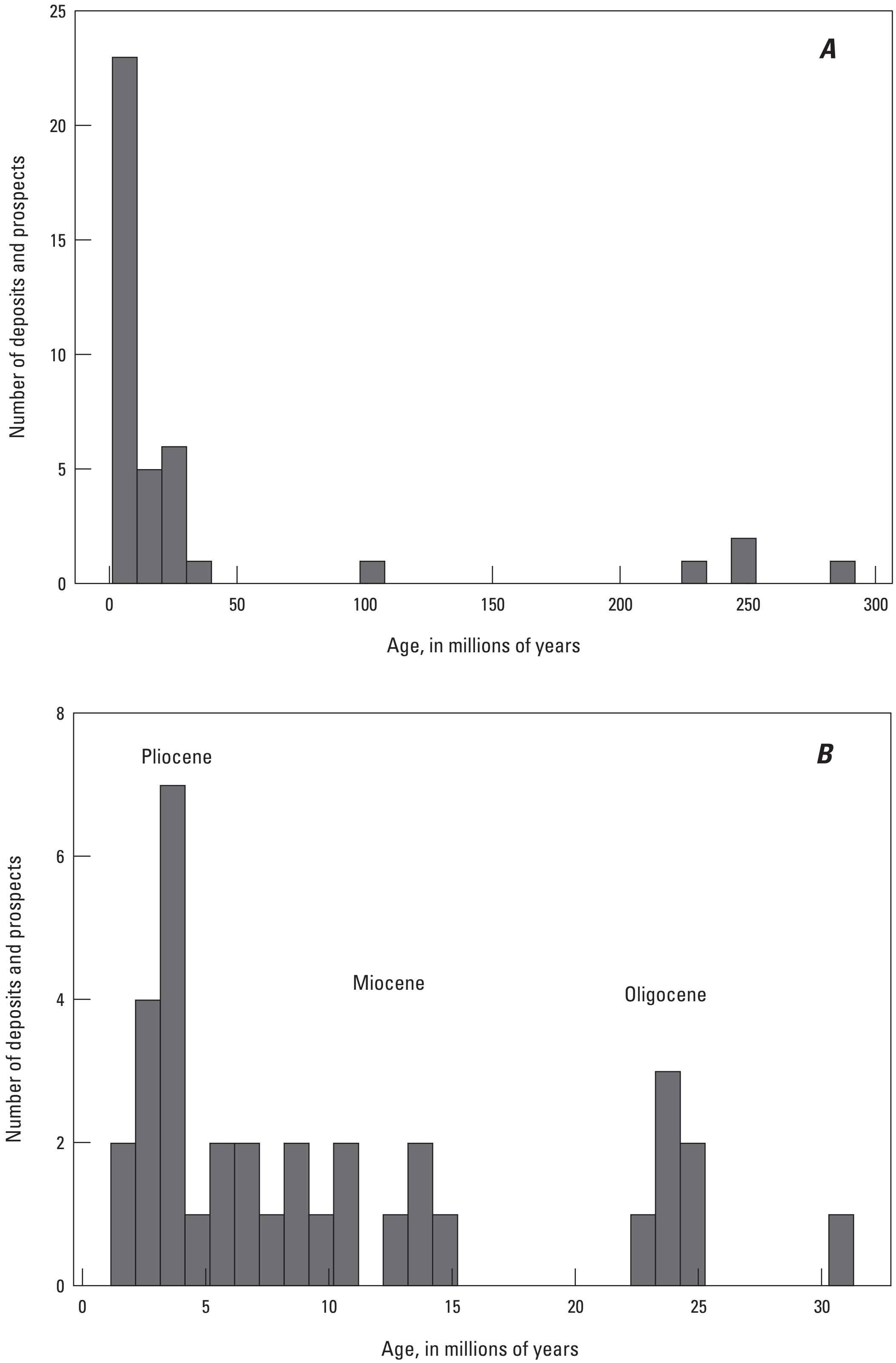


Figure 4. Chart of the age distribution of dated porphyry copper deposits and prospects in Southeast Asia. *A*, Time span for all dated deposits and prospects. *B*, Cenozoic Era.

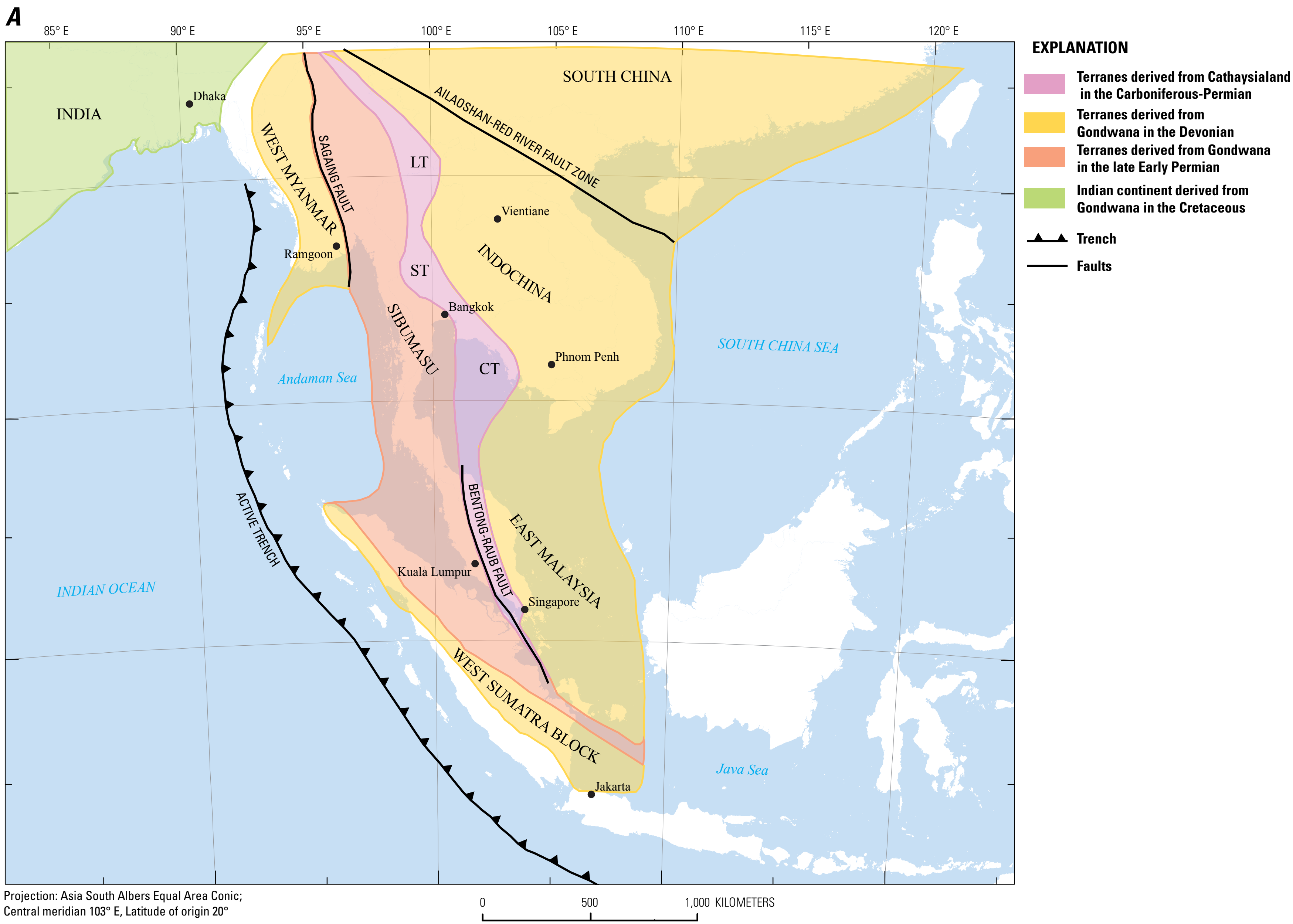
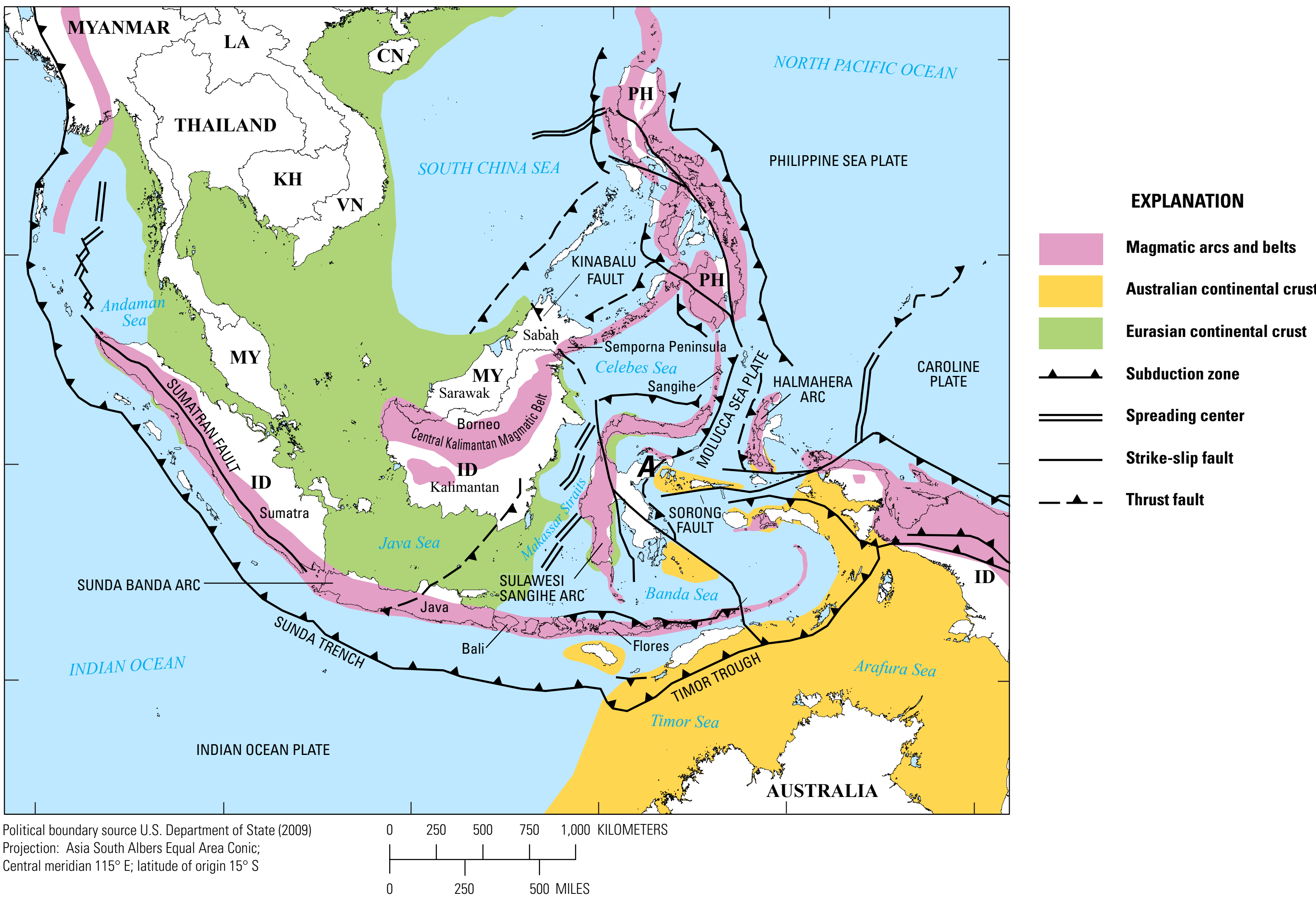


Figure 5. Map showing the regional tectonic setting of the Indochina Peninsula and western Indonesia. A, Continental blocks, Gondwana-derived terranes, and major faults in the Indochina Peninsula area. LT, Lincang terrane; ST, Sukhothai terrane; CT, Chanthburi terrane. Based on Metcalfe (2009). B, Present-day extent of Eurasian and Australian continental margins after Garwin and others (2005). ID, Indonesia; LA, Lao People's Democratic Republic; KH, Cambodia; MY, Myanmar; VN, Vietnam; PH, Philippines. C, Islands of western Indonesia and Malaysia.

B



Political boundary source U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 115° E; latitude of origin 15° S

Figure 5.—Continued

C

Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic
Central meridian 115° E; latitude of origin 15° S

0 250 500 750 1,000 KILOMETERS
0 125 250 375 500 MILES

Figure 5.—Continued

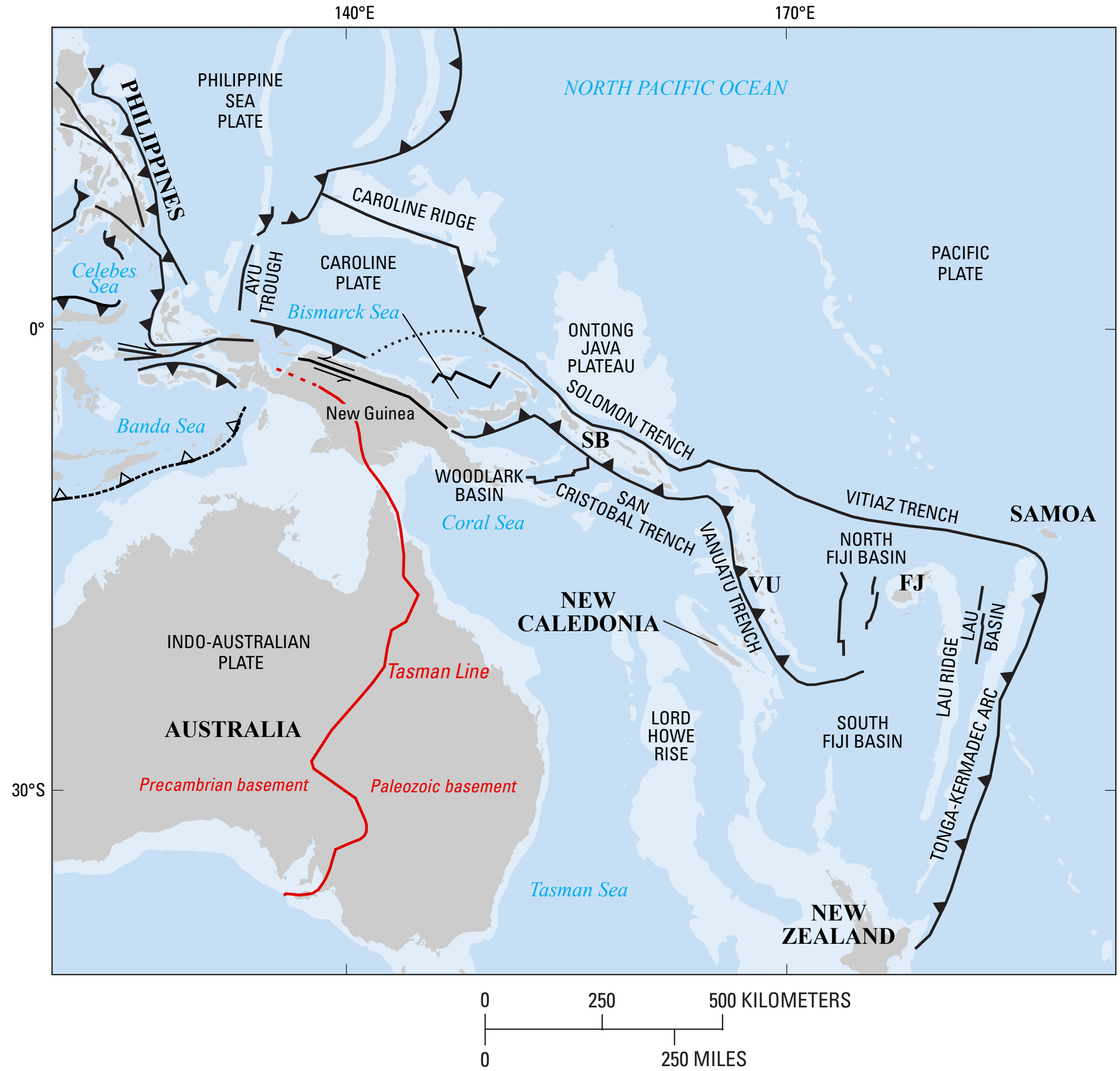


Figure 6. Map showing the regional tectonic setting of eastern Indonesia and Papua New Guinea (after Hill and Hall, 2003). Areas in light blue indicate continental shelf areas of Australia and Eurasia, areas of thickened oceanic crust, and arcs. Barbed lines represent active modern subduction zones. SB, Solomon Islands; VU, Vanuatu; FJ, Fiji. The Tasman Line marks the approximate boundary between basement of Precambrian continental crust of the Australian craton to the west and Paleozoic continental crust to the east.

terranes on New Guinea Island. The Ramu-Markham Fault in Papua New Guinea (fig. 8), a seismically active mid-crustal detachment, represents the suture between the Finisterre accreted island arc terrane and basement rocks of Australian origin. The fault connects offshore with the New Britain Trench (Stevens and others, 1998). In New Britain, subduction-related arc magmatism began again in the Pliocene and continues to the present.

Miocene Arcs

Maramuni Arc of Papua New Guinea

The calc-alkaline igneous suite of rocks that define the Miocene Maramuni Arc extends for 1,000 km along the southwestern margin of the New Guinea Mobile Belt (fig. 7). The Maramuni Arc probably formed due to subduction of the Solomon Sea under eastern New Guinea following a southward jump in subduction from the Melanesian Trench to the Maramuni Trench. The change in subduction likely was related to early to mid-Miocene collision of the Ontong Java Plateau with the Melanesian Arc (fig. 6). Quarles van Ufford and Cloos (2005) describe the Maramuni Arc forming as a result of subduction from 20 to 10 Ma along northeastern New Guinea. The arc was emplaced into Australian continental crust in Papua New Guinea. According to Quarles van Ufford and Cloos (2005), Maramuni Arc magmatism occurred between two major Cenozoic collisional orogenic events: (1) the Oligocene Peninsular Orogeny, recognized only in the Papuan peninsula, and (2) the Central Range Orogeny that began in middle Miocene time. The mobile belt is separated from the accreted arcs to the north by left-lateral strike-slip faults that include the Ramu-Markham Fault Zone in Papua New Guinea and the Sorong Fault system in Indonesia. The Sorong Fault, a left-lateral megashear, marks the boundary between continental crust related to Australia to the south and volcanic arcs and oceanic crust of the Molucca Sea Plate, Philippine Sea Plate, and Caroline Plates to the north (fig. 5*B*). To the south of Halmahera, the Sorong Fault splits into several splays that formed since the Pliocene (Hall and Wilson, 2000).

Late Miocene Melanesian Arc collision caused regional uplift of northern Papua New Guinea; exhumation of the Maramuni Arc (3–4 km) exposed mid-Miocene batholiths. Late Miocene porphyry copper-gold systems, such as Yandera, are localized along the margins of the exposed batholiths (Garwin and others, 2005).

Miocene Rocks of Western New Guinea Island, Indonesia

Igneous rocks of Maramuni age are present to the west of the international border in the Bird's Head (Moon Arc), at the base of the Bird's Neck along the southern margin of Cenderawasih Bay (Utawa Arc), and in the western part of the Bird's Body in the Ular Merah district in the Central Ophiolite Belt (Jackson, 2010) (fig. 7). Carlile and Mitchell (1994) proposed the name Moon-Utawa Arc for the mid-Miocene Moon Volcanics of the northern part of the Bird's Head and the mid-Miocene Utawa Diorite of the Bird's Neck. Garwin and others (2005) noted that although there is igneous activity in this region, the relation of the arc to a subduction zone is not clear. The Miocene rocks may have formed in a north-facing arc along a passive continental margin prior to south-directed thrusting in the Late Miocene (Melanesian orogeny) that displaced the Utawa Diorite to the south along the Weyland thrust (Carlile and Mitchell, 1994; Dow and Robinson, 1985). The Moon Volcanics may be linked to the Maramuni Arc, but as noted by Malaihollo and Hall (1996), the nature and distribution of the volcanism and its relation to the Maramuni rocks remains unclear. The Miocene igneous rocks in western New Guinea lie within allochthonous arc/forearc terranes and may have originated much farther (>500 km) northeast of their present location (Cloos and others, 2005). The Bird's Head block, or microplate, represents a recent escape tectonic zone formed by convergence of the Australian Plate with volcanic arcs (Pubellier and Ego, 2002).

The Miocene age of the igneous rocks in the Ular Merah area was only recently established by Jackson (2010). She showed that the 11 mid-Miocene intrusions at Ular Merah are adakitic in composition with an asthenospheric mantle component and are chemically distinct from coeval rocks in Papua New Guinea (Maramuni Arc) and from Pliocene rocks in the Medial New Guinea Magmatic Belt. She proposed that they formed due to mid-Miocene spreading in the Ayu Trough (fig. 6), an intraoceanic rift system that marks the southeastern boundary between the Philippine and Caroline Plates, prior to left-lateral fault displacement of the Ayu Trough during the past 4 million years. The relationship of these rocks to the Moon-Utawa area, if any, is unclear.

Late Miocene to Pliocene Magmatism

Medial New Guinea Magmatic Belt

The approximately 1,800-km-long late Miocene to Pliocene medial New Guinea magmatic belt runs along the central highlands of New Guinea within the Papuan Fold Belt (fig. 7). The belt includes mantle-derived, high-K calc-alkaline to alkaline intrusions associated with world-class porphyry copper deposits (Grasberg, Ok Tedi). Extreme uplift and erosion rates of about 1–2 mm per year since mid-Pliocene may explain the absence of coeval volcanic rocks in the western part of the belt (Weiland and Cloos, 1996). Intrusion emplacement was structurally controlled along margins of basement uplifts and north-northeast-trending lineaments that parallel basement structural trends and mark boundaries between different structural domains (Garwin and others, 2005). Intrusions are not directly related to subduction; they occur along local dilational zones formed at intersections of strike-parallel (generally east-west) crustal extensional faults and long-lived, strike-perpendicular crustal transfer structures/lineaments (Hill and others, 2002). The western part of the fold belt in Irian Jaya is characterized by high mountains (~5 km) and basement thrusts; thin-skinned folding and thrusting characterize the eastern part of the fold belt in Papua New Guinea, where elevations typically are

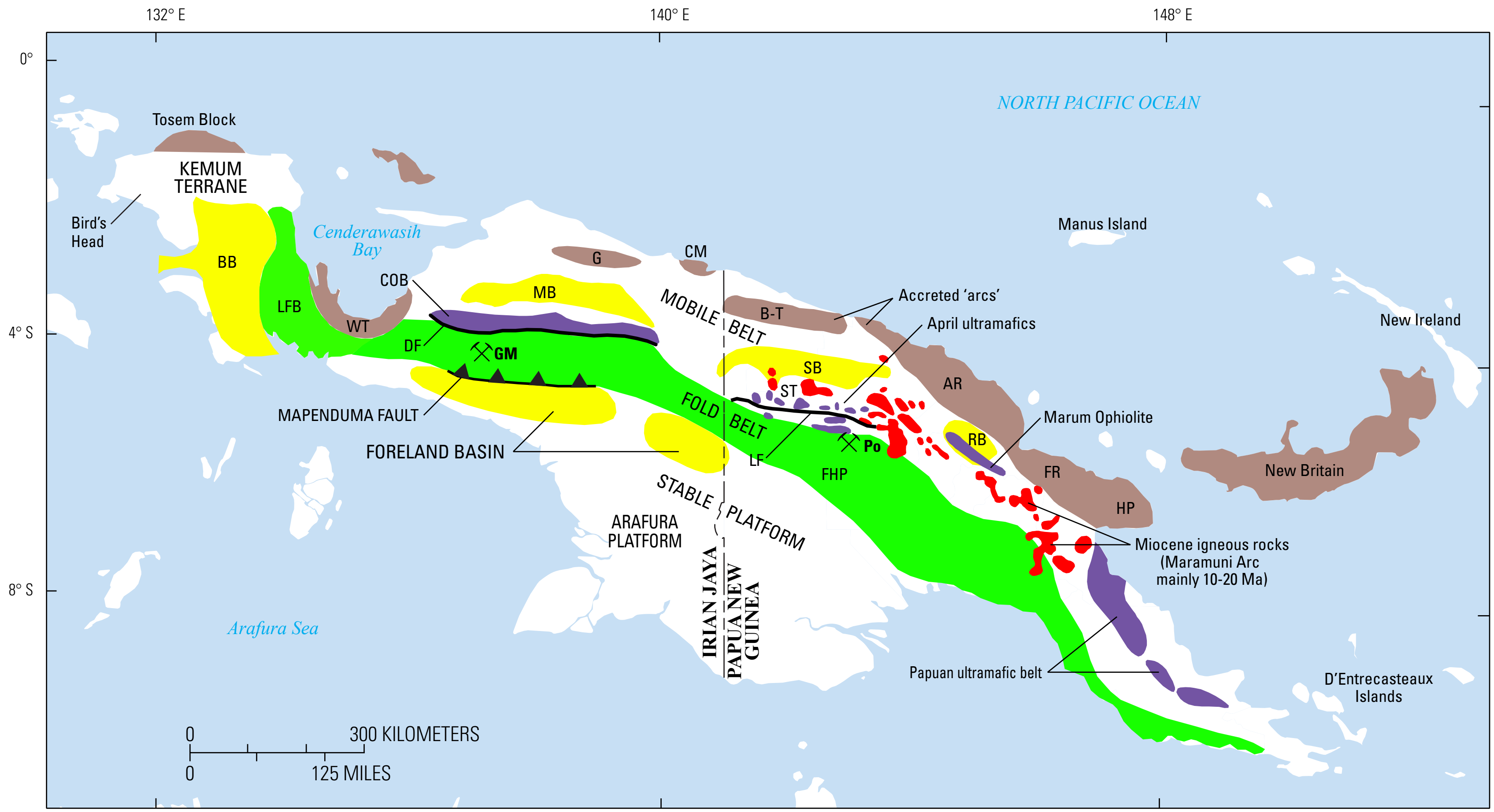


Figure 7. Map of tectonic belts of New Guinea Island, Indonesia and Papua New Guinea (after Hill and Hall, 2003). Different colors represent different tectonic elements: yellow, basins; green, Papuan fold and thrust belt; dark blue, ophiolites and ultramafic rocks; red, Miocene igneous rocks; brown, accreted blocks on New Guinea Island. AR, Adelbert Ranges; BB, Bintuni Basin; B-T, Bewani-Torricelli Mountains; CM, Cyclops Mountains; COB, Central Ophiolite Belt; DF, Direwo Fault; FHP, Fly-Highlands province; FR, Finisterre Ranges; G, Gauttier terrane; GM, Grasberg Mine; HP, Huon Peninsula; LF, Lagaip Fault (N limit of foreland fold and thrust belt); LFB, Lengguru Foldbelt; MB, Meervlakte Basin; Po, Porgera intrusive complex and mine; RB, Ramu Basin; SB, Sepik Basin; ST, Sepik terrane; WT, Weyland thrust.

2–3 km. This implies that deeper crustal levels are exposed in the western part of the belt.

Papua New Guinea and Melanesia

Late Miocene to Pliocene Magmatism

Outer Melanesian Arc

The Eocene to Holocene Outer Melanesian Arc forms a curvilinear belt of islands that extend more than 800 km in Papua New Guinea from Manus Island in the north, through New Ireland, the Bismarck Archipelago (Tabir, Feni, and Lihir), to Bougainville (fig. 8). The extended arc system continues to the south to Fiji as a series of arc segments, which include the Solomon Arc, the Vanuatu (New Hebrides) Arc, the relict Vitiaz Arc, and the arc and rift stages preserved in Fiji. When the Ontong Java Plateau first reached the Solomon segment of the Vitiaz Trench system at about 22 Ma, it was too thick to subduct, which led to cessation of subduction along the Vitiaz Trench and arc segmentation and rotation of arc segments.

Papua New Guinea. The northernmost islands of the Outer Melanesian Arc, Manus and New Ireland, host Miocene porphyry copper prospects. In the early Pliocene, subduction polarity reversed as northeasterly-directed subduction of the New Britain slab began beneath the Inner and Outer Melanesian Arcs. The strike and dip of the subducting New Britain slab varies throughout the Melanesian Arcs, as does the age and character of the magmatism. Bougainville hosts Pliocene deposits associated with calc-alkaline diorite to granodiorite stocks. The islands of the Bismarck Archipelago, which lie about 400 km above the subducting New Britain slab, represent a series of uplifted and eroded Pliocene to Holocene stratovolcanoes that have a shoshonitic geochemical signature interpreted as reflecting a contribution from subducted mantle material (Garwin and others, 2005). Lindley (2006) noted that major, generally north-trending, structural corridors localized the emplacement of mineralized Tertiary intrusive rocks in New Britain, New Ireland, and Manus Island. These structural corridors (fault zones, aligned intrusions) are oblique to major morphotectonic features, such as the New Britain Trench. High-angle structures predominate in the region, resulting in vertical uplift of crustal blocks such as the north-trending horst blocks that comprise the basement in the New Ireland offshore island chain (Lindley, 2006; Garwin and others, 2005).

Melanesia (Solomon Islands-Vanuatu-Fiji) Paleogene to Holocene tectonic interactions between the Pacific and Indo-Australian Plate led to formation, fragmentation, and reconfiguration of a series of magmatic arcs that are variably preserved in the Melanesian island nations of Oceania (Solomon Islands, Vanuatu, and Fiji). A complex system of trench-bounded arcs extends from the easternmost islands of Papua New Guinea southward through the Solomon Islands and Vanuatu (New Hebrides Islands) to Fiji and the Tonga-Kermadec Arc (fig. 6). The arc system developed in Eocene-Oligocene time owing to southwest-directed subduction of the Pacific Plate beneath the Australian Plate along the Vitiaz Trench system (fig. 9*A*). From the early Eocene to middle Miocene, the Solomon Islands, Vanuatu, Fiji, and the Tonga Islands were all part of a continuous arc (Vitiaz Arc, also referred to as Northern Melanesian Arc, or stage 1 arc of Petterson and others, 1999). West-dipping subduction of the Pacific Plate occurred along the Vitiaz Trench (Begg and Gray, 2002). The early arc stage (35–12 Ma) is recorded in the Solomon Islands, in the western belt of Vanuatu, and on Viti Levu, the main island of Fiji.

Collision of the Ontong Java Plateau (fig. 9*B*) with the Solomon topographic block shut down the Vitiaz subduction zone and initiated an arc polarity reversal along the Vanuatu Arc segment northwest of Fiji as a new east-dipping trench system developed west of the Solomon Islands and west of the Vanuatu Arc at about 8 Ma (Mann and Taira, 2004; Begg and Gray, 2002). The exact timing and nature of the collision are not well-established. The initial collision in the Solomon Islands may have occurred as early as 25–20 Ma as a “soft-docking event” that was sufficient to start the polarity reversal at 12–6 Ma. The main “hard” collision recorded in deformation in the Solomon Islands is placed at about 5 Ma or younger (Petterson and others, 1999). The modern Solomon Islands are bounded on the north by the North Solomon Trench system and on the south by the New Britain-San Cristobal Trench (fig. 6). The Ontong Java Plateau is converging on the North Solomon Trench at an oblique angle at a rate of 10 cm/yr (Phinney and others, 2004).

Paleocene/Eocene to early Miocene magmatism and associated hydrothermal activity in the arc system is related to the Vitiaz subduction. Late Miocene-Pleistocene arc magmatism in Vanuatu (stage 2 of Petterson and others, 1999) is related to northeast-dipping subduction of the Australian Plate along the San Cristobal-Vanuatu Trench system (fig. 9*B*). Major tectonic reorganization of the Vitiaz Arc system occurred after 8 Ma. Following the reversal in subduction polarity in the late Miocene (8.0–5.5 Ma), the arc fragmented north of Fiji as the North Fiji Basin (fig. 9*B*) opened by back-arc spreading with clockwise rotation of the Vanuatu Arc to the southwest, translation and clockwise rotation of the Tonga Arc, and counterclockwise rotation of the Fiji Platform. The east-west, left-lateral Fiji transform fault borders the Fiji platform on the north (fig. 9*C*). Intra-arc extension behind the Tonga Trench at about 5.5 Ma opened the Lau Basin (fig. 9*C*), which separated the relict arc of the Lau Ridge from the currently active Tonga (Tofoa)-Kermadec Arc (Fiji Ministry of Lands and Mineral Resources, 2010). Back-arc spreading in the North Fiji Basin, and later in the Lau Basin, separated the opposite-facing Vanuatu and Tonga Arcs as the Fiji Platform (Lau Ridge) rotated counterclockwise from about 5–3 Ma, subsequent to collision of the Melanesian Border Plateau[18] with the Melanesian Arc (Tanaka and others, 2010).

[18] Melanesian Border Plateau: a belt of seamounts and ridges of uncertain affinity developed on Pacific Plate that borders the Vitiaz Trench Lineament and extends 1,500 km west-northwest from the Samoan Islands (Pelletier and Auzende, 1996).

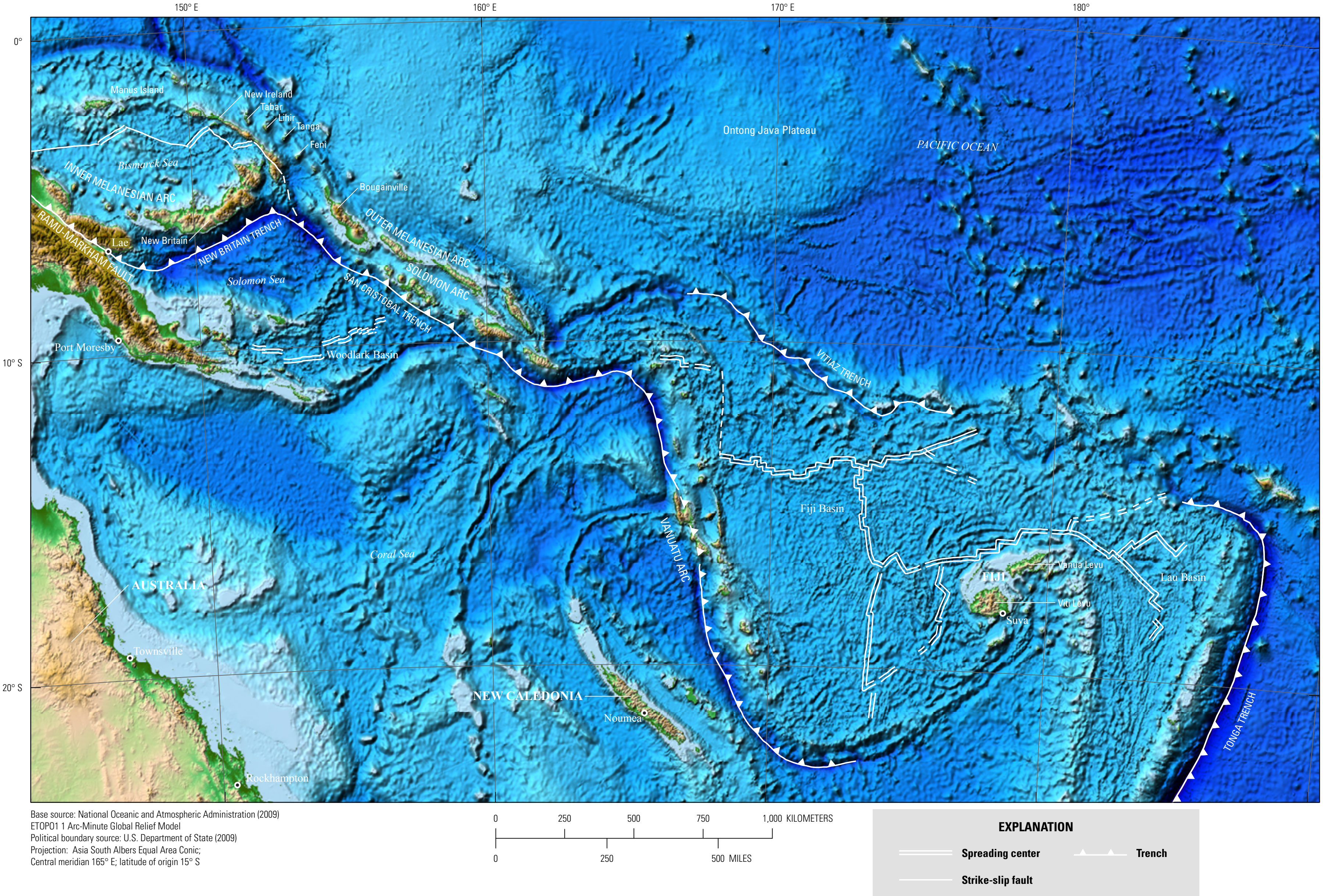


Figure 8. Map of the Inner and Outer Melanesian Arcs, Papua New Guinea. Locations of modern trenches and spreading centers plotted on sea floor bathymetry from the global relief model of Amante and Easkins (2009).

The Vitiaz Trench lineament, which forms the northern border of the North Fiji Basin, marks the relict Vitiaz subduction zone and separates Pacific Plate Cretaceous crust from Late Cenozoic crust of the North Fiji and Lau Basins (Pelletier and Auzende, 1996). Southerly propagation of a spreading center in the Lau Basin since 3 Ma separated the Lau and Tonga Ridge ancient arc segments. The Tonga-Kermadec subduction zone (fig. 6) is a classic intraoceanic arc with back-arc spreading that accommodates the fastest known rate of active subduction; the subduction zone represents a convergent boundary where the modern Pacific Plate subducts beneath the Indo-Australian Plate.

In Fiji, the period from 35 to 12 Ma is referred to as the early arc stage, followed by a 12–7 Ma mature arc stage marked by the Colo (Tholo) orogeny, early arc rifting (7–3 Ma), and a late arc rifting stage that continues today. Modern Fiji is situated between the opposing Tonga-Kermadec and Vanuatu convergence zones, bordered by the North Fiji Basin on the west and the Lau Basin to the east.

Assessment Data

Geologic Maps

Geologic maps at a variety of scales were used during the assessment. Maps included proprietary data provided by CCOP country representatives, commercially available digital geologic compilations, and paper geologic maps. Paper maps were scanned and georectified to incorporate them into GIS projects to serve as a basis for tract delineation. Page-size figures from a variety of publications were used as references to identify tectonic features and the extent of magmatic arcs. Specific data used for each tract are listed in the appendixes. The principal geologic maps used in addition to the proprietary data provided for the assessment are listed in table 3. See the appendixes for data used in determining the extent of each permissive tract.

Mineral Occurrence Data

A global database of porphyry copper deposits and prospects by Singer and others (2008) was supplemented with other global and regional mineral-occurrence databases, including the Geological Survey of Canada (Dunne and Kirkham, 2000), AMIRA (Khin Zhaw and others, 1999), and proprietary data from CCOP (Directorate of Mineral Resources and Inventory, 2004b). In addition, commercially available databases (InfoMine[19], Intierra[20], Metals Economic Group[21]), metallogenic maps, technical reports, company Web sites, publications and Web sites of geological surveys, and geologic literature were consulted. The U.S. Geological Survey On-Line Mineral Resources Data (MRDS)[22] includes information on mines, prospects, and mineral occurrences worldwide (U.S. Geological Survey, 2005). Many other geological surveys maintain online mineral databases (see, for example, Thailand at http://www.dpim.go.th.mne.mn.php).

The assessment team classified sites as deposits (where location, deposit characteristics, and resource grades and tonnages are known) or prospects (where location, deposit characteristics and type, and resource grades and tonnages are incompletely characterized). Some prospects reported in data sources could not be unambiguously classified as porphyry copper deposit types. Deposits and prospects that the team could classify as porphyry copper or porphyry-copper-related are included in the database for this report. Distributions of gold placers, skarns, and epithermal deposits, as well as unclassified copper and gold occurrences, were considered during the assessment, but they are not typically included in the database. Skarns and epithermal deposits may be included if the assessment team considered it likely that a porphyry system could be associated with them.

Other Data

Compilations of radiometric ages for igneous rocks in Southeast Asia provided information about permissive rocks that might not be represented on available geologic maps. The Southeast Asia radiometric age database of Malaihollo and others (2002) covers Indonesia and Papua New Guinea. A compilation of available ages for the western Central Range of Papua, Indonesia by Jackson (2010) includes new data that establishes a Miocene age for previously undated intrusions.

Global aeromagnetic data covers most of Southeast Asia (National Geophysical Data Center, 2009). The coarse spatial resolution of this aeromagnetic raster data limits its use for defining the subsurface extent of the magmatic arcs beneath shallow (<1 km) cover. A detailed aeromagnetic data set was acquired for part of the Central Highlands in western Papua New Guinea on New Guinea Island. Those data, as well as local aeromagnetic data reported on company Web sites, indicate that discrete, small (<2 km), circular, steep-gradient aeromagnetic anomalies correspond to mapped and shallow subsurface Neogene diatreme-like intrusions associated with some porphyry copper systems, such as the anomalies described at Batu Hijau and at Grasberg by Hoschke (2008).

Regional scale stream-sediment geochemical surveys have been undertaken by government agencies and private mineral-exploration companies in some regions, but availability, processing, and incorporation of such data for so many areas is beyond the scope of a global assessment. Regional stream-sediment and soil geochemistry is one of the primary mineral-exploration tools used in Southeast Asia to target areas for more detailed mapping, exploration geophysical surveys, exploration geochemical surveys using rock-chip sampling and trenching, and drilling.

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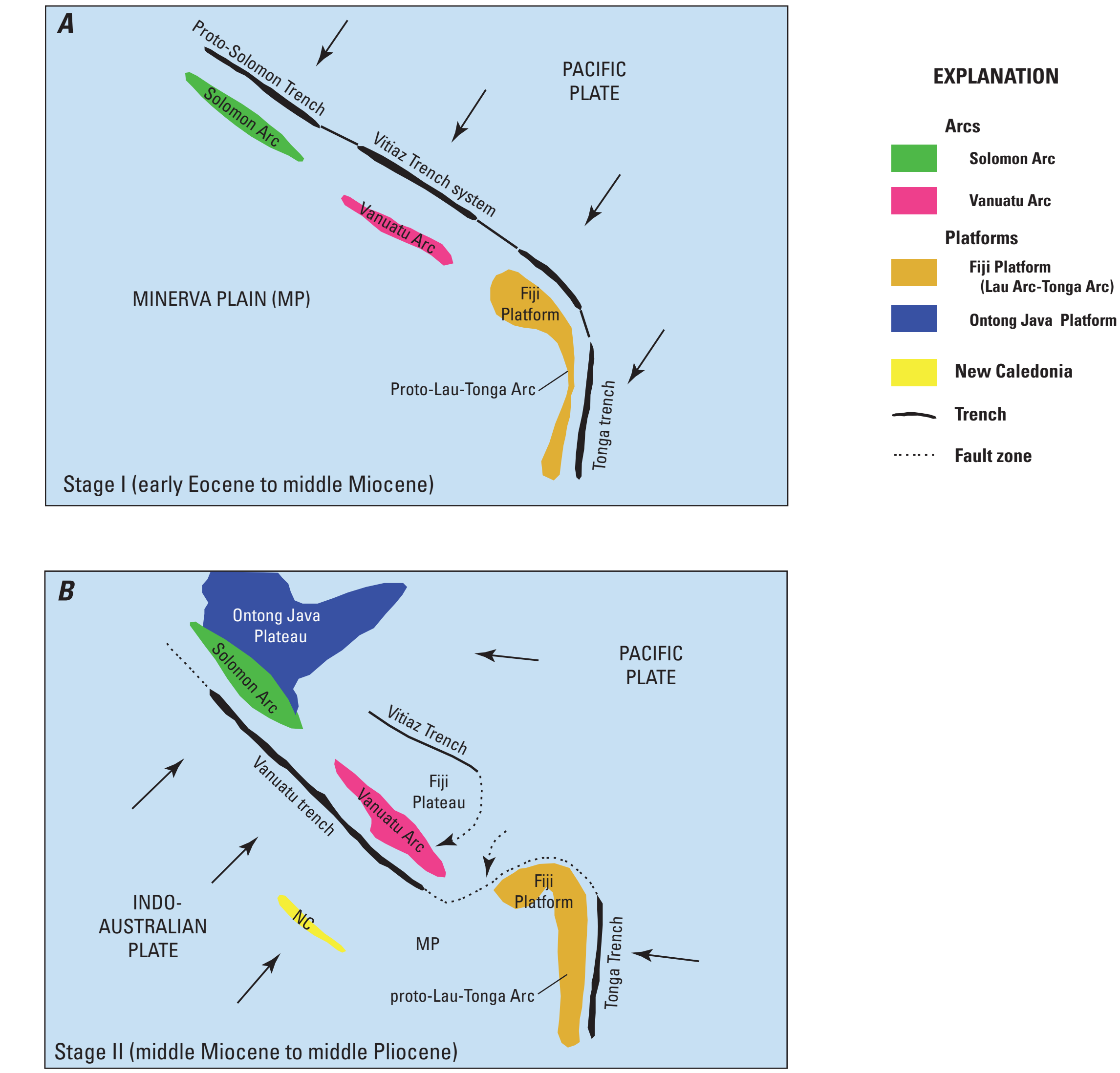
[19] http://www.infomine.com/.

[20] http://www.intierra.com/Homepage.aspx.

[21] http://www.metalseconomics.com/default.htm.

[22] http://mrdata.usgs.gov/.



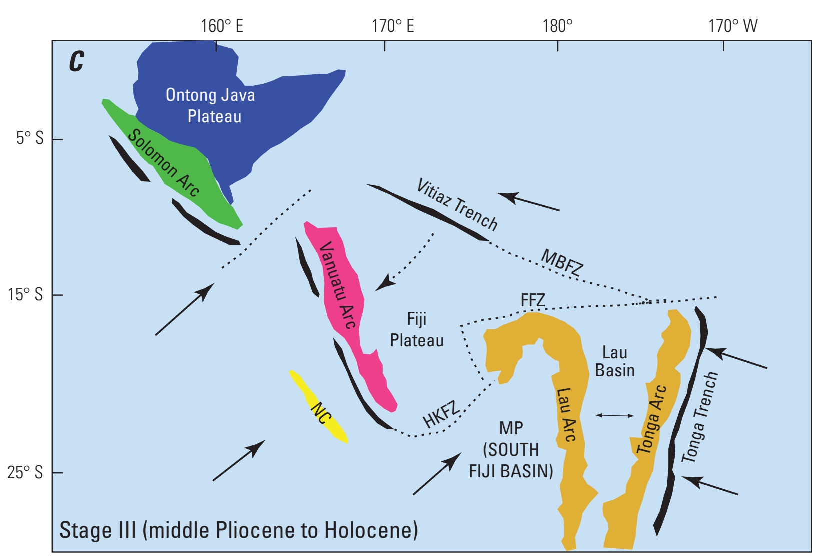


Figure 9. Diagrams showing the tectonic evolution of Melanesia (based on Colley and Greenbaum, 1980 and Colley and Hindle, 1984). A, Stage I, early Eocene to middle Miocene, southwestward subduction of the Pacific Plate along a continuous Solomon-Vitiaz-Tonga Trench system beneath the proto-Melanesian Arcs and opening of the Minerva Plateau (MP) marginal basin. B, Stage II, middle Miocene to middle Pliocene collision of the Ontong Java Plateau with the Solomon Arc, arc polarity reversal to northeasterly subduction of the Indo-Australian Plate along the Vanuatu Trench, with opening of the Fiji Plateau marginal basin. C, Stage III, middle Pliocene to Holocene opening of the Lau marginal basin, continued opening of the Fiji Plateau, and continued development of a complex transform fracture system that started in stage II. Note the stage III position of the Minerva Plain as the modern South Fiji Basin. MBFZ, Melanesian Border Fracture Zone; FFZ, Fiji Fracture Zone; HKFZ, Hunter-Kandavu Fracture Zone.

Satellite imagery proved helpful for confirming mine and prospect site locations and for locating and identifying topographic and structural features, such as lineaments and faults. In many areas, vegetation and cloud cover are too dense to allow identification of altered rocks.

Exploration History

Porphyry copper exploration in Southeast Asia has been cyclic, driven largely by global metal prices, government policies, and accessibility of the region. Although the area is considered among the most copper- and gold-endowed regions on earth, parts of the area remain underexplored (Feebrey, 1999). Political, social, cultural, and environmental issues, as well as mining laws, affect exploration in the region. Many areas have been closed to exploration for many years owing to wars. In addition, steep topography, lack of infrastructure, tropical climate and vegetation, and natural hazards, such as earthquakes, tsunamis, and volcanic eruptions, complicate exploration and development. Since the 1960s, changes in mining laws in several Southeast Asia countries have made the area more attractive for foreign investment in mineral exploration and development (van Leeuwen, 1994).

Examples of porphyry copper exploration cycles for Indonesia are described below, based on information provided in country reports presented at the 2010 CCOP-USGS Workshop in Busan, South Korea, by coauthors of this assessment.

Indonesia (Based on contributions of Bambang Tjahjono Setiabudi and Dwi Nugroho Sunuhadi)

van Leeuwen (1994) documented several phases of mineral exploration in Indonesia up to 1992 that were facilitated by a favorable investment climate. The 1961 to 1976 phase focused on prospects previously identified by Dutch investigations between the 1840s and 1930s. Porphyry exploration in the early 1970s in the Sunda Arc, Sulawesi, and Irian Jaya led to discoveries and award of the first contract of work (COW[23]) at the Ertsberg skarn. Intense gold exploration characterized the period from 1984 to 1990 with a focus on the Cenozoic magmatic belts. Grasberg was recognized as a porphyry system in the 1970s; Batu Hijau was discovered by stream-sediment sampling in 1991. In his 1994 paper, van Leeuwen attributed “the unprecedented high level of mineral exploration over the past 25 years” to the prospectivity of Indonesia and the attractive position for foreign investment, and he predicted a new (post-1994) phase of exploration for a variety of commodities, with a focus on copper, gold, and coal. However, exploration and mining development in Indonesia decreased following the 1999 implementation of a forestry regulation that prohibited open-pit mining in protected forests. Other factors that inhibited exploration included violence related to illegal mining activities and pressure from social and environmental groups opposed to mining. A new mineral and coal mining law passed in 2009, Law No. 4/009, is anticipated to revitalize the climate for mineral exploration and mining to promote national development and provide for the welfare of the Indonesian people (Setiabudi and Sunuhadi, written commun., 2010).

Permissive Tracts

Tract Delineation

The geology-based strategy for permissive-tract delineation used in this assessment is described herein. The appendixes contain detailed descriptions for individual tracts. Digital geologic data were processed in a GIS using ESRI ArcGIS software, as follows:

- Regional-scale geologic maps and geologic literature were used to identify fundamental units for tract delineation, which were defined as magmatic arcs, or belts of igneous rocks, of a given age range.
- Digital geologic maps at scales ranging from 1:200,000 to 1:1,000,000 were then used to select map units to define preliminary permissive tracts for porphyry copper deposits. Igneous map units were separated by age groups and classified as permissive or non-permissive based on lithology. Permissive rocks include calc-alkaline and alkaline plutonic and volcanic rocks. Other igneous rocks, such as ultramafic rocks, highly evolved granites, peraluminous granites, and pillow basalts were excluded from tract delineation as they are unlikely to be associated with porphyry copper deposits.
- Buffers were applied to the polygons that represent these permissive rocks to account for spatial uncertainty and extension of permissive units under shallow cover rocks. Typically, a 10-km buffer[24] was applied to plutonic rock polygons and a 2-km buffer to volcanic rock polygons; this generally expanded the area of the tract to include all known porphyry copper deposits and significant associated prospects. The buffer also accounts for uncertainties in the cartographic position of mapped contacts, as well as possible unexposed or unmapped permissive rocks. After

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[23] COW (Contract of Work): The Indonesian legal framework for foreign investment initiated in 1967.

[24] For some small islands and areas where cross sections on geologic maps indicated steep-sided intrusions, a buffer distance of 5 km was used. See appendixes for criteria used to delineate each tract.

Table 3. Principal geologic maps used for the assessment of Southeast Asia and Melanesia.

Description	Reference
Digital geologic map of East and Southeast Asia	CCOP and Geological Survey of Japan (1997)
Digital geologic maps of Myanmar, Laos, Cambodia, Thailand, Vietnam, and Yunnan Province, China	Khin Zaw and others (1999), Geological Survey of Vietnam (1991)
Digital geologic map of Indonesia	Directorate of Mineral Resources and Inventory (2004a) [proprietary data]
Geologic map of Irian Jaya, Indonesia (1:1,000,000)	Dow and others (1986)
Systematic 1:250,000-scale geologic maps of Indonesia	Directorate of Mineral Resources and Inventory (1987–2000)
Digital geologic map of Sabah (1:500,000)	Director-General Geological Survey of Malaysia (1985)
Digital geologic map of Papua New Guinea compiled from 1:250,000-scale geologic maps	Papua New Guinea Geological Survey (2002)
Geology of Papua New Guinea	Bain and others (1972)
Digital and paper geologic maps of the British Solomon Islands	Geological Survey Division of the Ministry of Natural Resources (1969)
Geologic maps of the New Hebrides Islands (1:100,000)	New Hebrides Geological Survey (1972, 1975, 1977)
Geological map of Fiji (1:500,000)	Geological Survey Department, Fiji (1965)
Metallogenic maps of Vanua Levu and Viti Levu, Fiji (1:250,000)	Mineral Resource Division—Fiji (1978a,b)

buffering, the assessment team examined available data on mineral deposits, prospects, and occurrences; locations of dated igneous rock samples; and geophysical and geochemical information to ensure that the tract included any other evidence of unmapped permissive rocks or hydrothermal systems.

- An aggregation and smoothing routine was applied to the resulting polygons, and the tracts were edited by hand to honor post-mineral fault boundaries. In some cases, more detailed geologic maps were acquired to resolve tract-boundary issues, or page-size map illustrations from the literature were incorporated to fill in gaps in available digital geologic maps.
- Volcanic centers and other areas of volcanic cover where the thickness of cover was known to exceed 1 kilometer were generally excluded from tracts by using a buffer zone around the volcano based on topography. Intrusions younger than the designated tract age and ophiolitic and ultramafic rocks also were excluded. Volcanic rocks younger than the designated tract age, but inferred to be less than 1 kilometer thick, may be present as cover over permissive areas.
- Resulting tract boundaries were clipped to shorelines to eliminate undersea areas using small-scale digital international land-boundary polygon files from the U.S. Department of State (2009)[25], which incorporate high-tide coastline data from the U.S. National Geospatial-Intelligence Agency's World Vector Shoreline[26]dataset.

Permissive Tracts for Porphyry Copper Deposits in Southeast Asia and Melanesia

Twenty two permissive tracts for porphyry copper deposits were delineated within the study area (table 4, figs. 1, 10–13). Permissive tracts primarily are based on the mapped extent of igneous rocks that are permissive for porphyry copper deposits. Permissive tracts may represent segments of an arc or magmatic belt that are differentiated from other segments based on different geologic characteristics (such as levels of exposure), different amounts of information, and (or) different probabilities of occurrence of undiscovered deposits. Permissive tracts are listed by geographic area, along with the countries included within each tract and the fundamental geologic features delineated for the assessment (table 4). Brief summaries of the tracts, by area, are included in this discussion. More detailed tract descriptions are presented in the appendixes. Porphyry copper deposits with reliable identified resources are listed by area and by permissive tract in table 5. Deposits and significant prospects and

[25] The political boundaries used in this report are, in accord with U.S. Government policy, the small-scale digital international boundaries (SSIB) provided by the U.S. Department of State (U.S. Department of State, 2009). In various parts of the world, some political boundaries are in dispute. The use of the boundaries certified by the U.S. Department of State does not imply that the U.S. Geological Survey advocates or has an interest in the outcome of any international boundary disputes.

[26] http://shoreline.noaa.gov/data/datasheets/wvs.html.

Table 4. Permissive tracts for porphyry copper deposits in Southeast Asia and Melanesia.

Appendix	Coded _Id	Tract name	Countries	Geologic feature assessed
Indochina peninsular area				
A	142pCu7021	Sukhothai	China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam	An assemblage of Carboniferous through Triassic rocks that were formed as both island arcs and continental arcs by subduction of Paleotethyan oceanic crust below the South China block in Yunnan, and below Indochina (the Loei and Truong Son volcanic arcs)
B	142pCu7022	Malaysia	Malaysia, Thailand, Singapore, and Indonesia	An assemblage of Carboniferous through Triassic rocks that were formed as both island arcs and continental arcs by subduction of Paleotethyan oceanic crust below the East Malaya terrane
C	142pCu7023	Mekong Delta	Vietnam, Cambodia, and Lao People's Democratic Republic	A field of Jurassic and Cretaceous intrusive and volcanic rocks that are the result of subduction of the Pacific Plate beneath southern Indochina
D	142pCu7024	Wuntho-Popa	Myanmar and India	A linear belt of Late Cretaceous through Holocene volcanic rocks related to subduction of the Indian Ocean Plate below Indochina
Indonesian Islands area				
E	142pCu7020	Sumatra Island	Indonesia	An Eocene-Pliocene continental magmatic arc that straddles the northwest-trending Sumatran Fault Zone in western Sumatra. Known porphyry copper deposits and prospects are Miocene-Pliocene in age.
F	142pCu7025a	Sunda Banda Arc	Indonesia	The eastern part of the Eocene to Holocene Sunda-Banda magmatic arc; Java Island
	142pCu7025b			The eastern part of the Eocene to Holocene Sunda-Banda magmatic arc; Bali to West Flores Islands
	142pCu7025c			The eastern part of the Eocene to Holocene Sunda-Banda magmatic arc; east Flores to Wetar Islands
G	142pCu7026	West Sulawesi	Indonesia	Miocene to Pliocene igneous rocks in the southern portion of the 1,200 km long Sulawesi-Sangihe magmatic arc, located in southwestern Sulawesi
H	142pCu7027	North Sulawesi-Sangihe	Indonesia	Miocene to Pliocene volcanic and intrusive rock portion of the North Sulawesi-Sangihe magmatic arc
I	142pCu7019	Central Kalimantan	Indonesia and Sabah and Sarawak, Malaysia	A dispersed belt of Tertiary intermediate intrusive and volcanic rocks that postdate pre-Eocene subduction and deformation, uplift, and erosion of pre-Miocene rocks and continental basement in Kalimantan
J	142pCu7201	Ambon Arc, Central Molucca Islands	Indonesia	Plio-Quaternary Ambon island arc (northern Outer Banda Arc), eastern Indonesia
K	142pCu7202	Halmahera Arc, North Molucca Islands	Indonesia	Neogene Halmahera island arc
New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea islands				
L	142pCu7205	Moon-Utawa -Ular Merah Areas	Indonesia	Miocene Moon-Utawa arc in Papua and West Papua Provinces, Indonesia
M	142pCu7203	Western Medial New Guinea Magmatic Belt	Indonesia	Late Miocene to Pliocene-Pleistocene Medial New Guinea magmatic belt
N	142pCu7204	Rotanburg-Taritatua Area	Indonesia	Late Miocene to Pliocene-Pleistocene intrusive rocks.
O	009pCu7203a	Eastern Medial New Guinea Magmatic Belt	Papua New Guinea	Late Miocene to Pliocene-Pleistocene Medial New Guinea magmatic belt
	009pCu7203b		Papua New Guinea	
P	009pCu7205	Maramuni Arc	Papua New Guinea	Miocene Maramuni magmatic arc
Q	009pCu7206	Miocene Alkaline Rocks, Southeastern Papua New Guinea	Papua New Guinea	Miocene alkaline island arc intrusive rocks
R	142pCu7208	Inner Melanesian Arc Terranes I- Indonesia	Indonesia	Eocene-Oligocene to early Miocene accreted Inner Melanesian magmatic arc terranes of Papua, Indonesia
S	009pCu7208	Inner Melanesian Arc Terranes II- Papua New Guinea	Papua New Guinea	Eocene-Oligocene to early Miocene accreted Inner Melanesian magmatic arc terranes of New Guinea Island
T	009pCu7209	Inner Melanesian Arc (New Britain)	Papua New Guinea	Eocene-Oligocene to early Miocene Inner Melanesian Arc on New Britain
U	009pCu7207	Outer Melanesian Arc I -Papua New Guinea	Papua New Guinea	Eocene to Holocene Outer Melanesian Arc
Melanesia				
V	009pCu7210	Outer Melanesian Arc II- Melanesia	Solomon Islands, Vanuatu, and Fiji	Eocene to Holocene Outer Melanesian Arc

occurrences are tabulated and plotted on figures in appendixes A–V. Site locations and attributes are included in a shapefile in appendix W. Readers should refer to figures in the appendixes for locations of deposits mentioned in the following subsections of the report.

Indochina Peninsula Area

Four permissive tracts for porphyry copper deposits are delineated in the Indochina Peninsula area (fig.10, table 4). See appendixes A–D for assessment details and additional references.

Two tracts, Sukhothai (142pCu7021) and Malaysia (142pCu7022) are defined by Carboniferous through Triassic rocks that represent both island and continental arcs related to the subduction of Paleotethyan oceanic crust. The permissive rocks are chiefly of intermediate, metaluminous I-type composition, and they contrast sharply with the collision-related peraluminous S-type granitoids that are widely distributed on the Indochina Peninsula. The larger tract, Sukhothai (354,260 square kilometers, km^2), consists of three belts of permissive rocks. The westernmost belt, known as the Sukhothai island-arc system, extends from southern Yunnan Province, in China, through western Lao People's Democratic Republic, Thailand, and, after interruption by the Gulf of Thailand, through the eastern part of Peninsular Malaysia (as tract 142pCu7022). The second, the Loei Belt just to the east, is in the Lao People's Democratic Republic and Thailand, and the third belt, Truong Son, trends southeastwards through the Lao People's Democratic Republic [labeled as Laos on fig. 10] and Vietnam. The tract includes the 250 Ma Phu Kham porphyry copper-gold deposit (table 5) and several significant prospects in Thailand and Vietnam, as well as the very large Sepon copper-gold skarn and replacement district in the Lao People's Democratic Republic.

The Malaysian tract (142pCu7022) extends for 60,000 km^2 across Malaysia and parts of Thailand, Singapore, and Indonesia. The tract includes the Mengapur deposit (45 Mt, 1.8 percent copper, 0.6 g/t gold) that was classified as a porphyry copper deposit by Singer and others (2008). However, the deposit is better classified as a copper-gold-iron skarn with porphyry copper affinity. Six oxidized orebodies currently are being mined, and there are also seven sulfide bodies, all surrounding a weakly mineralized adamellite intrusion (Kiang, 2008). Scattered copper- and gold-bearing vein and skarn prospects, as well as gold-rich polymetallic vein deposits throughout the tract are indicative of the porphyry copper environment.

The 91,220 km^2 Mekong Delta tract (142pCu7023) delineates Jurassic and Cretaceous intrusive and volcanic rocks formed by subduction of the Pacific Plate beneath southern Indochina. The tract covers parts of Vietnam, Cambodia, and Lao People's Democratic Republic. The tract is an excellent example of an underexplored area, in this case, because of prolonged warfare in the late 20th century.

The Wuntho Popa tract (142pCu7024) in Myanmar defines a belt of Miocene through Holocene volcanic rocks related to oblique subduction of the Indian Ocean Plate beneath Indochina. The only porphyry copper deposit known within the tract is the 5.8 Ma Monywa deposit, which contains more than 6 Mt copper (table 5), although there are other poorly documented prospects surrounding the deposit.

Indonesian Islands Areas

Seven permissive tracts for porphyry copper deposits are delineated in the Indonesian Islands (fig. 11, table 4). See appendixes E–K for assessment details.

The Sumatra Island tract (142pCu7020) delineates Eocene-Pliocene continental magmatic arc rocks that straddle the northwest-trending Sumatran Fault Zone in western Sumatra. The only porphyry copper deposit with identified resources within the 131,030 km^2 tract is the 11 Ma Tangse deposit with 900,000 t contained copper (table 5).

The Sunda-Banda Arc tract (142pCu7025) consists of the eastern parts of the 3,800-km-long Eocene to Holocene Sunda-Banda Arc. The tract was assessed in three segments based on differences in crust underlying the arc: sub-tract 142pCu7020a, the Java segment, which is developed on continental crust of the Sundaland part of the Eurasian Plate; sub-tract 142pCu7020b, the arc segment from Bali to west Flores Islands, which is an island arc constructed on oceanic crust; and sub-tract 142pCu7020c, from east Flores to Wetar Islands, which is an arc constructed on oceanic crust or highly thinned continental crust (Carlile and Mitchell, 1994). The world-class Batu Hijau (fig. 1) porphyry copper-gold deposit (>7 Mt contained copper), discovered in 1991, is in sub-tract b and represents the only known porphyry copper deposit with identified resources in the arc.

The island of Sulawesi was assessed using two tracts, both part of the 1,200-km-long, Eocene to Holocene, Sulawesi-Sangihe magmatic arc. The West Sulawesi tract (142pCu7206) is partly developed on continental crust containing pre-Tertiary polymetamorphic rocks and Cretaceous plutons and has a complex history, including three overlapping volcanic-arc events. No porphyry copper deposits are known in the West Sulawesi tract. However, the tract does contain the 4.14 Ma Malala low-fluorine porphyry molybdenum deposit in the northern part of the tract and the Sassak porphyry copper prospect. The North Sulawesi-Sangihe tract (142pCu7207) outlines an island arc complex developed on Cretaceous to Paleogene oceanic crust (Carlile and others, 1990). It formed during multistage and multidirectional subduction from the Eocene to present in the complex convergence zone of the Eurasian, Pacific, and Australian Plates (Kavalieris and others, 1992; Hall, 1996, 2002; Pearson and Caira, 1999; Simandjuntak and Barber, 1999). The tract includes the 3.75 Ma Tapadaa (232,200 t contained copper) and the 3.0 Ma Tombulilato (~1.8 Mt contained copper) deposits, both developed in shallowly emplaced quartz

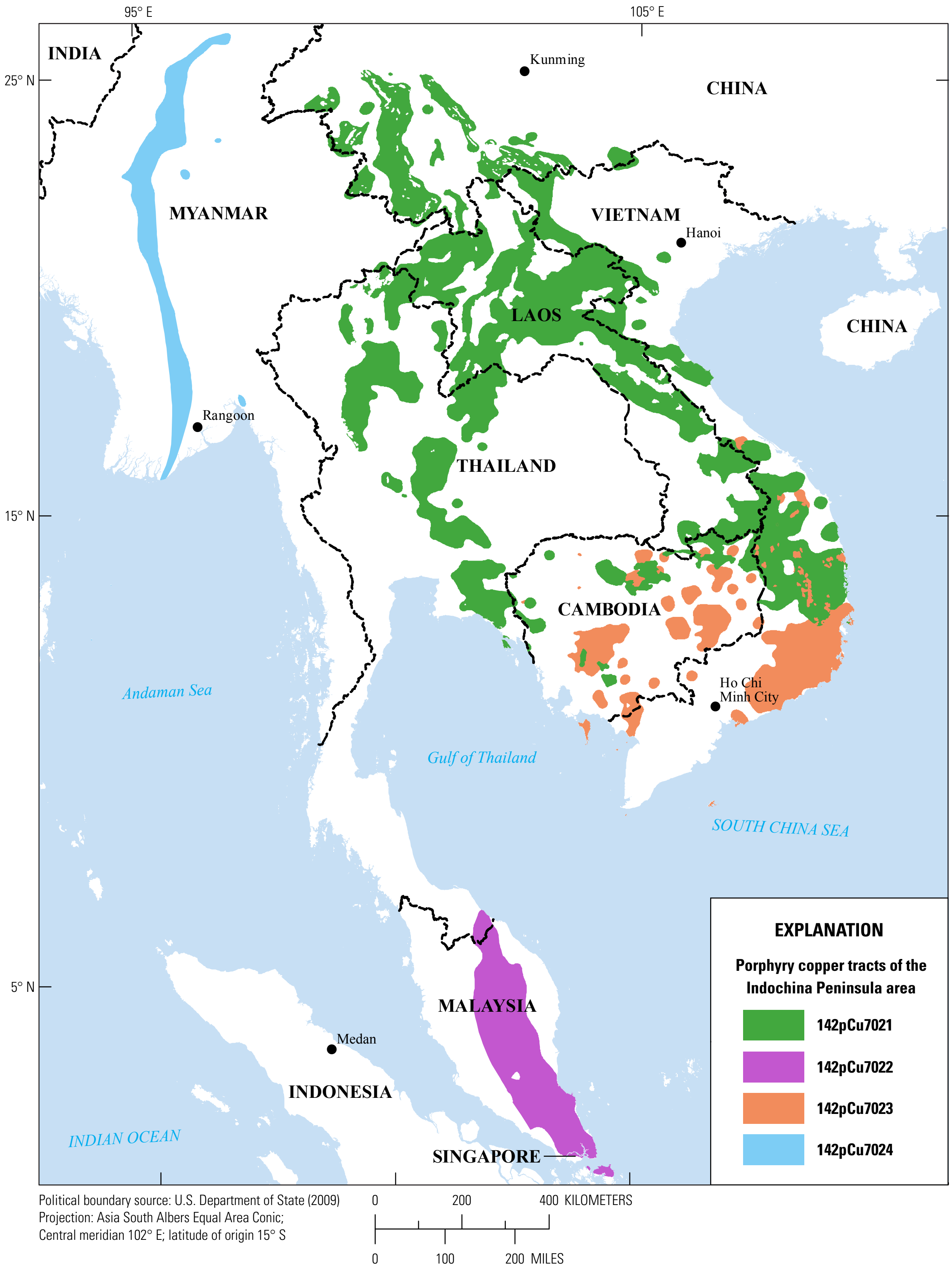


Figure 10. Map of permissive tracts for porphyry copper deposits, Indochina Peninsula Area, Southeast Asia. Tract coded identifiers and tracts names are: 142pCu7021 (Sukhothai), 142pCu7022 (Malaysia), 142pCu7023 (Mekong Delta), and 142pCu7024 (Wuntho-Popa).

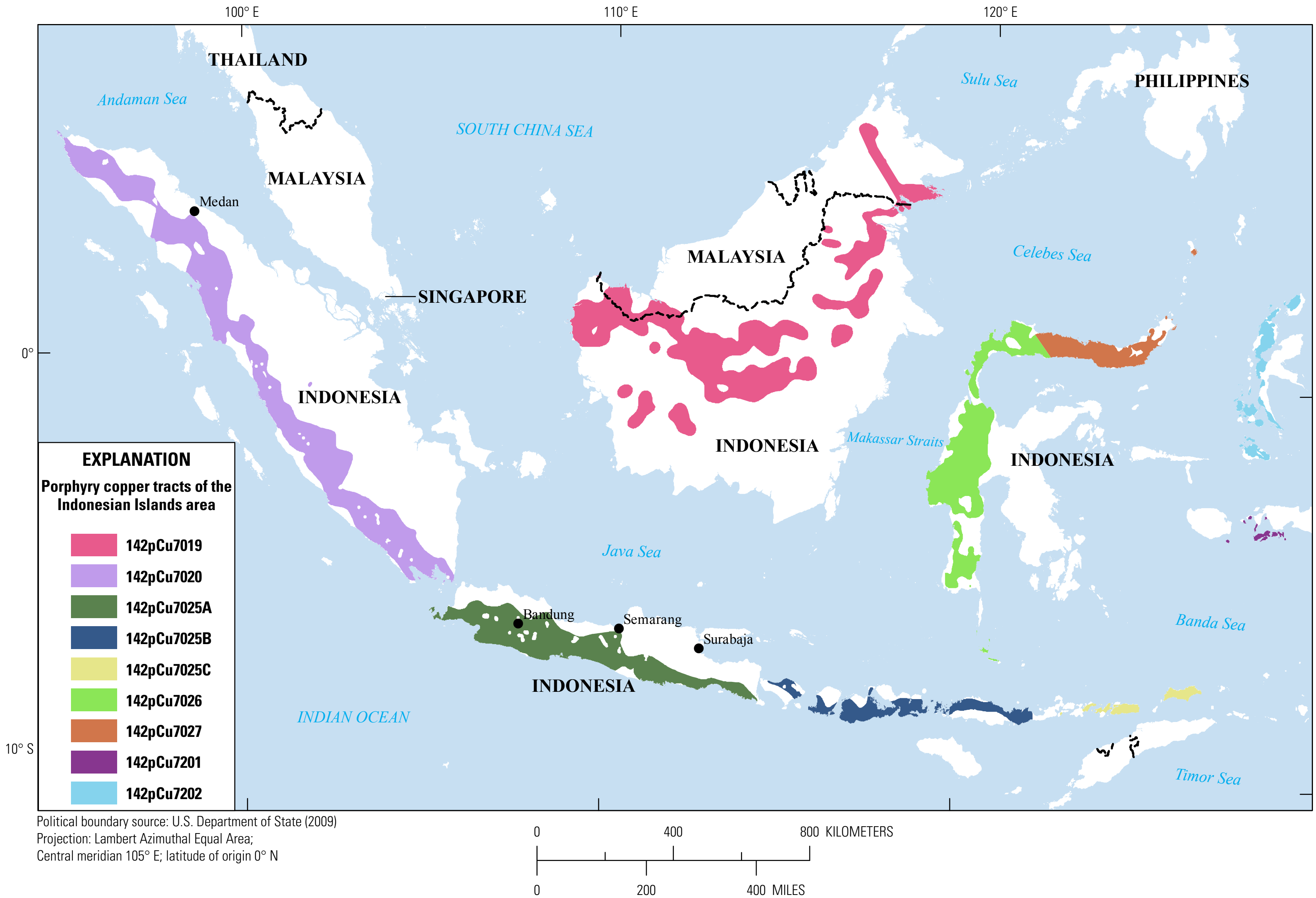


Figure 11. Map of permissive tracts for porphyry copper deposits, Indonesian Islands Area, Southeast Asia. Tract coded identifiers and tracts names are: 142pCu7019 (Central Kalimantan), 142pCu7020 (Sumatra Island), 142pCu7025 (Sunda Banda Arc, sub-tracts a, b, and c), and 142pCu7026 (West Sulawesi), 142pCu7027 (North Sulawesi-Sangihe), 142pCu7201 (Ambon Arc, Central Molucca Islands), and 142pCu7202 (Halmahera Arc, North Molucca Islands).

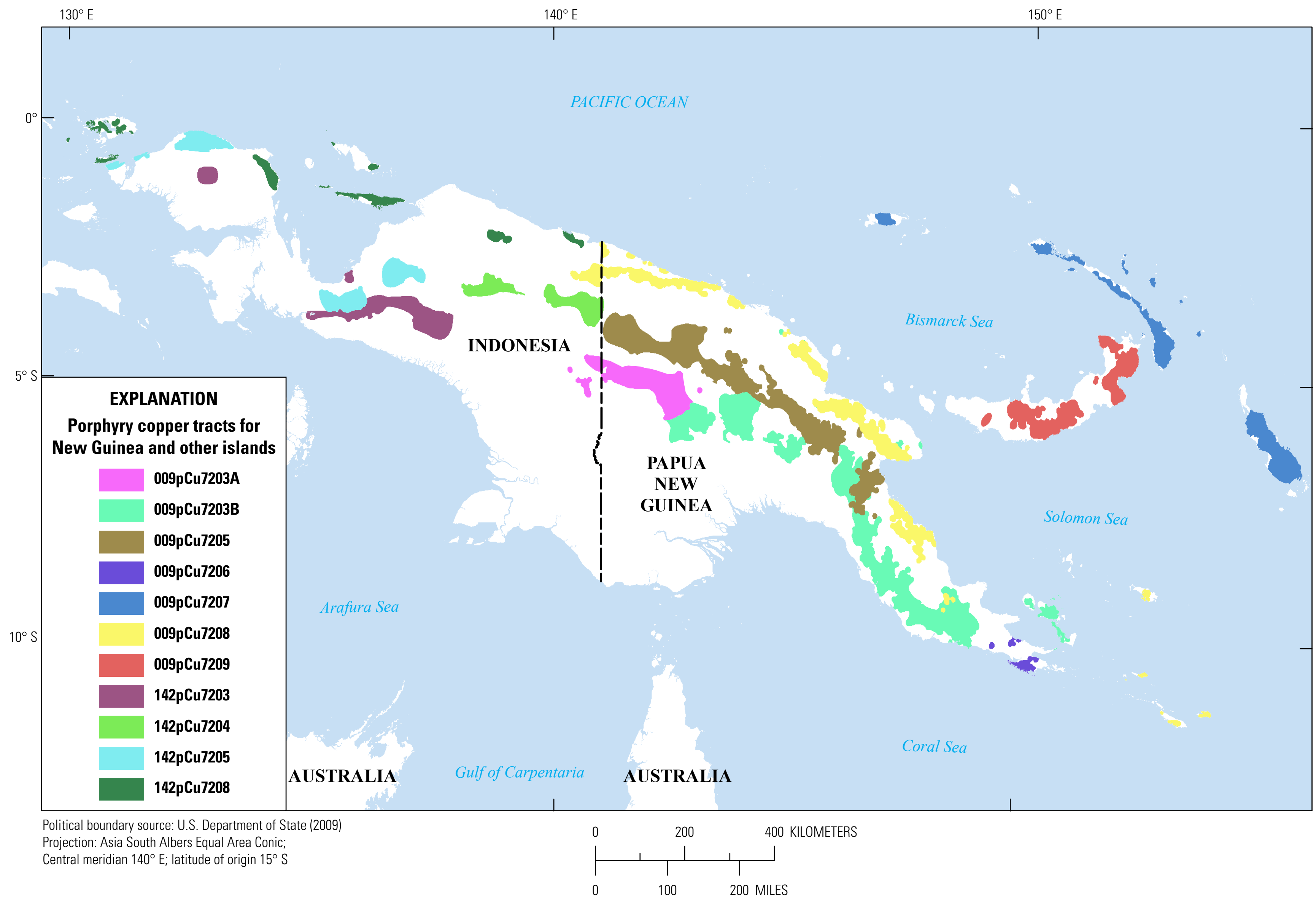


Figure 12. Map of permissive tracts for porphyry copper deposits, New Guinea Island, Indonesia and Papua New Guinea, and other Papua New Guinea Islands, Southeast Asia. Tract coded identifiers and tracts names for Papua New Guinea (Oceania region): 009pCu7203 (Western Medial New Guinea Magmatic Belt, sub-tracts a and b), 009pCu7205 (Maramuni Arc), 009pCu7206 (Miocene Alkaline Rocks, Southeastern Papua New Guinea), 009pCu7207 (Outer Melanesian Arc I—Papua New Guinea), 009pCu7208 (Inner Melanesian Arc Terranes II—Papua New Guinea), and 009pCu7209 (Inner Melanesian Arc—New Britain). Tract coded identifiers and tracts names for Indonesia (Asia region): 142pCu7203 (Western Medial New Guinea Magmatic Belt-Indonesia), 142pCu7204 (Rotanburg-Taritatua Area), 142pCu7205 (Moon-Utawa-Ular Merah Areas), and 142pCu7208 (Inner Melanesian Arc Terranes I—Indonesia).

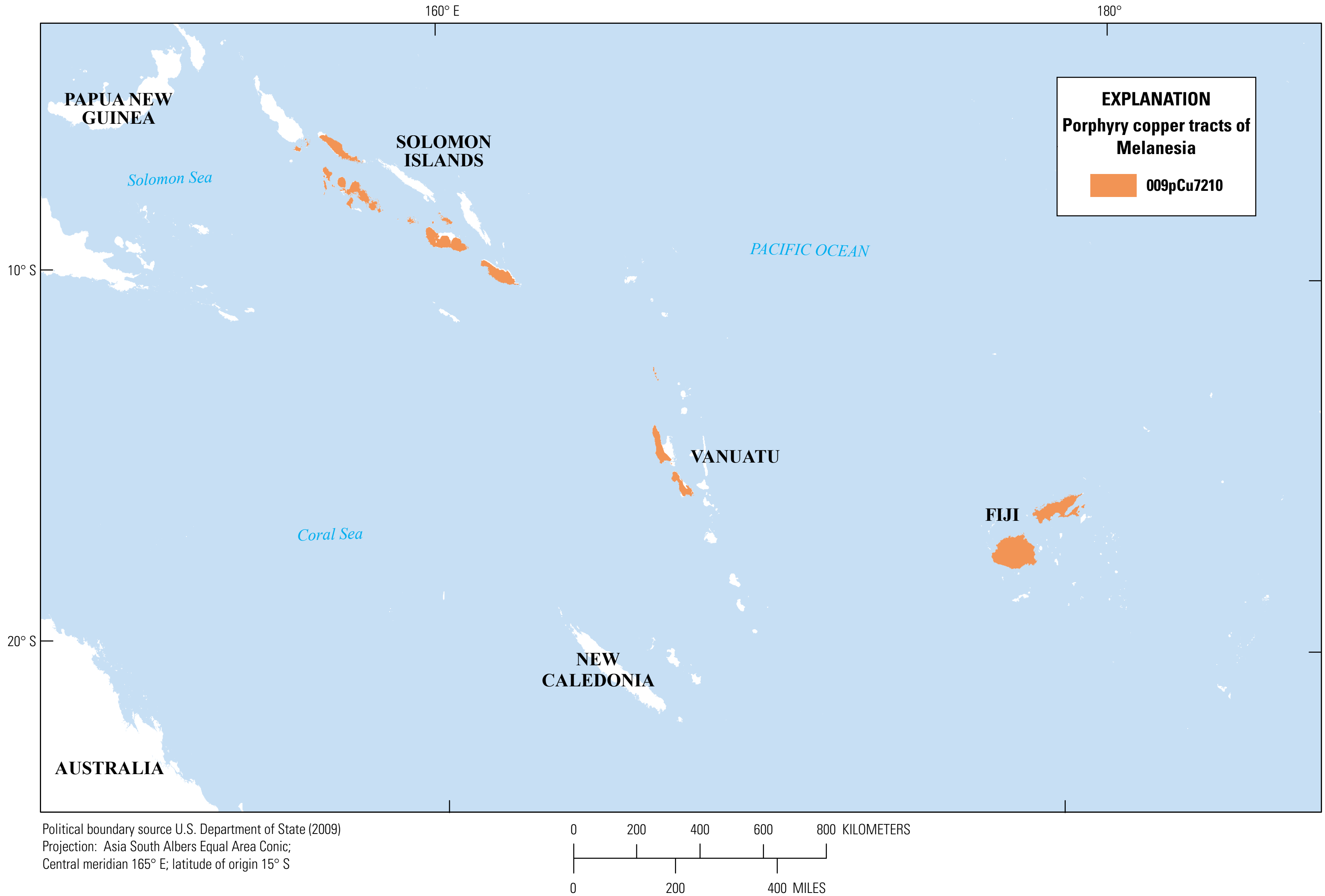


Figure 13. Map of permissive tract for porphyry copper deposits 009pCu7210 (Outer Melanesian Arc II—Melanesia). The tract includes 3 segments: Solomon Islands (SI), Vanuatu (V), and Fiji (F).

Table 5. Summary of identified resources in porphyry copper deposits of Southeast Asia and Melanesia.

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton (= parts per million); -, no data. *, Mengapur is included as a porphyry copper deposit in Singer and others (2008) but is better classified as a skarn deposit]

Tract	Tract name	Name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Au (t)
Indochina peninsular area										
142pCu7021	Sukhothai	Phu Kham	292	183	0.64	-	0.24	2	1,171,200	44
142pCu7022	Malaysia	Mengapur*	Triassic	45	1.80		0.60		810,000	27
142pCu7024	Wuntho-Popa	Monywa	Miocene	1,700	0.37	-	-	-	6,290,000	-
								Total for Indochina peninsular area	8,271,200	71
Indonesian Islands area										
142pCu7020	Sumatra Island	Tangse	11	600	0.15	0.02	-	-	900,000	-
142pCu7025	Sunda Banda Arc	Batu Hijau	3.7	1,640	0.44	-	0.35	0.55	7,216,000	574
142pCu7027	North Sulawesi	Tapadaa	3.75	43	0.54	-	0.08	-	232,200	3
142pCu7027	North Sulawesi	Tombulilato	3	287	0.63	-	0.47	-	1,808,100	135
142pCu7019	Central Kalimantan	Mamut	7	196	0.48	0.001	0.50	2.5	940,800	98
142pCu7202	Halmahera Arc	Kaputusan	Miocene?	77	0.33	-	0.25	-	254,100	19
								Total for Indonesian Islands area	11,351,200	829
New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea islands										
142pCu7203	Western Medial New Guinea Magmatic Belt	Grasberg	3	4,000	0.60	-	0.64	2	24,000,000	2,560
009pCu7203a	Eastern Medial New Guinea Magmatic Belt	Ok Tedi	1.15	854	0.64	0.011	0.78	-	5,465,600	666
009pCu7203a	Eastern Medial New Guinea Magmatic Belt	Star Mount Futik	3.65	65	0.54	-	0.10	-	351,000	7
009pCu7203a	Eastern Medial New Guinea Magmatic Belt	Star Mount Nong River	3.55	60	0.50	-	-	-	300,000	-
009pCu7203b	Eastern Medial New Guinea Magmatic Belt	Kodu (Ofi Creek, Mount Bini)	4.40	276	0.28	0.008	0.30	1.75	759,000	83
009pCu7203b	Eastern Medial New Guinea Magmatic Belt	Wafi-Golpu	9	540	0.90	0.01	0.56	-	4,860,000	302
009pCu7203b	Eastern Medial New Guinea Magmatic Belt	Yandera	7	1,639	0.35	0.01	0.07	1.5	5,749,926	115
009pCu7205	Maramuni Arc	Frieda River	12	1,900	0.45	0.004	0.22	0.7	8,550,000	418
009pCu7209	Inner Melanesian Arc (New Britain)	Simuku	24	200	0.36	0.008	0.07	2	720,000	12
009pCu7207	Outer Melanesian Arc I - Papua New Guinea	Arie	15	165	0.32	-	0.10	-	528,000	-
009pCu7207	Outer Melanesian Arc I - Papua New Guinea	Panguna	3.4	1,420	0.47	0.005	0.57	1.1	6,603,000	809
								Total for New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea islands	57,886,526	4,972
Melanesia										
009pCu7210	Outer Melanesian Arc II-Melanesia	Koloula (Guadalcanal Joint Venture)	2	50	0.170	-	-	-	85,000	-
009pCu7210	Outer Melanesian Arc II-Melanesia	Namosi	-6	1,792	0.370	0.014	0.12	-	6,630,400	215
009pCu7210	Outer Melanesian Arc II-Melanesia	Waivaka	-6	23	0.750	-	0.25	-	172,500	5.8
								Total for Melanesia	6,887,900	221
								Total for Southeast Asia	84,396,826	6,095

diorite intrusions and with local supergene copper enrichment (Lowder and Dow, 1976, 1978).

The Central Kalimantan tract (142pCu7019) encloses a dispersed belt of late Oligocene to Pliocene intermediate intrusive and volcanic rocks across Kalimantan, Indonesia and parts of Sabah and Sarawak, Malaysia (fig. 11). The igneous rocks postdate folding, thrusting, uplift, and erosion of pre-Miocene rocks and continental basement in Kalimantan. The relationship of these mid- to late-Tertiary igneous rocks to subduction is unclear, and the porphyry copper deposits that occur in this tract postdate subduction and have an origin similar to the postsubduction porphyry copper-gold deposit model described by Richards (2009). The only deposit with identified resources within the tract is the 7 Ma Mamut porphyry copper-gold deposit (fig. 1, table 5).

The Halmahera tract (142pCu7202) outlines permissive rocks of the Neogene Halmahera Arc in the North Molucca Islands, Indonesia. Neogene arc rocks include diorite to granodiorite intrusions emplaced into andesitic volcanic rocks and have geochemical signatures indicating contributions of continental crust. The continental-crust component is attributed to underlying Australian continental crust displaced along the Sorong Fault (Garwin and others, 2005). The Kaputusan (fig. 1) porphyry copper-gold deposit on Bacan Island contains identified resources of 77 Mt at 0.33 percent copper and 0.25 g/t gold. The tract also includes the Pliocene Gosowong quartz- alunite epithermal gold deposit that is currently mined.

The Ambon tract (142pCu7201) outlines Pliocene to Pleistocene intrusive and volcanic rocks within the Pliocene to Holocene Ambon island arc. The Ambon Arc is the northwesternmost curved segment extension of the Banda Arc system. The west-facing, curvilinear Banda Arc system formed at the intersection of the Indo-Australian, Pacific, and Eurasian Plates. Honthaas and others (1999) defined the Ambon Arc as a separate arc based on its distinctive Pliocene and younger volcanic-rock geochemistry. Seismic data (McCaffrey, 1988) suggest that the Banda Arc overlies two discrete subduction zones: (1) southward subduction of Irian Jaya continental crust beneath Seram along the Seram Trough; and (2) northward subduction beneath Wetar to Manuk. The tract contains the Hila porphyry copper-gold prospect and associated copper and gold occurrences.

New Guinea Island and Papua New Guinea Islands

Ten permissive tracts are delineated on New Guinea Island and the Papua New Guinea Islands of New Britain, Manus, Bougainville, New Ireland, and the D'Entrecasteaux and Tabar-Fini-Lihir island groups (figs. 7, 8, and 12). Because the island of New Guinea includes two countries, Indonesia (UN region 142) and Papua New Guinea (UN region 009), the permissive tracts for this region are numbered accordingly. Tracts outline Eocene-Oligocene arc segments, Miocene arc segments, and late Miocene to Pliocene arc segments.

The Moon-Utawa-Ular Merah tract (142pCu7205) delineates igneous rocks associated with the middle to late Miocene igneous rocks on western New Guinea Island. The Moon Arc area in the northern part of the Bird's Head region of Indonesia and the Utawa diorite at the base of the Bird's Neck are age-equivalent to the Maramuni Arc (009pCu7205) in the Mobile Belt of Papua New Guinea. No deposits are known in the Moon-Utawa Arc, although exploration projects are active in the Moon Arc area. Carlile and Mitchell (1994) considered the Moon-Utawa Arc to be underexplored at that time. The Utawa segment lacks volcanic rocks (that is, it may be too deeply eroded to preserve porphyry deposits); however, anomalous gold has been detected by exploration in the area, mainly in stream sediments. We include the recently dated Miocene intrusions of the Ular Merah area in the tract, although the relations to the Moon-Utawa Arc, if it exists, are enigmatic. The Ular Merah area is centered on a Miocene (17.4–16.6 Ma) porphyry system that intruded the allochthonous Central Ophiolite Belt in Irian Jaya, about 150 km northwest of the Erstberg mining district (Jackson, 2010). PT Freeport Indonesia explored the Ular Merah area in 2007; five cores drilled in areas of anomalous copper and gold in soil samples showed little evidence of copper mineralization (Jackson, 2010).

The western part of the Medial New Guinea magmatic belt, an 1,800-km-long, east-west belt of discontinuous exposures of late Miocene to Pliocene igneous rocks in the fold belt of central New Guinea Island in Indonesia, is delineated as tract 142pCu7203. The tract, which includes the Grasberg mine, extends eastward to a 300-km-wide "gap" in Neogene intrusions that extends to the Papua New Guinea border; the gap area is lower in elevation (generally <2,000 m) than the Grasberg area (Cloos and others 2005). The intrusions in the western Medial New Guinea magmatic belt represent post-collisional magmas emplaced through continental crust. Pliocene intrusions are present at the highest elevations in the Central Range (Cloos and others, 2005); coeval volcanic rocks are absent.

The eastern part of the Medial New Guinea magmatic belt in Papua New Guinea is represented by tract 009pCu7203. The basement rocks of the magmatic belt differ from west (tract 142pCu7203a) to east (tract 009pCu7203b). The belt is bisected by the Tasman Line (fig. 6) that defines the boundary between two crustal provinces in northern Australia: Paleozoic basement composed of Paleozoic accreted terranes of the Tasman orogen lie to the east of the line, whereas the stable craton with Precambrian basement lies to the west (Hill and Hall, 2003). These differences in basement affect the crustal response to deformation, and may influence the character of porphyry-related magmas. The tracts include several discrete subareas. The western tract includes an area of the Bird's Head where no permissive rocks are mapped at the surface but were encountered at depth (>500 m) during exploration drilling (Arc Exploration, 2009), as well as an area of permissive volcanic rocks along the eastern side of Cenderawasih Bay, and the Grasberg mine area. Approximately 16 small (a few to several hundred square meters), hypabyssal Pliocene intrusions have been identified in the Gunung Bijah mining district; the largest intrusions (a few square km in outcrop area) are the Erstberg Diorite (3.00 ± 0.08 Ma) and the Grasberg Igneous Complex (2.6–4.4 Ma). The Grasberg (fig. 1) supergiant deposit (4,000 Mt at 0.6 percent copper, 0.64 g/t gold) is the largest copper-gold porphyry deposit in the world and the largest porphyry deposit in Southeast Asia. The eastern part of the magmatic belt, mainly in Papua New Guinea, is assessed in two segments based on differences in relative amounts of volcanic and intrusive rocks. Sub-tract 009pCu7203a includes porphyritic rocks of the Star Mountain Intrusives associated with the Ok Tedi, Star Mount Futik, and Star Mount Nong River porphyry copper-gold deposits (fig.1). Sub-tract 009pCu7203b includes several areas of late Miocene to Pliocene intrusions and coeval volcanic rocks in the Central Highlands, Papuan Peninsula, and scattered areas along the northern coast of New Guinea Island. The sub-tract includes the 450 Mt Yandera deposit, Wafi-Golpu, and the Kodu (Mt. Bini) deposits (fig. 1), as well as several active exploration projects.

The Maramuni Arc (tract 009pCu7205) is defined by mapped early to late Miocene intrusive and volcanic-rock exposures, including the rocks of the Frieda River Intrusive Complex. The complex contains at least seven centers of porphyry copper mineralization, including the Horse-Ivaal-Trukai deposit, which is considered one of the world's largest undeveloped porphyry copper-gold deposits with estimated resources of 7.5 Mt of copper and 14.3 million ounces of gold (D. Saroa, written commun., 2010).

Tract 009pCu7206 outlines four areas of middle Miocene alkaline intrusions of probable island arc affinity in southeastern Papua New Guinea. These rocks were described by Smith (1972) as a suite of high-potassium (shoshonitic) intrusions that may represent small volumes of magma intruded into a subvolcanic environment at the beginning of a period of late Cenozoic uplift. The Poi porphyry copper-gold prospect is associated with these rocks.

Three areas on New Guinea Island are treated as qualitative tracts. No estimate of undiscovered porphyry deposits was made of these tracts because of uncertainties about map units and lack of evidence of mineral occurrences that might be related to porphyry copper deposits. Further characterization of these areas, or access to information that was unavailable for this assessment, could change our assessment. The tracts are (1) an area of igneous rocks mapped as late Miocene to Pliocene in the Rotanburg-Taritatua of Indonesia (tract 142pCu7204), and (2) Late Cretaceous to early Miocene accreted terranes of the Inner Melanesian Arc in Indonesia and Papua New Guinea (tracts 142pCu7208 and 009pCu7208, respectively).

The Eocene to Oligocene Inner Melanesian Arc on New Britain is assessed as tract 009pCu7209. The Simuku deposit in the tract has inferred resources of 200 Mt at 0.36 percent copper, 0.07 g/t gold, 0.0076 percent molybdenum, and 2 g/t silver. Resources in this deposit are incompletely defined. Several other porphyry copper prospects on New Britain were dated at 24–25 Ma (Whalen and McDougal, 1980). The Sinivit gold mine (a quartz-alunite epithermal system) in the northeastern part of the island exploits an oxidized cap containing copper and gold along a 1-km-wide by 10-km-long structural zone (Lindley, 1998; New Guinea Gold Corporation, 2009; Stagg, 2006). Porphyry style alteration (potassic, argillic, sericitic, propylitic) is associated with a composite porphyry intrusion located west of the Mount Sinivit gold deposit.

Segments of the more than 800-km-long Outer Melanesian Arc in Papua New Guinea are delineated as tract 009pCu7207 (fig. 12). See figure 8 for locations of the islands of the Outer Melanesian Arc. Porphyry copper prospects on Manus are associated with middle Miocene calc-alkaline intrusions. In the New Ireland area, the tract includes early or middle Oligocene and middle Miocene intrusions of the Lemau Intrusive Complex and younger porphyritic diorite and quartz diorite intrusions. The Legusulum porphyry copper prospect is associated with diorite, diorite porphyry, gabbro, granodiorite and associated agglomerate, and pyroclastic rocks (Mason and McDonald, 1978) intruded into volcanic and sedimentary rocks. The islands of the Bismarck Archipelago east of New Ireland (Tabar-Lihir-Feni) represent eroded Quaternary volcanoes with epithermal systems overprinting porphyry copper-gold systems. Active hydrothermal systems are present on some islands. The Ladolam gold deposit on Lihir Island is developed in the floor of the alkaline Luise Caldera, where sector collapse at 0.3 Ma resulted in telescoping of the hydrothermal system and superposition of a giant epithermal deposit on a weakly mineralized porphyry system.

The 3.4 Ma Panguna (Bougainville) porphyry copper-gold deposit in the south-central part of Bougainville Island contains 1,420 Mt at 0.465 percent copper, 0.005 percent molybdenum, and 0.57 g/t gold. This mine produced 2 percent of the world's copper supply at one time. The mine operated from 1972 until 1989, when political unrest caused a shutdown and a cessation of any exploration activity. A 1989 study estimated that more than1,000 Mt of mineable ore remains (Mining Journal, 2009), resulting in the resource estimate above. As of 2011, studies to reopen the mine were underway.

Melanesia

The Outer Melanesian Arc south of Papua New Guinea is assessed as a single permissive tract 009pCu7210 composed of three segments—Solomon Islands, Vanuatu, and Fiji. Although the arc system represents different episodes of arc development and fragmentation since the Paleogene, it started as a single continuous arc, the Vitiaz Arc. Age information on permissive igneous rocks is scarce. In many areas, igneous complexes associated with both pre- and postsubduction reversals are essentially colocated. Porphyry copper deposits and prospects are associated with both stages of arc evolution.

Most of the porphyry copper deposits and prospects of the Melanesian Arcs are associated with the late Miocene-Pliocene arc magmatism, including the 2 Ma Koloulu deposit in Guadalcanal in the Solomon Islands (85,000 t contained copper) and the 5.6 Ma Namosi deposit in Fiji (>6 Mt contained copper). The Poha and Mbetilonga porphyry copper prospects on Guadalcanal and active exploration projects in the Shortland Islands (northernmost Solomon Islands) are associated with Eocene-Oligocene to early Miocene diorite and andesitic volcanic rocks. No deposits are known on Vanuatu; however, the western belt of late Oligocene to middle Miocene volcanic rocks that formed part of the relict Vitiaz Arc prior to subduction reversal contains hydrothermally altered, chalcopyrite-bearing, fault-controlled, high-level late Miocene intrusions that may be associated with porphyry copper systems (Vanuatu Department of Geology, Mines, and Water Resources, 1995). In Fiji, major porphyry copper and epithermal gold deposits are associated with the mature arc (12–7 Ma) and early rifting stage (7–3 Ma) tholeiitic to calc-alkalic rocks (Fiji Ministry of Lands and Mineral Resources, 2010). In the Namosi district of Viti Levu, Fiji, more than 15 major porphyry copper and gold prospects have been explored since the early 20th century (Imai and others, 2007).

Other Areas

Timor Leste (East Timor) (Based on contributions of Norberta Soares da Costa)

No magmatic-arc rocks have been delineated by mapping in Timor Leste. Copper occurs in three areas as chalcopyrite associated with ophiolite sequences, as stringers in serpentinite, and as native copper. These occurrences have not been fully evaluated; however, on the basis of available geologic information, Timor Leste does not appear to be permissive for porphyry copper deposits. Pending changes in the Mining Law may attract foreign investment in exploration for base and precious metals resulting in better characterization of the country's resource potential.

Grade and Tonnage Models

The grade and tonnage models for porphyry copper deposits in Singer and others (2008) were used for the simulation of undiscovered resources in Southeast Asia. Available models include a global general porphyry Cu-Au-Mo model based on 422 deposits, a Cu-Au subtype model based on 115 deposits, a Cu-Mo subtype model based on 51 deposits, and a Cu subtype based on the 256 deposits that do not fit the other subtypes. If known deposits were present in a tract, grades and tonnages of deposits within the tracts were tested against global models using statistical tests (*t*-test or analysis of variance (ANOVA)). At the 1-percent screening level adopted for this study, the assessment team determined that the global porphyry Cu-Au subtype model was acceptable for most of the tracts (table 6). For permissive tracts that lack identified resources for statistical tests, geologic rationale was used to select the appropriate model (table 6). Most of the porphyry copper deposits of Southeast Asia fit the Cu-Au subtype model, evenly distributed above and below the median tonnage for the model (see figure 14). For many deposits, byproduct metal grades are not reported. Statistical tests for silver grades, where available, indicated that neither the general, nor the Cu-Au subtype model were rejected for any tract. For a comparison of assessment results using different grade and tonnage models, see appendix L (table L7, fig. L3).

The Assessment Process

Several workshops were held between CCOP and USGS authors, where CCOP representatives presented country reports, provided data, and participated in tract delineation and estimation of undiscovered resources. Project workshops were held in Bangkok, Thailand (2003, 2004); Kunming, China (2005); and Busan, South Korea (2010). Preliminary results from the early workshops were updated for the 2010 meeting and refined after internal USGS reviews. Brief biographies of assessment team members are included in appendix X.

Estimates of Numbers of Undiscovered Deposits

The assessment team evaluated the available data and made individual, subjective estimates of the numbers of undiscovered porphyry copper deposits using expert judgment. Estimates are expressed in terms of different levels of certainty. Estimators are asked for the least number of deposits of a given type that they believe could be present at a three specified levels of certainty (90 percent, 50 percent, and 10 percent). For example, on the basis of all the available data, a team member might estimate that there was a 90-percent chance (or better) of at least 1, a 50-percent chance of at least 3, and a 10-percent chance of at least 5 undiscovered deposits in a permissive tract. The individual estimates were discussed as a group, and a single team estimate was agreed upon for each tract. The estimates are converted to a mean number of deposits and standard deviation based on an algorithm developed by Singer and Menzie (2005). The algorithm can be described by the following general equations to calculate a mean number of deposits (λ) and a standard deviation (s_x) based on estimates of numbers of undiscovered deposits predicted at different quantile levels[27] (N_{90}=90-percent level, N_{50}=50-percent level, and so on):

$$\lambda = 0.233\, N_{90} + 0.4\, N_{50} + 0.225\, N_{10} + 0.045\, N_{05} + 0.03\, N_{01} \quad (1)$$

$$s_x = 0.121 - 0.237\, N_{90} - 0.093\, N_{50} + 0.183\, N_{10} + 0.073\, N_{05} + 0.123\, N_{01} \quad (2)$$

These equations were programmed in a simple spreadsheet to allow the team to quickly evaluate estimates. The spread in the number of deposits associated with the 90th percentile to the 10th percentile or 1 percentile reflects uncer-

[27] To use the equation in cases where three non-zero quantiles (90-50-10) are estimated, use the N_{10} values for N_{05} and N_{01}; where four quantiles (90-50-10-5) are estimated, use the N_{05} value for N_{01}.

Table 6. Statistical test results, porphyry copper assessment, Southeast Asia and Melanesia.

[Pooled *t*-test results assuming equal variances; ANOVA tests used for tracts with a single deposit; $p>0.01$ indicates that the deposits in the tract are not significantly different from those in the model at the 1-percent level; $p<0.01$ indicates that the deposits in the tract are significantly different from those in the model at the 1-percent level, and therefore, the tract fails the selected test (as indicated in boldface italic font) and the model is inappropriate for the assessment. -, no data; tests for silver, where reported, were not rejected for either model]

Code	Tract name	N_{known}	Porphyry Cu-Au-Mo model				Porphyry Cu-Au subtype model				Model selected	Basis for selection
			Tons	Cu	Mo	Au	Tons	Cu	Mo	Au		
Indochina peninsular area												
142pCu7021	Sukhothai	1	0.92	0.72	-	0.82	0.82	0.76	-	0.25	Cu-Au	Deposit grade, geological rationale, ANOVA results support either model
142pCu7022	Malaysia	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7023	Mekong Delta	0	-	-	-	-	-	-	-	-	Cu-Au-Mo	Default to general model
142pCu7024	Wuntho-Popa	1	0.19	0.73	-	-	-	-	-	-	Cu-Au-Mo	ANOVA result, geologic rationale
Indonesian Islands area												
142pCu7020	Sumatra Island	1	0.54	0.02	0.62	-	-	-	-	-	Cu-Au-Mo	ANOVA result, no gold grade to test
142pCu7025a	Sunda Banda Arc	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7025b	Sunda Banda Arc	1	0.2	0.97	-	0.54	0.13	0.99	-	0.82	Cu-Au	Geologic rationale, ANOVA results support either model
142pCu7025c	Sunda Banda Arc	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7026	West Sulawesi	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7027	North Sulawesi-Sangihe	2	0.48	0.36	-	0.84	0.55	0.4	-	0.07	Cu-Au	Geologic rationale, t-tests support either model
142pCu7019	Central Kalimantan	1	0.9	0.82	0.012	0.37	0.98	0.85	0.16	0.67	Cu-Au	ANOVA result; Mo barely passes using the general model
142pCu7201	Ambon Arc, Central Molucca Islands	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7202	Halmahera Arc, North Molucca Islands	1	0.46	0.56	-	0.72	0.49	0.55	-	0.71	Cu-Au	Geologic rationale, ANOVA results support either model
New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea islands												
142pCu7205	Moon-Utawa-Ular Merah Areas	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7204	Rotanburg-Taritatua Area	0	-	-	-	-	-	-	-	-	No assessment	-
142pCu7203	Western Medial New Guinea Magmatic Belt	1	0.06	0.48	-	0.28	0.03	0.52	-	0.39	Cu-Au	Deposit grades, geologic rationale, statistical tests support either model
009pCu7203a	Eastern Medial New Guinea Magmatic Belt	3	0.6	0.34	0.92	0.53	0.72	0.39	0.21	0.4	Cu-Au	Deposit grades, geologic rationale, statistical tests support either model
009pCu7203b		3	0.84	0.71	0.99	0.21	0.98	0.76	0.07	0.93	Cu-Au	Deposit grades, geologic rationale, statistical tests support either model
009pCu7205	Maramuni Arc	1	0.32	0.68	0.27	0.6	0.23	0.72	0.9	0.66	Cu-Au	Deposit grades, geologic rationale, statistical tests support either model
009pCu7206	Miocene Alkaline Rocks, Southeastern Papua New Guinea	0	-	-	-	-	-	-	-	-	Cu-Au	Geologic rationale
142pCu7208	Inner Melanesian Arc Terranes I, Indonesia	0	-	-	-	-	-	-	-	-	No assessment	-
009pCu7208	Inner Melanesian Arc Terranes II, Papua New Guinea	0	-	-	-	-	-	-	-	-	No assessment	-
009pCu7209	Inner Melanesian Arc (New Britain)	1	0.91	0.69	0.49	***<0.001***	0.99	0.68	0.58	***<0.001***	Cu-Au-Mo	Default to general model; see discussion in appendix T
009pCu7207, 009pCu7210	Outer Melanesian Arc -Papua New Guinea and Melaneisa	5	0.76	0.55	0.6	0.46	0.93	0.55	0.2	0.45	Cu-Au subtype	Deposit grades, geologic rationale, statistical tests support either model

tainty; large differences in number suggest great uncertainty. The mean number of deposits for the permissive tract, or the numbers associated with a given probability level, reflect favorability. Another useful parameter for reporting uncertainty associated with an estimate is the coefficient of variation (C_v), defined as:

$$C_v = s_x / \lambda. \quad (3)$$

The coefficient of variation is often reported as percent relative variation ($100 \times C_v$).

The final team estimates reflect both the uncertainty in what may exist and the favorability of the tract (Singer, 1993). The estimates are combined with appropriate grade and tonnage models in a Monte Carlo simulation using the EMINERS computer program (Bawiec and Spanksi, 2012; Duval, 2012), based on the original Mark 3 computer program described by Root and others (1992), to provide a probabilistic estimate of amounts of resources that could be associated with undiscovered deposits. No economic filters are applied, so results must be viewed with the realization that deposits, if discovered, might not be developed.

The rationales for individual tract estimates are discussed in the appendixes. In some cases, the number of significant porphyry copper prospects within a tract served as the primary basis for estimates at the 90th and 50th quantiles. Particular weight was given to prospects classified as porphyry copper-related in published literature and recent exploration reports. The location, number, deposit type, and relative importance of other prospects also were considered. Recent literature, company Web sites, and technical reports for exploration projects were checked for descriptions of geology, mineralogy, deposit type, rock alteration, and sampling results to evaluate the likelihood that a prospect is associated with a porphyry copper system similar to those in the grade and tonnage models. In some cases, team members provided information about prospects based on personal observations from site visits.

The level of exploration in different regions was a factor in making estimates. In thoroughly explored areas, such as Papua New Guinea and parts of Indonesia that have well-documented mineral occurrence databases, prospects were ranked informally using a numeric scale:

5: deposit (identified resources),

4: prospect in Singer and others (2008), or <16,000 t of ore established by drilling,

3: drilled, with >20 m of 0.2 percent copper,

2: drilled, or trenched, with <20 m or <0.2 percent copper; past or ongoing exploration, and

1: stream sediment, magnetic anomaly, or mineralized structural trend.

The occurrence of prospects ranked as 3 or 4 typically contributed to estimates at the N_{90} quantile based on reasoning that further exploration of some proportion of these prospects was likely to lead to delineation of a deposit. The total numbers of prospects, and prospects ranked as 2 or 3, as well as the level of exploration throughout the tract area contributed to the other quantile estimates. In addition, the distribution of reported copper and gold occurrences of unknown type and placer gold workings were considered as a factor in making estimates. In less thoroughly explored areas, and areas with poor documentation of mineral occurrences, such methods could not be used, and the spread in estimates and high coefficients of variations associated reflect the team's uncertainty (table 7). Other considerations include the fact that much of Southeast Asia and Melanesia is heavily vegetated, has rugged and steep terrain, and that much of the area has been inaccessible to exploration for 20 years or more because of political turmoil, years of war and social conflicts in some areas, environmental concerns, and local opposition to mineral development.

Final team estimates of undiscovered deposits are summarized in table 7, along with statistics that describe mean numbers of undiscovered deposits, the standard deviation and coefficient of variation associated with the estimate, the number of known deposits, and the implied deposit density for each tract. In two cases, separate estimates were made for different parts of a tract because the team concluded that the expected distribution of undiscovered deposits varied throughout the tract. Therefore, separate estimates are reported for sub-tracts for the Sunda-Banda Arc (142pCu7025) and for the Eastern Medial New Guinea magmatic belt (009pCu7203). For many of the other tracts, geographically distinct tract segments or areas are described, but the probabilistic assessment applies to the entire tract.

Permissive tracts primarily are based on mapped geology. Some tracts necessarily are small because the mapped geology reflects the surface exposures of parts of complex or fragmented arc systems; many of the islands are small, and permissive rocks that comprise arcs, such as the Ambon Arc, extend offshore. The assessment is limited to onshore areas of Southeast Asia and Melanesia.

The assessment predicts a mean of 89 undiscovered porphyry copper deposits in all tracts, or about four times as many deposits as already have been discovered and well-delineated (23 known deposits).

Summary of Probabilistic Assessment Results

Simulation results for mean and median[28] estimates of contained copper and gold in undiscovered deposits are reported in table 8 along with total identified resources in known deposits in each tract. Identified resources are based on total production, if any, and published data for measured, indicated, and inferred reserves and resources at the lowest cutoff

[28] Amount of metal at the 0.5 quantile; 50 percent chance of occurrence of that amount of metal or more based on simulation for the estimated numbers of undiscovered deposits.

grade reported. Identified resources may include substantial amounts of metal that already have been produced.

About one-third of the 22 permissive tracts contain no identified resources. Some tracts may contain porphyry copper systems that are currently, or have been, explored, but no reliable grade and tonnage estimates are yet available; these were considered as significant prospects with a high probability of representing deposits like those in the grade and tonnage models.

Simulation results are reported at selected quantile levels, along with the mean amount of metal, the probability of the mean, and the probability of no metal. The amount of metal reported at each quantile represents the least amount of metal expected. The quantile results represent ranked data from the 4,999 Monte Carlo simulations. The quantiles are linked to each tract simulation and, therefore, should not be added. Mean estimates, however, can be added to obtain total amounts of metal and mineralized rock in undiscovered deposits. Mean estimates of copper, gold, molybdenum, silver, and rock for each tract are listed in table 8. Note that byproduct metals in deposits with reliable tonnages and copper grades frequently are not reported (table 5).

Discussion

This probabilistic assessment of the metal resources associated with undiscovered porphyry copper deposits in Southeast Asia indicates that significant amounts of additional resources may be present (table 8). The mean estimate of undiscovered copper resources in the study area (~288 Mt) is about 3.5 times the amount of copper present in identified resources (84 Mt). However, these resources, if present, may be inaccessible or uneconomic. Results should be interpreted with caution pending

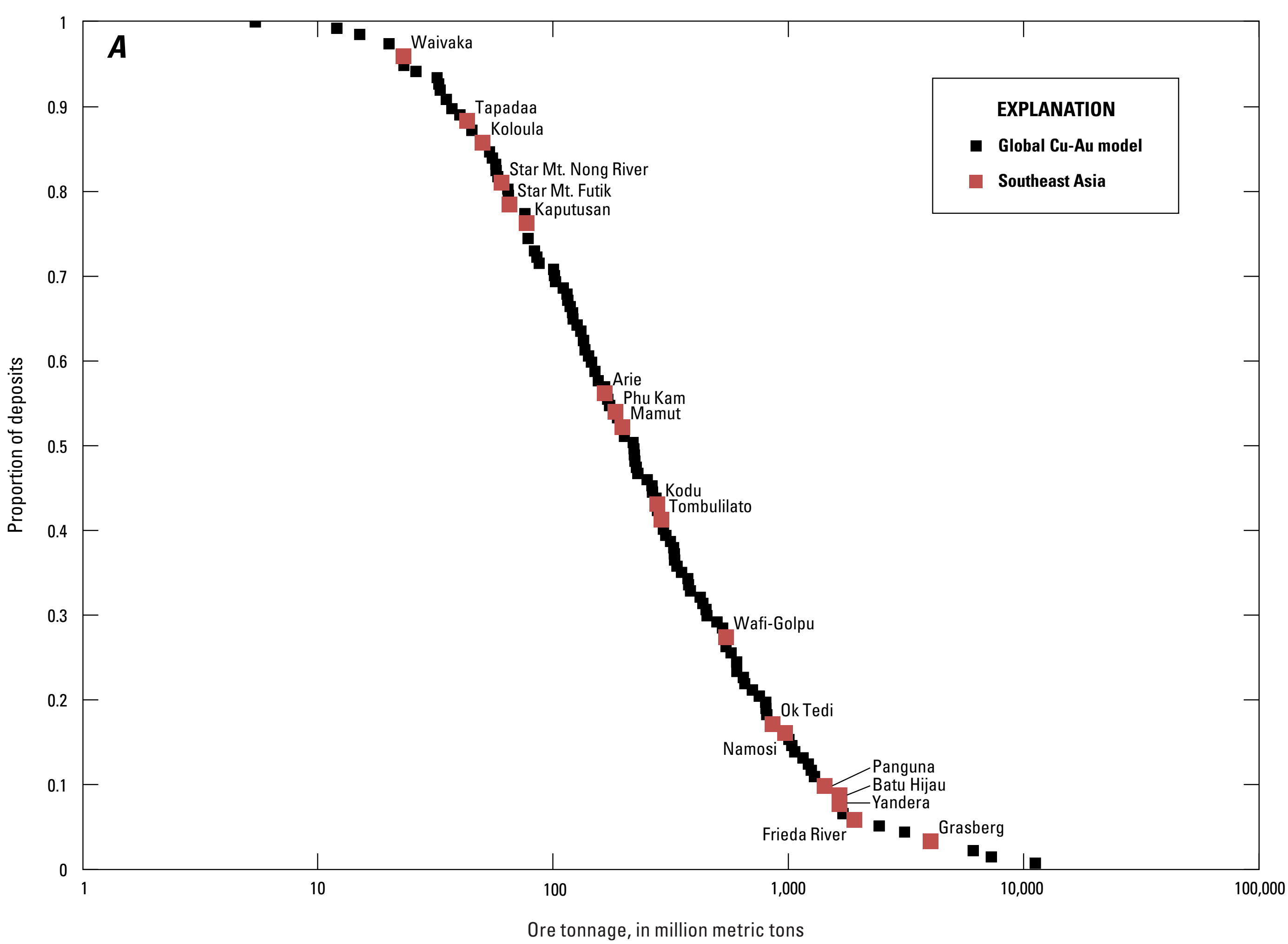


Figure 14. Plot of global tonnage and grade models for porphyry copper deposits, Cu-Au subtype (Singer and others, 2008) showing Southeast Asia porphyry Cu-Au deposits included in the model relative to deposits in other parts of the world. *A*, Tonnage. *B*, Copper grade. Note the spread of tonnages and grades above and below the median tonnage (that is, proportion of deposits = 0.5).

application of economic filters to evaluate what part of the estimated undiscovered resources might be economic under various conditions, such as mining method, metal prices, and capital development costs. Identified resources are compared with mean and with median estimates of undiscovered copper resources by area and by tract in figures 15 *A–D*.

Assessment results are summarized on a regional basis in figure 16. These data indicate that the Indochina Peninsula and Indonesian and Malaysian islands, especially Kalimantan (fig. 16*C*), may contain significantly more copper and gold in undiscovered porphyry copper deposits. Papua New Guinea and the Melanesian island nations also are expected to contain undiscovered resources, but the ratios of undiscovered resources to identified resources are much lower for these areas. One possible explanation for the lower ratios is that the latter areas have been more fully explored and have a longer history of mine development.

Considerations for Users of this Assessment

Assessment products represent a synthesis of current, readily available information. Ideally, assessments are done on a recurring basis, at a variety of scales, because available data change over time. This assessment is based on the descriptive and grade and tonnage data contained in published mineral-deposit models. Data in the grade and tonnage models represent average grades of each commodity of possible economic interest and tonnages based on the total of production, reserves, and resources at the lowest

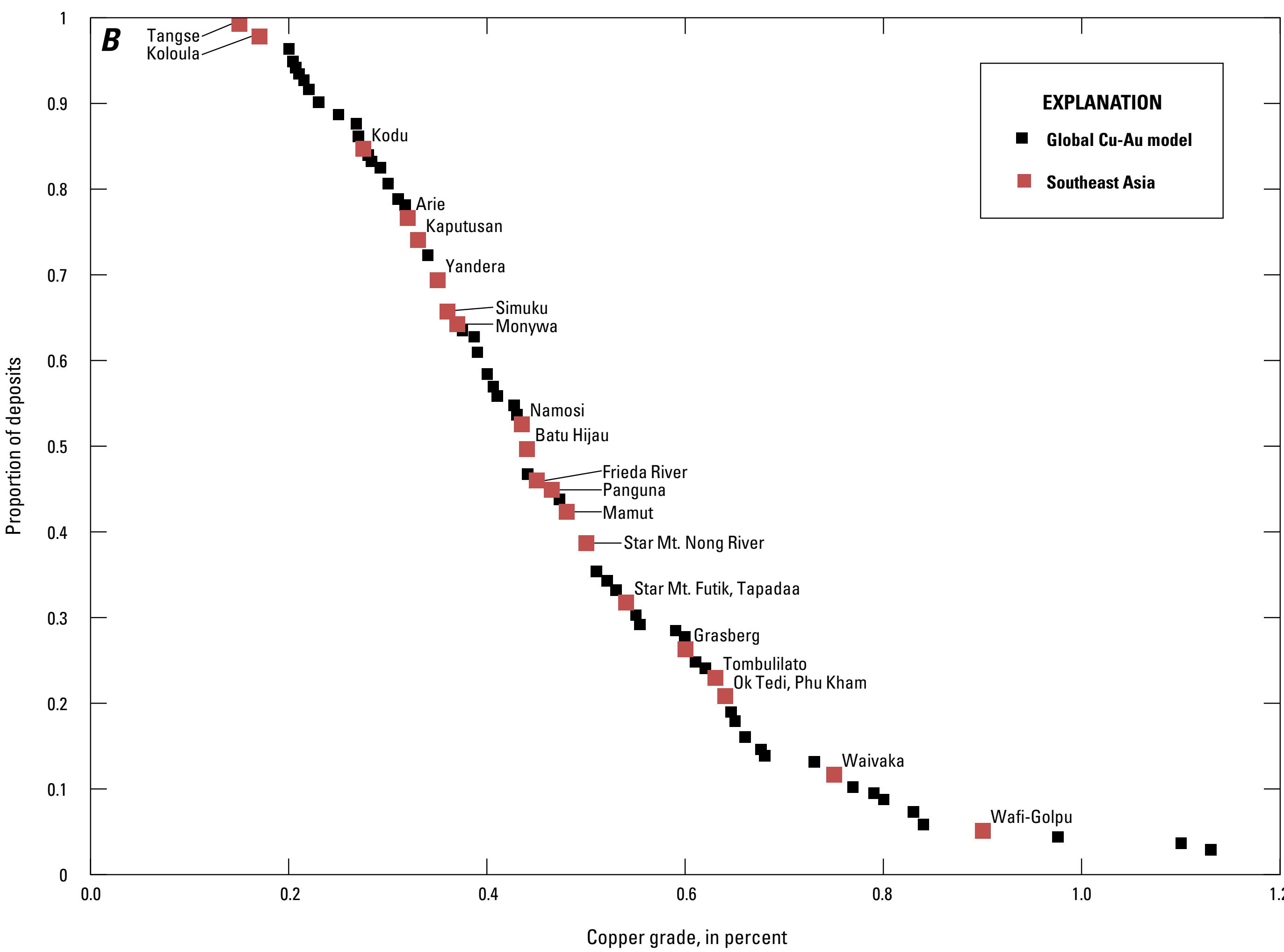


Figure 14.—Continued

Table 7. Estimates of numbers of undiscovered porphyry copper deposits in Southeast Asia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers; deposit density, reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). -, no estimate made]

Appendix	Coded_Id	Tract Name	Consensus undiscovered deposit estimates					Summary statistics					Tract Area (km^2)	Deposit density (N_{total}/100k km^2)	Estimated /known deposits
			N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}			
		Indochina peninsular area													
A	142pCu7021	Sukhothai	3	8	26	26	26	12.0	8.5	73	1	13.0	354,260	4	12.0
B	142pCu7022	Malaysia	1	2	6	6	6	2.8	2	70	1	3.8	60,000	6	-
C	142pCu7023	Mekong Delta	1	6	16	16	16	7.4	5.4	73	0	7.4	91,220	8	-
D	142pCu7024	Wuntho-Popa	0	1	5	9	9	2.2	2.7	120	1	3.2	45,260	7	2.2
		Area total						24.4			3.0	27.4			
		Indonesian Islands area													
E	142pCu7020	Sumatra Island	1	5	13	13	13	6.1	4.3	71	1	7.1	131,030	5	6.1
F	142pCu7025a	Sunda Banda Arc	1	2	8	8	8	3.4	2.7	80	0	3.4	61,200	6	-
	142pCu7025b		1	4	10	10	10	4.8	3.3	68	1	5.8	22,550	26	4.8
	142pCu7025c		0	0	2	2	3	0.6	1	160	0	0.6	5,670	11	-
G	142pCu7026	West Sulawesi	0	1	2	3	3	1.1	0.98	91	0	1.1	60,270	2	-
H	142pCu7027	North Sulawesi-Sangihe	1	2	6	6	6	2.8	2	70	2	4.8	20,330	24	1.4
I	142pCu7019	Central Kalimantan	3	8	30	30	30	13.0	10	78	1	14	144,580	10	13.0
J	142pCu7201	Ambon Arc, Central Molucca Islands	0	1	2	2	2	1.0	0.79	79	0	1.0	1,540	65	-
K	142pCu7202	Halmahera Arc, North Molucca Islands	0	1	3	6	6	1.5	1.8	110	1	2.5	12,250	20	1.5
		Area total						34.3			6.0	40.3			
		New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea Islands													
L	142pCu7205	Moon-Utawa-Ular Merah Areas	0	1	2	2	2	1.00	0.79	79	0	1.0	13,580	7	-
M	142pCu7203	Western Medial New Guinea Magmatic Belt	1	3	10	10	10	4.43	3.40	77	1	5.4	13,270	41	4.4
N	142pCu7204	Rotanburg-Taritatua Area	-	-	-	-	-	-	-	-	-	-	9,370	-	-
O	009pCu7203a	Eastern Medial New Guinea magmatic belt	0	1	4	4	4	1.60	1.54	97	3	4.6	14,230	32	0.5
	009pCu7203b		1	4	16	16	16	6.63	5.58	84	3	9.6	53,220	18	2.2
P	009pCu7205	Maramuni Arc	0	2	8	8	8	3.20	3	93	1	4.2	38,970	11	3.2
Q	009pCu7206	Miocene Alkaline Rocks, Southeastern Papua New Guinea	0	0	1	1	3	0.36	0.75	210	0	0.4	1,640	24	-
R	142pCu7208	Inner Melanesian Arc Terranes I, Indonesia	-	-	-	-	-	-	-	-	-	-	7,720	-	-
S	009pCu7208	Inner Melanesian Arc Terranes II, Papua New Guinea	-	-	-	-	-	-	-	-	-	-	29,140	-	-
T	009pCu7209	Inner Melanesian arc (New Britain)	1	2	4	4	4	2.23	1.2	54	1	3.2	17,990	18	2.2
U	009pCu7207	Outer Melanesian Arc I - Papua New Guinea	2	5	10	10	10	5.47	3	54	2	7.5	16,830	45	2.7
		Area total						24.9			11.0	35.9			
		Melanesia													
V	009pCu7210	Outer Melanesian arc II- Melanesia	1	5	10	10	10	5.2	3.2	61	3	8.2	38,180	21	1.7
		Southeast Asia total						88.9			23.0	107.9			

Table 8. Summary of simulations of undiscovered resources in porphyry copper deposits and comparison with identified copper and gold resources in porphyry copper deposits within each permissive tract , Southeast Asia.

[t, metric tons; Mt, million metric tons, -, not determined; NA, not applicable (only means are additive)]

Appendix	Coded_Id	Tract Name	Known copper resources (t)	Undiscovered copper resources		Known gold resources (t)	Undiscovered gold resources		Mean estimate		
				Mean estimate (t)	Median estimate (t)		Mean estimate (t)	Median estimate (t)	Undiscovered molybdenum resources (t)	Undiscovered silver resources (t)	Rock (Mt)
Indochina peninsular area											
A	142pCu7021	Sukhothai	1,171,200	37,000,000	24,000,000	44	2,700	1,900	210,000	12,000	7,400
B	142pCu7022	Malaysia	810,000	8,900,000	3,500,000	27	640	300	52,000	2,900	1,800
C	142pCu7023	Mekong Delta	0	28,000,000	16,000,000	0	710	380	790,000	9,200	5,700
D	142pCu7024	Wuntho-Popa	6,290,000	8,800,000	1,700,000	0	230	23	250,000	3,000	1,800
	Total for Indochina peninsula area		8,271,200	82,700,000	NA	71	4,280	NA	1,302,000	27,100	16,700
Indonesian Islands area											
E	142pCu7020	Sumatra Island	900,000	23,000,000	13,000,000	0	600	300	640,000	7,800	4,800
F	142pCu7025a	Sunda Banda Arc	0	10,000,000	4,200,000	0	770	350	59,000	3,500	2,100
	142pCu7025b		7,216,000	15,000,000	8,000,000	574	1,100	650	91,000	5,000	3,100
	142pCu7025c		0	2,100,000	0	0	150	0	12,000	690	420
G	142pCu7026	West Sulawesi	0	3,400,000	650,000	0	240	66	19,000	1,100	680
H	142pCu7027	North Sulawesi-Sangihe	2,040,300	8,900,000	3,800,000	138	650	310	51,000	2,900	1,800
I	142pCu7019	Central Kalimantan	940,800	40,000,000	25,000,000	98	2,900	1,900	230,000	13,000	8,100
J	142pCu7201	Ambon Arc, Central Molucca Islands	0	3,100,000	660,000	0	230	65	18,000	1,000	620
K	142pCu7202	Halmahera Arc, North Molucca Islands	254,100	4,800,000	870,000	19	340	80	29,000	1,600	970
	Total for Indonesian Islands area		11,351,200	110,300,000	NA	829	6,980	NA	1,149,000	36,590	22,590
New Guinea Island, Indonesia and Papua New Guinea and other Papua New Guinea Islands											
L	142pCu7205	Moon-Utawa-Ular Merah Areas	0	3,200,000	660,000	0	230	560	18,000	1,100	640
M	142pCu7203	Western Medial New Guinea Magmatic Belt	24,000,000	14,000,000	6,500,000	2,560	1,000	560	80,000	4,500	2,800
N	142pCu7204	Rotanburg-Taritatua Area	-	-	-	-	-	-	-	-	-
O	009pCu7203a	Eastern Medial New Guinea Magmatic Belt	6,116,600	5,100,000	1,200,000	673	360	110	29,000	1,700	1,000
	009pCu7203b		11,368,926	20,000,000	10,000,000	500	1,500	830	120,000	6,700	4,100
P	009pCu7205	Maramuni Arc	8,550,000	9,900,000	3,300,000	418	710	290	56,000	3,200	2,000
Q	009pCu7206	Miocene Alkaline Rocks, Southeastern Papua New Guinea	0	1,200,000	0	0	82	0	7,000	340	230
R	142pCu7208	Inner Melanesian Arc Terranes I, Indonesia	-	-	-	-	-	-	-	-	-
S	009pCu7208	Inner Melanesian Arc Terranes II, Papua New Guinea	-	-	-	-	-	-	-	-	-
T	009pCu7209	Inner Melanesian arc, New Britain	720,000	8,500,000	3,200,000	12	210	62	230,000	2,700	1,700
U	009pCu7207	Outer Melanesian Arc I, Papua New Guinea	7,131,000	17,000,000	9,800,000	809	1,200	830	95,000	5,400	3,400
	Total for New Guinea Area		57,886,526	78,900,000	NA	4,972	5,292	NA	635,000	25,640	15,870
V	009pCu7210	Outer Melanesian Arc II- Melanesia	6,887,900	16,000,000	9,100,000	221	1,200	760	92,000	5,100	3,200
	Total for Southeast Asia		84,396,826	287,900,000	NA	6,093	17,752	NA	3,178,000	94,430	58,360

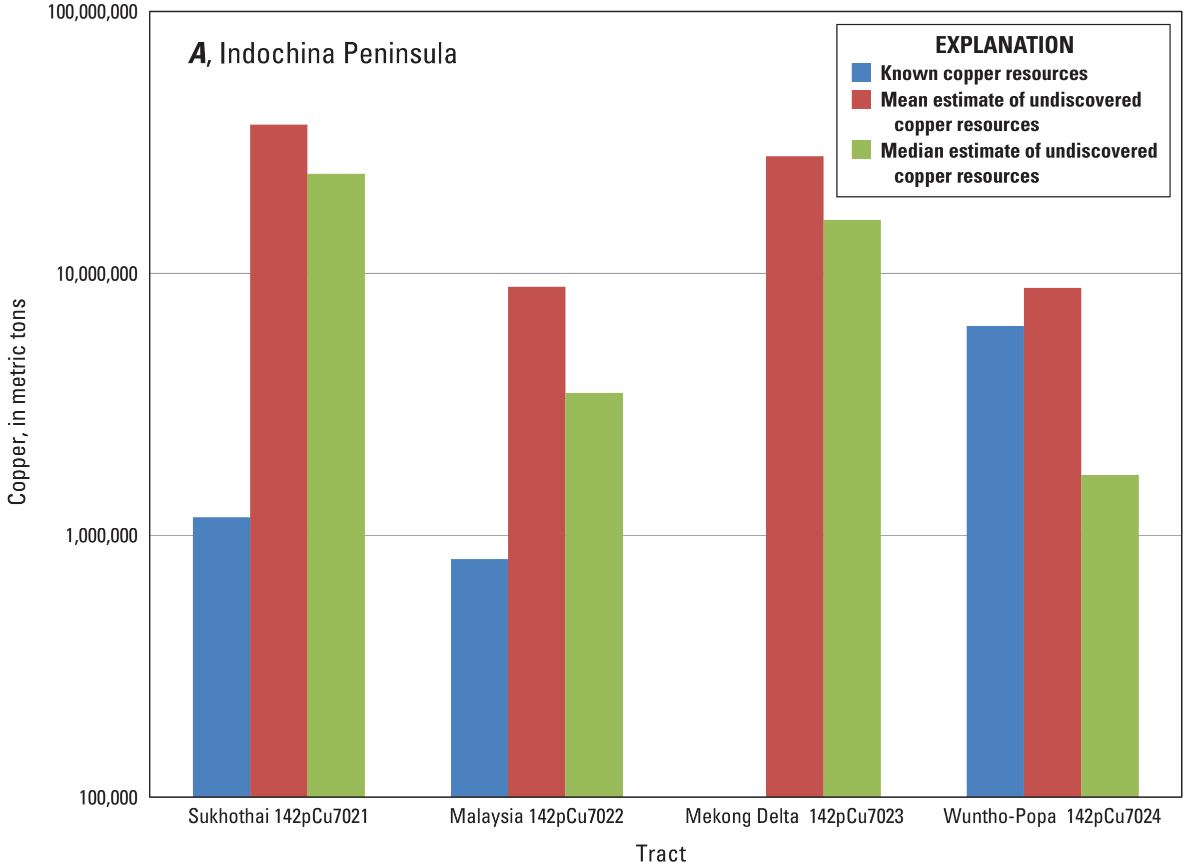
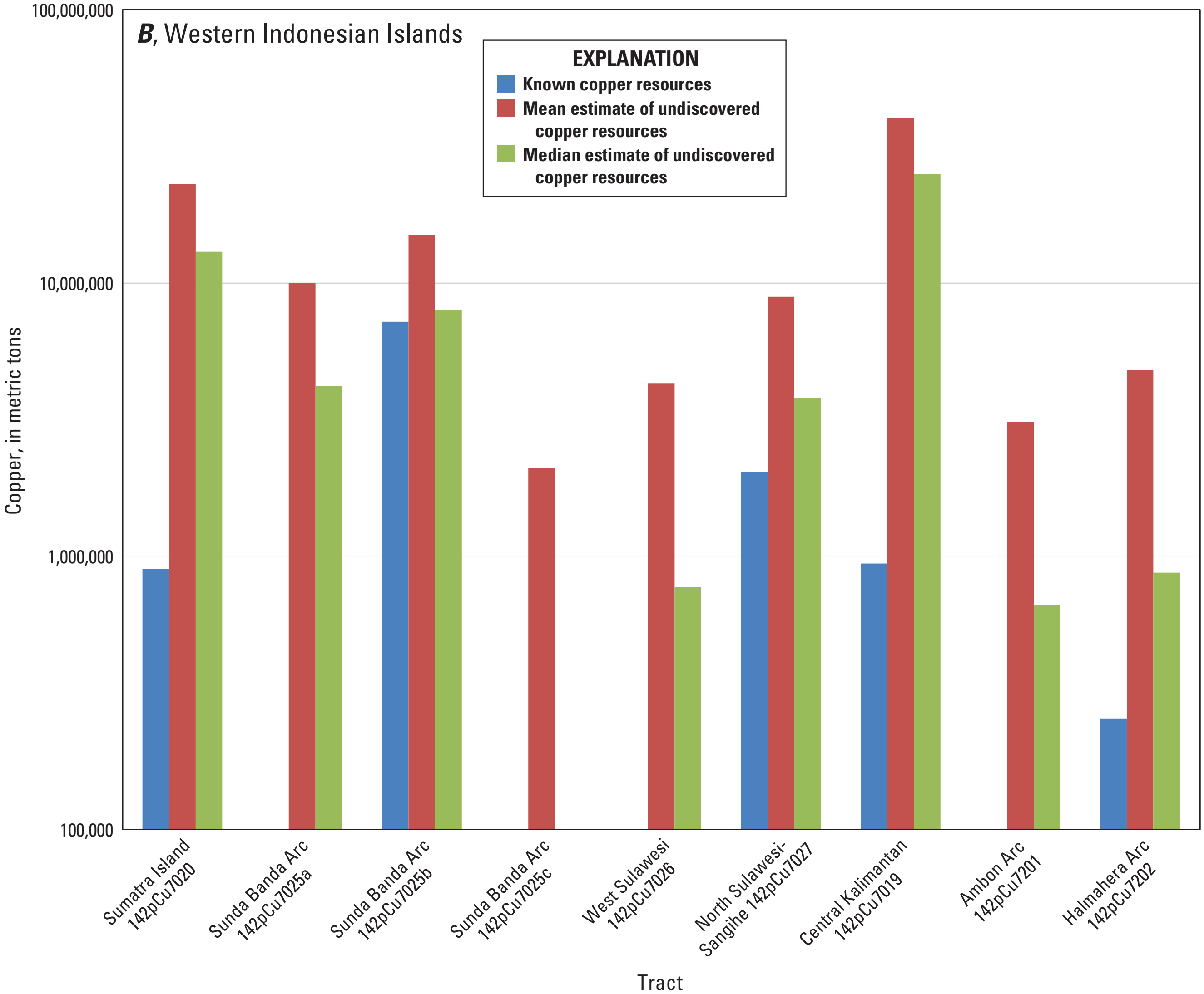


Figure 15. Bar charts comparing known copper resources, mean, and median estimated copper resources in undiscovered porphyry copper deposits in Southeast Asia and Melanesia on a tract by tract basis. See table 4 for tract names and countries included. Values that plot on the base of the diagram indicate no resources. *A*, Indochina Peninsula. *B*, Western Indonesian Islands. *C*, New Guinea Island, Indonesia and Papua New Guinea. *D*, Melanesian Arcs, Papua New Guinea and Melanesia.



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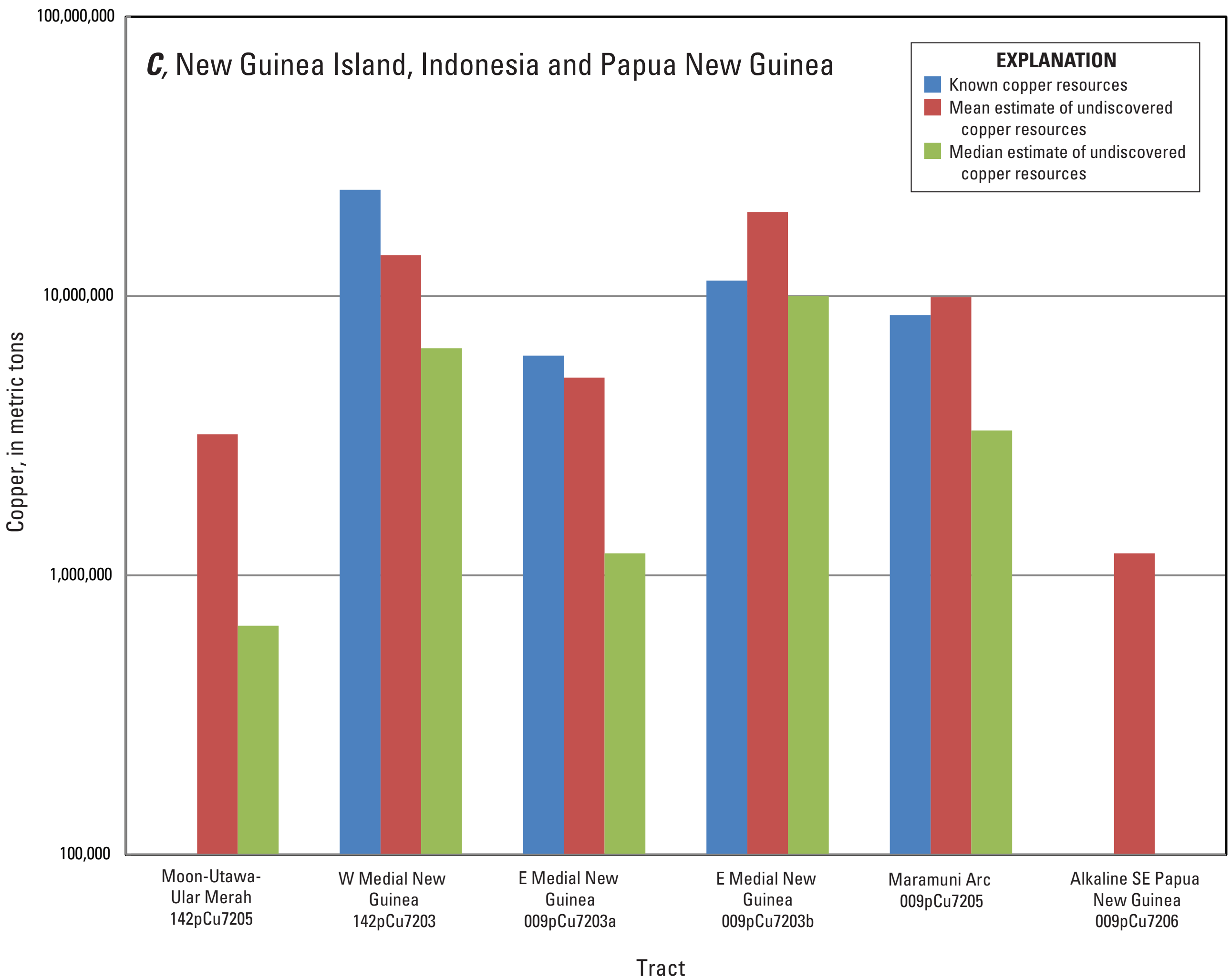

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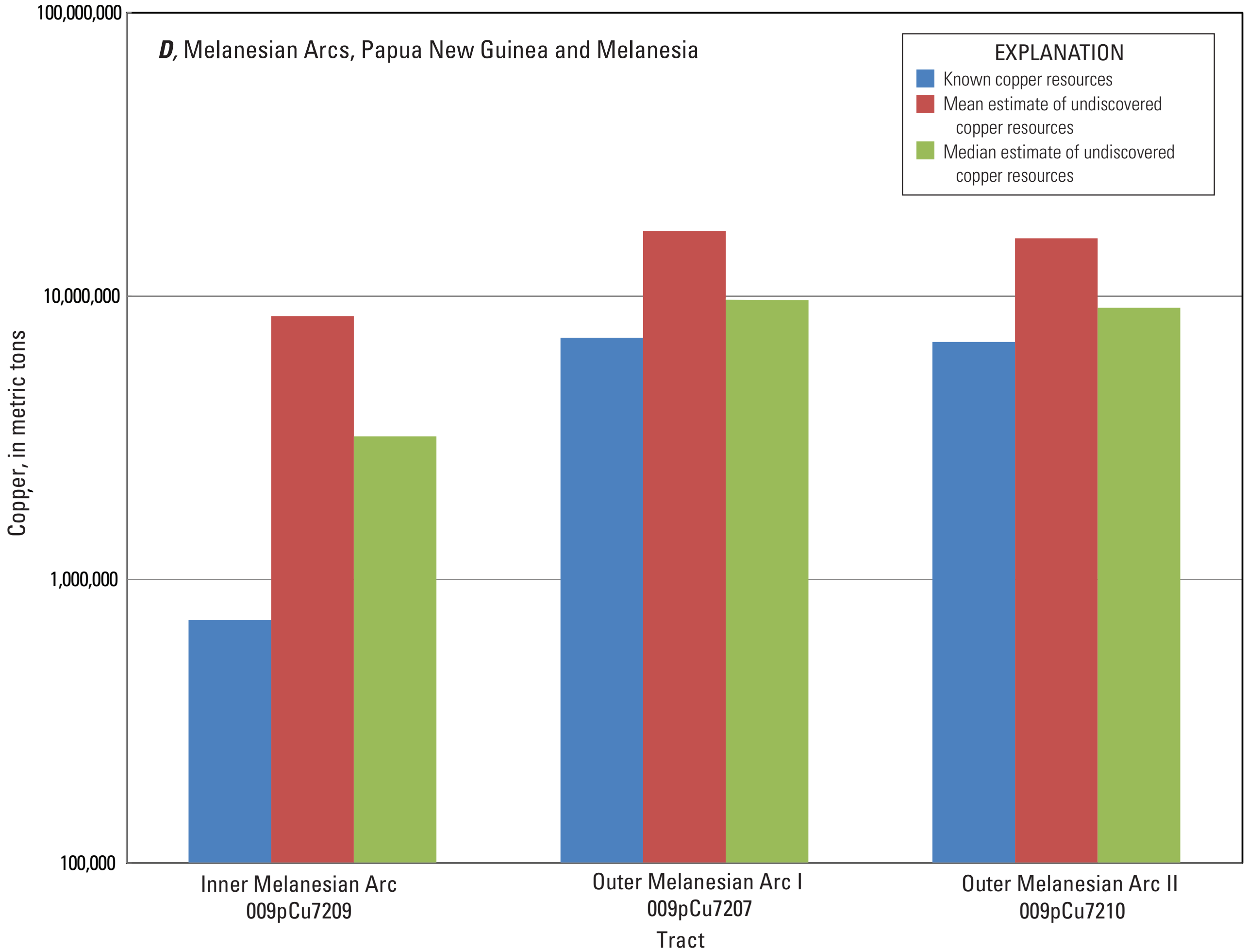

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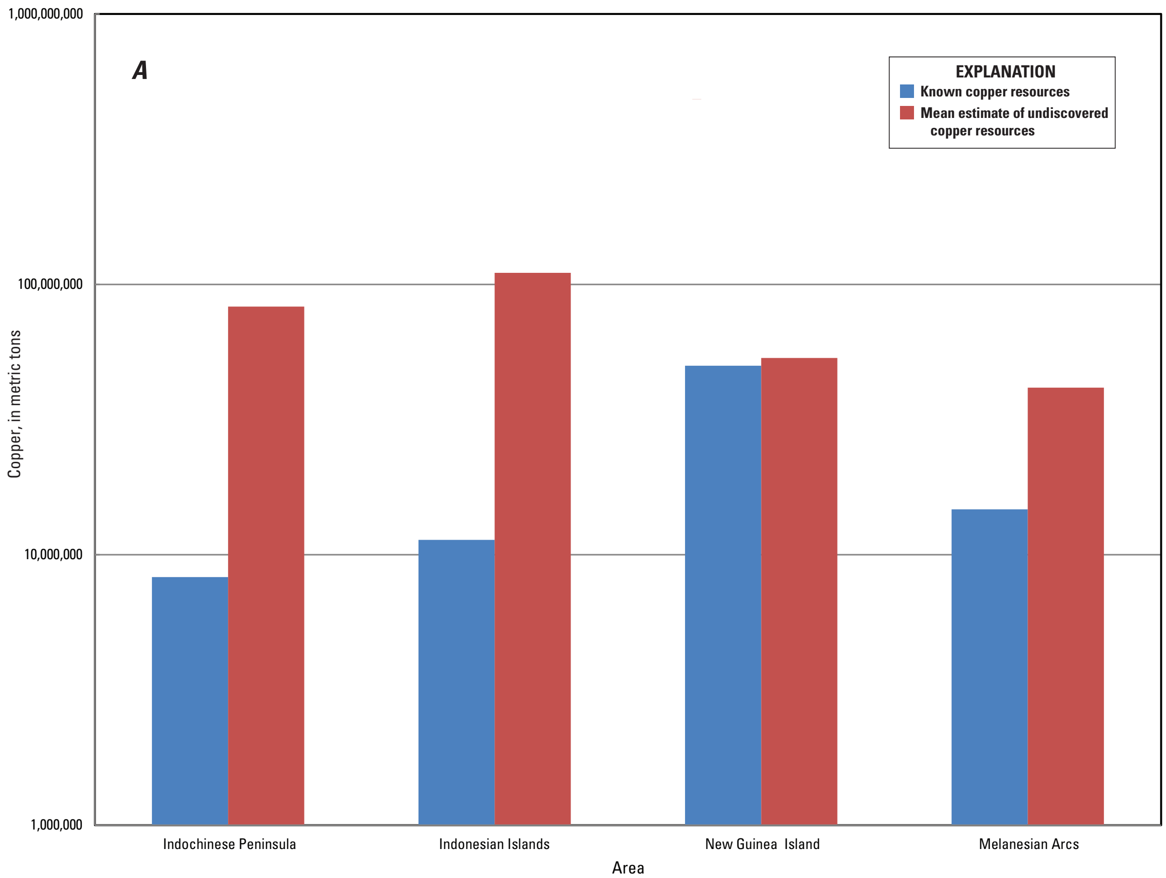

Figure 16. Bar charts comparing known and mean resource estimates on a regional basis. *A*, Copper. *B*, Gold.

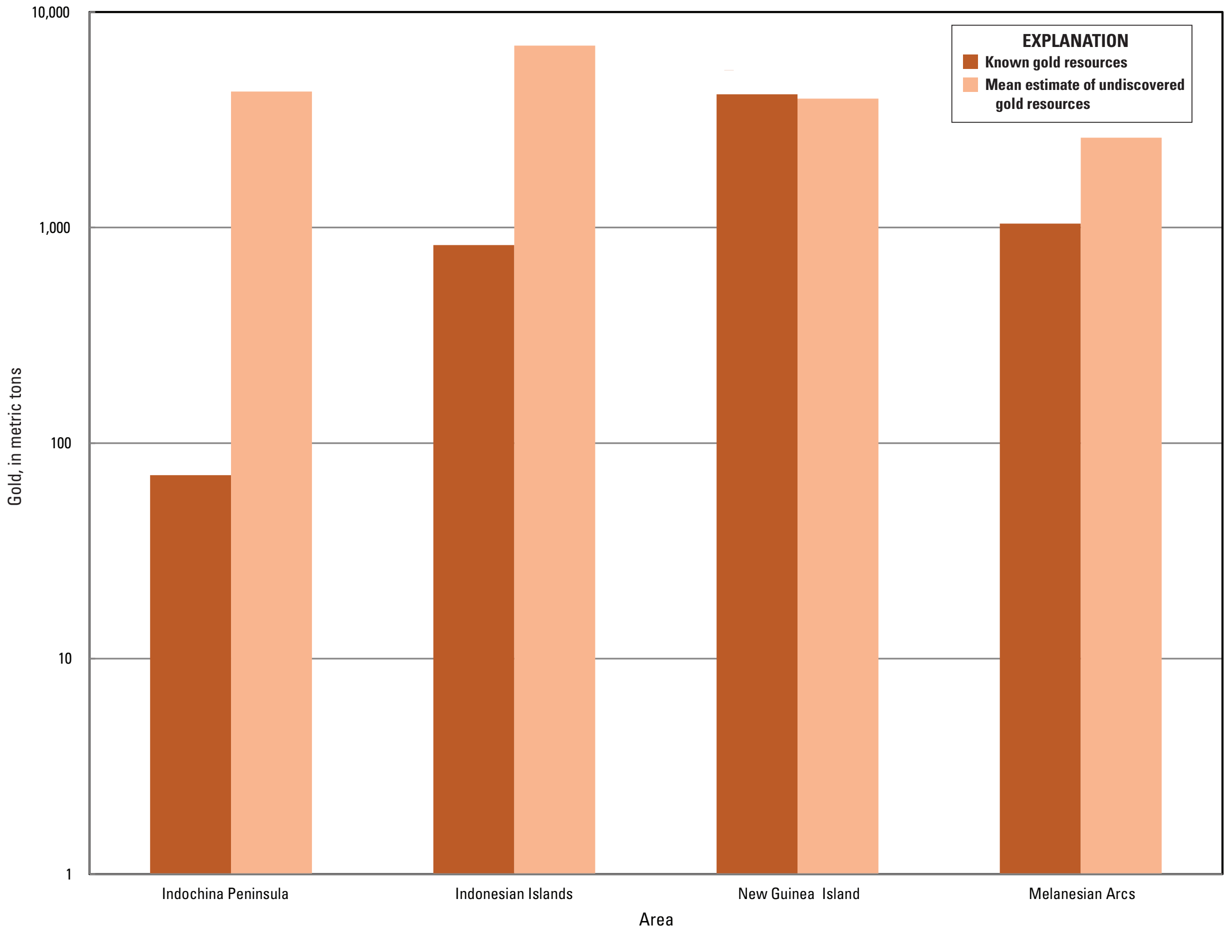

Figure 16.—Continued

cutoff grade for which data were available when the model was constructed. The present-day economic viability of the deposits used to construct the models varies widely, so care must be exercised when using the results of this assessment to answer questions that involve economics. Furthermore, these estimates are of numbers of deposits that are likely to exist, not necessarily those likely to be discovered (Singer, 2007b). Prospects, revealed by past or current exploration efforts, may become deposits when further drilling and characterization takes place. These probable deposits are treated here as undiscovered deposits, albeit ones with a high degree of certainty of existence. The mineral industry explores for extensions of identified resources, as well as for greenfields projects in new exploration areas. Extensions of identified resources are not estimated in this assessment, although they are commonly a substantial part of newly discovered copper resources each year. This assessment considers the potential for concealed deposits within 1 km of the surface. Very high-grade deposits may be exploited at greater depths. However, exploration for, and exploitation of such deposits may be so expensive that deposits, if present, may not be discovered in the near term. If they are discovered, the costs and logistics related to mining a deeply buried porphyry deposit might prohibit their development into mines given current or near-term metal prices and technology.

Permissive tracts are based on geology, irrespective of political boundaries; therefore, tracts may cross country boundaries or include lands that already have been developed for other uses, or have been withdrawn from mineral development as protected areas. The tracts are constructed at a scale of 1:1,000,000 and are not intended for use at larger scales.

Acknowledgments

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Appendixes A–X

Appendix A. Porphyry Copper Assessment for Tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam

By Steve Ludington[1], Wudhikarn Sukserm[2], Jane M. Hammarstrom[3], and Gilpin R. Robinson, Jr.[3], with contributions from Pairatt Jarnyaharn[2], Pichai Otarawanna[2], Boonsong Yokartt[2], Sompob Wongsomasak[2], Nguyen Van Quy[4], Sieng Sotham[5], I.M. Sim[5], and Takehiro Sakimoto[2]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table A1 summarizes selected assessment results.

Table A1. Summary of selected resource assessment results for tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	354,260	1,171,200	37,000,000	24,000,000

Location

The tract extends for about 3,500 km from central Yunnan province in China in two belts, a western belt that runs through Thailand, northern Lao People's Democratic Republic (Laos), and western Cambodia, and an eastern belt that trends southeast through much of the length of Vietnam and Lao People's Democratic Republic, including some areas in northern Cambodia (fig. A1).

Geologic Feature Assessed

Carboniferous through Triassic island and continental arcs formed by subduction of Paleotethyan oceanic crust (the Loei and Truong Son volcanic arcs).

[1]U.S. Geological Survey, Menlo Park, California, United States.
[2]Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.
[3]U.S. Geological Survey, Reston, Virginia, United States.
[4]Department of Geology and Minerals of Vietnam, Hanoi, Vietnam.
[5]Department of Geology and Mines, Phnom Penh, Cambodia.

Delineation of the Permissive Tract

Tectonic Setting

The plate tectonic history of Southeast Asia is still a matter of contention. The widespread Carboniferous through Triassic magmatic rocks that define the Sukhothai tract are, however, all related to the amalgamation of a series of microcontinents that were rifted off Gondwana and drifted north as a result of subduction of the Paleotethyan ocean (Wakita and Metcalfe, 2005). The Sukhothai island arc system, as defined by Sone and Metcalfe (2008), is the result of the eastward subduction of Paleotethyan ocean floor beneath Indochina that began in the latest Carboniferous. This arc, which ended in Late Triassic time when the Sibumasu terrane (fig. 5*A*) collided with Indochina, constitutes the western part of the tract. In northern Thailand and northern Lao People's Democratic Republic, the Loei Belt consists of similar Permian and Triassic volcanic and plutonic rocks, although the Loei Belt is exposed at a somewhat deeper erosion level (Royal Thai Government Department of Mineral Resources, 2010). The Loei Belt also contains Silurian-Devonian volcanic and volcaniclastic rocks, but these are not part of the Sukhothai system (Koshitanont and others, 2008). Further east, the Truong Son igneous belt, in Lao People's Democratic Republic and Vietnam, consists of Permian and Triassic intermediate and felsic volcanic and plutonic rocks, mostly calc-alkaline, with a few peraluminous granites (Hoa and others, 2008).

Geologic Criteria

The digital geologic map used to select the rocks that define the permissive tract is a compilation of digital maps of each of the countries involved, Myanmar, Lao People's Democratic Republic, Cambodia, Thailand, Vietnam, and China (Yunnan) that were prepared by a group at the University of Tasmania (Khin Zaw and others, 1999). These maps were compiled from a number of sources of varying quality and scale. Geological studies of many areas, particularly near national borders, have been hampered by difficult terrain, lack of infrastructure, wars and insurgencies, widespread land mines and unexploded bombs, and freelance bandits (Burret, 1999).

The digital geologic map does not always reflect the most recent radiometric age determinations or petrologic studies on the rocks in the tract, whose ages are not always accurately known. Many of the rocks have not been dated precisely nor have they been studied petrologically. Hence, it is likely that some rocks that are not permissive for porphyry copper deposits are included, either because they are not actually Carboniferous or Permo-Triassic in age, are peraluminous, or are otherwise not strictly part of the volcanic-arc assemblage. Ultramafic rocks, peraluminous granites, and widespread areas of dominantly silicic volcanism are excluded, but overall, the team chose to err on the side of inclusion.

To define the area included in the permissive tract, igneous map units were classified as permissive or nonpermissive, based on the geologic criteria described above, that is calc-alkaline and alkaline volcanic and plutonic rocks of Late Carboniferous, Permian, and Triassic ages (table A2). A 10-km buffer was applied to the polygons for permissive plutonic rocks, and a 2-km buffer was applied to permissive volcanic-rock polygons. This expanded the area of the tract to include all known porphyry copper deposits and significant associated prospects and accounts for uncertainties in the cartographic position of mapped boundaries, as well as possible unexposed or unmapped permissive rocks.

After buffering, the limited geophysical and geochemical information was examined to be sure that any other evidence of unmapped permissive rocks or hydrothermal systems was included. A smoothing routine was applied to the resulting polygons, and the tract was trimmed by any terrane-bounding faults. The resulting tract was compared to several maps that delineate parallel belts of granitoids of contrasting composition in Southeast Asia to ensure that the tract was restricted to the I-type calc-alkaline rocks; these maps include those of Cobbing and others (1992) and Putthapiban (2002). In addition, a newly compiled 1:1,000,000-scale digital geologic map of Thailand provided by the Royal Thai Government Department of Mineral Resources (written commun., 2010) was used to refine that part of the tract in Thailand. Finally, any areas that are intruded by post-Triassic intrusions were excluded, and the resulting tract shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009). The tract is shown in figure A1.

Known Deposits

The Phu Kham porphyry copper-gold deposit (table A3) in the Lao People's Democratic Republic is emplaced in a sequence of Permian mixed volcanic and clastic rocks about 120 km north of Vientane, the Lao capital. The deposit is 90-percent owned by PanAust, an Australian mining company, and it went into production as an open-pit mine in April 2008, with a scheduled mine life of more than 12 years (PanAust, 2010). Few geologic details have been published, but Kamvong (2006) reported that the mineralization is associated with a series of intermediate-composition granitoid rocks whose zircons have been dated by U-Pb methods at about 292 Ma (Manaka and others, 2008).

The present resource (measured + indicated + inferred) at Phu Kham is 183,000,000 tons at 0.64 percent copper, 0.24 g/t gold, and 2.0 g/t silver (no molybdenum reported) at a cutoff grade of 0.3 percent copper. The resource is open to the north and beneath the floor of the designed pit and further development drilling continues (PanAust, 2010). A slightly larger resource (277,000,000 tons at 0.51 percent copper) based on a lower cutoff grade was reported by Singer and others (2008).

Several other undeveloped copper-gold prospects, including one called Pha Nai, are present within the PanAust concession within 20 km of Phu Kham.

Table A2. Map units that define tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[Map unit, age range, and principal lithologies are based on digital map compilations, as cited in table A5]

Map unit	Map symbol	Lithology	Age range
		Intrusive rocks	
16-Granitoid plutons (Laos)	gMz	Granite, tonalite, and granodiorite	Triassic to Jurassic
18-Granitoid plutons (Laos)	gPz3	Granodiorite and monzogranite	Permian to Triassic
19-Granitoid plutons (Laos)	gPz3	Granodiorite and monzogranite	Carboniferous
240-Intrusive rocks (Vietnam)	R123-4	Granite, granophyre, and granodiorite	Late Paleozoic to Early Mesozoic
250-Intrusive rocks (Vietnam)	U2-4		
255-Intrusive rocks (Vietnam)	d1-4		
391-Intrusive rocks (Yunnan)	rn4-rn52	Monzonitic granite	Late Paleozoic to Mesozoic
403-Intrusive rocks (Yunnan)	rx41	K-feldspar granite	Early late Paleozoic
404-Intrusive rocks (Yunnan)	rn41	Monzonitic granite	Early late Paleozoic
405-Intrusive rocks (Yunnan)	rd41	Granodiorite	Early late Paleozoic
834-Granite (Thailand)	gr	Granite, granodiorite, and granite	Paleozoic to Mesozoic
		Volcanic rocks	
7-Shallow shelf sequence (Laos)	Pz3	Volcanosedimentary rocks	Permian-Triassic
12-Volcanosedimentary sequence (Laos)	Pz1	Volcanosedimentary rocks	Cambrian to Silurian (some are Permian to Triassic)
82-Stratified rocks (Yunnan)	P21	Basalt with pyroclastic rocks	Upper Permian
83-Stratified rocks (Yunnan)	P2	Basalt, carbonate rocks, clastic rocks	Upper Permian
113-Stratified rocks (Vietnam)	T2	Acid volcanics	Middle Triassic
132-Stratified rocks (Vietnam)	C-P	Intermediate volcanics	Carboniferous to Permian
515-Dacite and tuffs (Cambodia)	T2	Dacite and tuffs	Middle Triassic
517-Rhyolite, dacite, tuffs (Cambodia)	T1-2	Rhyolite, dacite, and tuffs	Middle Triassic
520-Volcanoclastics (Cambodia)	T	Volcanoclastics	Triassic
524-Andesite, rhyolite (Cambodia)	C3-P	Andesite and rhyolite	Upper Carboniferous to Permian
526-Andesite, rhyolite, tuffs (Cambodia)	C	Andesite, rhyolite, and tuffs	Carboniferous
832-Volcanics complexes (Thailand)	Mv	Rhyolite, andesite, tuff, and agglomerate	Mesozoic
		Rhyolite, tuff, and agglomerate	Permian to Triassic

Although Singer and others (2008) included Phu Lon (Thailand) in their global porphyry copper database, Phu Lon (see below) is a skarn deposit, not a porphyry copper deposit.

Prospects, Mineral Occurrences, and Related Deposit Types

The descriptions of prospects (table A4) are divided into those with most of the characteristics of porphyry copper systems and those that are primarily skarn deposits, although they are associated with calc-alkaline granitoid intrusions.

Porphyry Copper Prospects

PanAust is actively exploring the Puthep project in northern Thailand, about 100 km southwest of the Lao capital of Vientane (fig. A1). There are two sites of interest there, now called Put 1 and Put 2, formerly known as Phu Hin Lek Fai and Phu Thong Daeng. These prospects were discovered

Table A3. Identified porphyry copper resources in tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; n.d., no data. Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Phu Kam[1]	18.918	102.907	Cu-Au	292	183	0.64	n.d.	0.24	2	1,171,200	PanAust (2010)

[1]Deposit is open to the north and below the planned pit, and development continues.

Table A4. Significant prospects and occurrences in tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[%, percent; g/t, grams per metric ton; Mt, million metric tons, Ma, million years]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference
Puthep (Put 1 and 2)	17.45	101.8	Permian–Triassic(?)	Partial resource: >264 Mt at 0.43% Cu and 0.13 g/t Au (cut-off grade 0.25% Cu).	PanAust (2010)
Sa Thay	14.39	107.83	Triassic	Cu up to 0.43%; Au up to 0.3 ppm; Mo up to 840 ppm.	Hoa and others (2006)
Phu Lon	18.2	102.14	244	Skarn; 53 Mt tons at 1.7% Cu and 0.45 g/t Au.	Kamvong and Khin Zaw (2005)
Sepon	16.96	106	Permian–Triassic(?)	Skarn and replacement: 2 Mt of Cu; 4 Moz of Au.	Manini and Albert (2003)

in the 1960s (Jacobsen and others, 1969) and are about 10 km apart. Put 1 has a resource (measured + indicated + inferred) of 264,000,000 tons at 0.43 percent copper and 0.13 g/t gold at a cutoff grade of 0.25 percent copper. Put 2 has an inferred resource of 72,000,000 tons at 0.42 percent copper at a cutoff grade of 0.1 percent copper. Both prospects remain under active development (PanAust, 2010).

These outcropping porphyry copper systems are hosted in Carboniferous limestone and shale and are related to intermediate-composition intrusions of presumed Permo-Triassic age. The majority of the copper is in a subhorizontal bed of supergene chalcocite that averages 30 m in thickness (PanAust, 2010). The deposits were discovered by exploring occurrences of magnetite and malachite in gossans exposed at the surface.

In Vietnam, near Sa Thay, chalcopyrite-bearing quartz veinlets and disseminations have been discovered in the subvolcanic Middle to Late Triassic Van Canh Complex. Numerous varieties of intermediate-composition granitoid and volcanic rocks are found in the region. Several areas of pyrite-quartz-sericite alteration have been identified in the region, along with traces of secondary potassium feldspar. Copper contents of surface samples are as high as 0.43 percent, with gold as high as 0.3 g/t. Notably, molybdenite is part of the assemblage, and molybdenum contents reach 840 ppm (Hoa and others, 2006).

Copper-Gold Skarn Deposits

The Phu Lon deposit in Thailand (fig. A1) is a copper-gold skarn deposit associated with a composite intermediate-composition granitoid intrusion (Muenlek and others, 1988; Pisutha-Arnond and others, 1993; Sitthithaworn and others, 1993; Kamvong and Khin Zaw, 2005, 2009). It is located in the northern part of the country in the Loei magmatic belt, adjacent to the Mekong River, which forms the border with Lao People's Democratic Republic. It was partially drilled in the 1980s, and a resource of nearly 20,000,000 tons was delineated with grades greater than 1 percent copper, gold grades near 1 g/t, and silver grades of 4–5 g/t. The presently accepted resource (Vudhichativanich and Sitthithaworn, 1993) is 53,000,000 tons at 1.7 percent copper and 0.45 g/t gold, although other values have been published. The present state of development of this deposit is not known.

The deposit consists primarily of mineralized garnet-clinopyroxene skarn that is immediately adjacent to the southern part of the Phu Lon pluton. The pluton consists of diorite, monzodiorite, and quartz monzonite and shows evidence of magma mingling; the pluton has a middle Triassic U-Pb zircon date of 244±4 Ma (Kamvong and Khin Zaw, 2005, 2009).

In south-central Lao People's Democratic Republic, the Sepon project is a 1,250 km^2 contract area of various gold and copper deposits that, as of 2009, contain nearly 4 million oz of gold and nearly 2 million tons of copper (MMG, 2009). Gold has been produced since 2002, with copper production starting in 2005. The production is from numerous open-pit mines throughout the area.

The copper deposit currently being mined (Khanong) is a near-surface, supergene-enriched chalcocite and copper-oxide orebody derived from skarn and replacement deposits in carbonate rocks; it is extremely high-grade, with head grades in excess of 5 percent copper. As of 2009, the total supergene copper resource (measured + indicated + inferred) at Sepon was 58,800,000 tons at 2.4 percent copper; the total primary copper resource was 23,300,000 tons at 1.0 percent copper, 0.3 g/t gold, and 6 g/t silver. There are two larger prospect areas about 7 km away that have not been fully explored.

CRA-Rio Tinto and Oxiana discovered the deposits during 1993–2003 (Manini and Albert, 2003), but exploration of the district is far from complete. The known deposits appear to be related to emplacement of presumably Permo-Triassic intermediate-composition granitoid stocks into Devonian through Carboniferous marine sedimentary rocks. The resulting mineral deposits are primarily Cu-Au skarns and disseminated Au deposits, but Mo-Cu stockwork mineralization is associated with the stocks (Manini and Albert, 2003), and Sillitoe (2010) has called the district a porphyry copper deposit.

Several other copper-bearing skarn and vein occurrences are present throughout the Sukhothai tract, but few details about them are known (Khin Zaw and others, 1999; Royal Thai Government Department of Mineral Resources, 2010). One cluster is in northern Lao People's Democratic Republic in the northern part of the Sukhothai island arc, where several small copper vein occurrences are known. Farther north and east, in the northernmost part of the Loei Belt, several more copper-bearing skarns and veins lie just to the northeast of the Pha Nai prospect being explored by PanAust. Another cluster of copper-bearing vein occurrences is further east, along the border with Vietnam. Copper-bearing vein occurrences also are common in the central part of the Loei Belt, from just north of the Phu Lon skarn deposit southwest to the region surrounding the Puthep project. Further south in the Loei Belt, copper-bearing skarn and vein occurrences become less common, but a few are found even in Cambodia, where the Loei Belt disappears under the Gulf of Thailand. These copper-bearing skarn and vein occurrences are even less common along the Lao-Vietnam border in the Truong Son Belt, but difficulty of access makes this area extremely poorly known. The Minle deposit, in southwest Yunnan Province, China, has been described as a porphyry copper deposit (Li, 2000) and is described by Hou and others (2007), along with the nearby Wenyu copper deposit, as being related to a Triassic post-collisional bimodal volcanic suite. Unfortunately, these deposits can neither be located, nor is a description of them available.

Exploration History

Throughout much of this region, exploration for porphyry copper deposits is at a very early stage. In a 1999 review of copper and gold exploration in Southeast Asia, Feebrey (1999) did not mention any of the deposits and prospects compiled for this tract. Vietnam, Lao People's Democratic Republic, and Cambodia have been engulfed in war from the 1940s until very recently, and many of the countries are still in the process of developing effective mining laws that support modern mineral-exploration activities. Cambodia, for example, passed its first mining law in 2001 (Wu, 2002). There is not an adequate aeromagnetic map of the region, and there have been very few regional stream-sediment geochemical surveys.

The following summary of geologic mapping is based on Burrett (1999). Geologists of the British Geological Survey mapped Myanmar, but there has been little activity since 1939. Lao People's Democratic Republic has only begun to be adequately mapped, mostly since the mid 1990s. Cambodia and Vietnam were mapped by French geologists prior to the 1950s and 1960s, but modern work is limited. Yunnan has been mapped by the Chinese, but detailed maps are not available. Geologic maps of peninsular Malaysia, produced by the Malaya Geological Survey, are reliable. In Thailand, there was little geological study prior to the 1950s, although the maps made more recently by the Geological Survey division of the Royal Thai Department of Mineral Resources are of high quality.

There has been a steady acceleration of exploration by outside corporate geologists, many from China and Australia, in the first decade of the 21st century, but the results of that work are only beginning to be reported. The earliest outside workers may have been with CRA Exploration (now Rio Tinto), which began work in Lao People's Democratic Republic in 1989 (Feebrey, 1999).

Sources of Information

Principal sources of information used by the assessment team for delineation of the tract are listed in table A5.

Grade and Tonnage Model Selection

The gold grade at Phu Kam is consistent with the porphyry copper-gold model. The data on prospects and related skarn deposits also suggests that gold will be an important part of the resource at any undiscovered deposits in the tract. ANOVA tests comparing the known deposit with a global porphyry copper-gold model indicate that this model (or a general model) is appropriate for the simulation of undiscovered resources in the tract, although no data are available for testing molybdenum (table 6). We used the porphyry copper-gold submodel of Singer and others (2008) for the assessment of the Sukhothai tract.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The tract contains one known porphyry copper deposit (Phu Kam) and at least one other advanced prospect (Phutep project), as well as other surface indications of porphyry copper-style mineralization (Sa Thay). There are also two

Table A5. Principal sources of information used for tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[NA, not applicable; MMAJ, Metal Mining Agency of Japan; AMIRA, AMIRA International Ltd (http://www.amira.com.au/); CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Name or Title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic maps of Myanmar, Laos, Cambodia, Thailand, Vietnam, and Yunnan Province, China	1;250,000; 1:500,000	Khin Zaw and others (1999)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	AMIRA database	NA	Khin Zaw and others (1999)
	MMAJ database	NA	Metal Mining Agency of Japan (1998)
	World Minerals Geoscience Database	NA	Natural Resources Canada (2010)

Table A6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates						Summary statistics				Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
3	8	26	26	26	12	8.5	73	1	13	354,260	4

gold-rich skarn districts with porphyry copper affinity (Sepon and Phu Lon). In addition, there are numerous copper- and gold-bearing vein and skarn prospects throughout the tract that are indicative of the porphyry copper environment.

The tract is heavily vegetated, and much of the terrain is steep and rugged, limiting accessibility and inhibiting exploration. Political turmoil prevented any serious exploration in most parts of the tract from the 1940s until nearly the end of the 20th century. The aftermath of war—continued political turmoil and large numbers of unexploded mines and bombs—continues to inhibit mineral exploration. When compared to many other parts of the world, this tract must be considered underexplored.

All these factors contributed to the assessment team's estimate that there is at least a 50-percent chance that eight or more undiscovered deposits exist in the tract (table A6). The Phutep project will almost certainly become a deposit in the future, and the team concluded that at least two of the other mineralized areas probably contain a porphyry deposit that will be revealed by continued exploration and development, thus three undiscovered deposits at the 90-percent probability level are estimated. It is also likely that another discovery will be made near Phu Kam.

The team did not apply the deposit density models of Singer and others (2005) directly during the assessment; however the team estimate of 4 deposits/100,000 km^2 is low compared to the observed range in deposit density in thoroughly explored, highly prospective porphyry copper tracts worldwide.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table A7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. A2). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table A7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7021, Sukhothai—China, Myanmar, Thailand, Lao People's Democratic Republic, Cambodia, and Vietnam.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	900,000	2,900,000	24,000,000	90,000,000	110,000,000	37,000,000	0.38	0.03
Mo	0	0	89,000	590,000	830,000	210,000	0.31	0.11
Au	84	250	1,900	6,300	7,700	2,700	0.4	0.03
Ag	0	220	5,200	35,000	52,000	12,000	0.29	0.08
Rock	200	640	5,100	18,000	22,000	7,400	0.4	0.03

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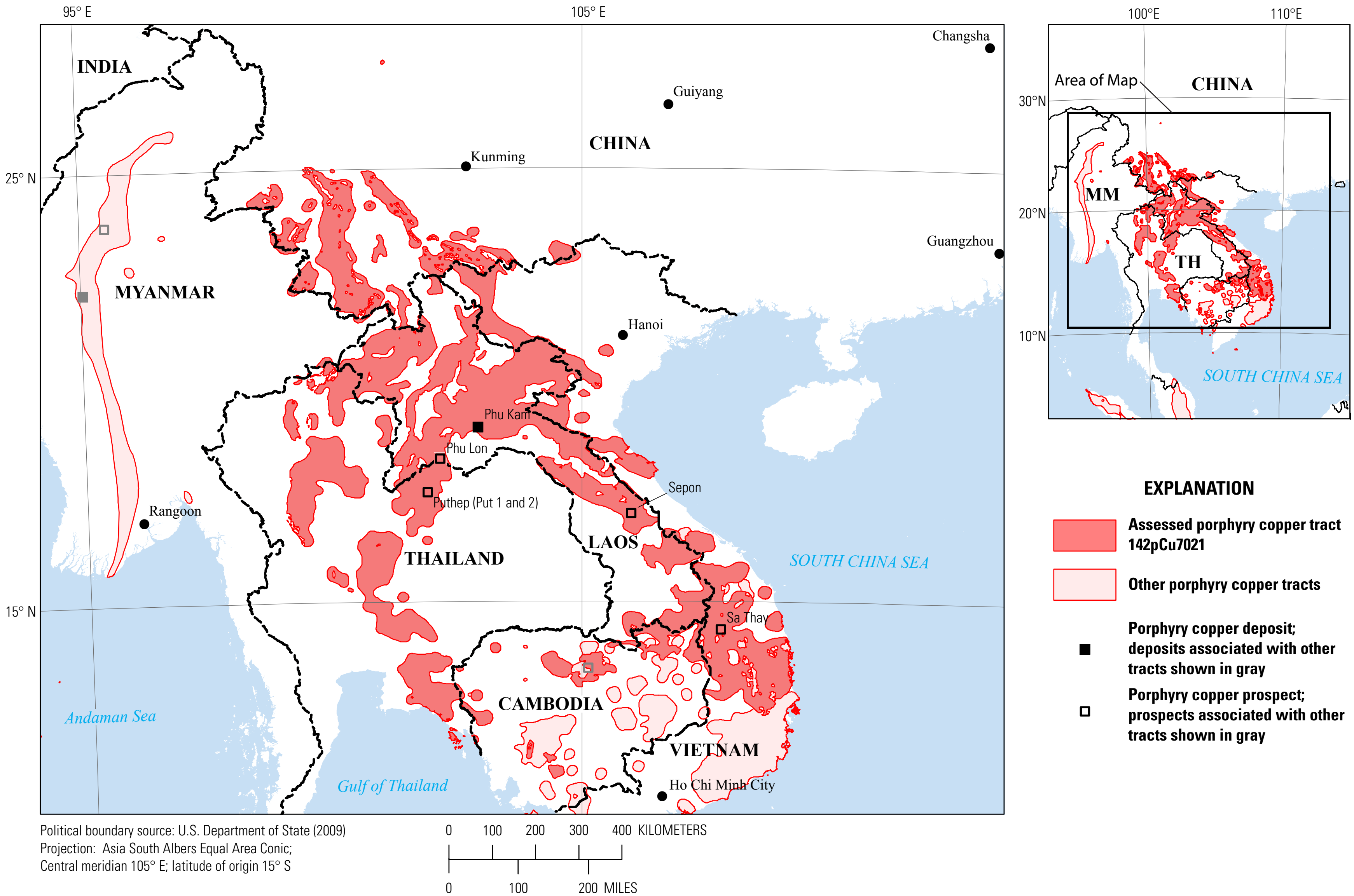

Figure A1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7021, Sukhothai—China, Thailand, Myanmar, Lao People's Democratic Republic, Cambodia, and Vietnam. MM, known deposits, Myanmar; TH, Thailand.

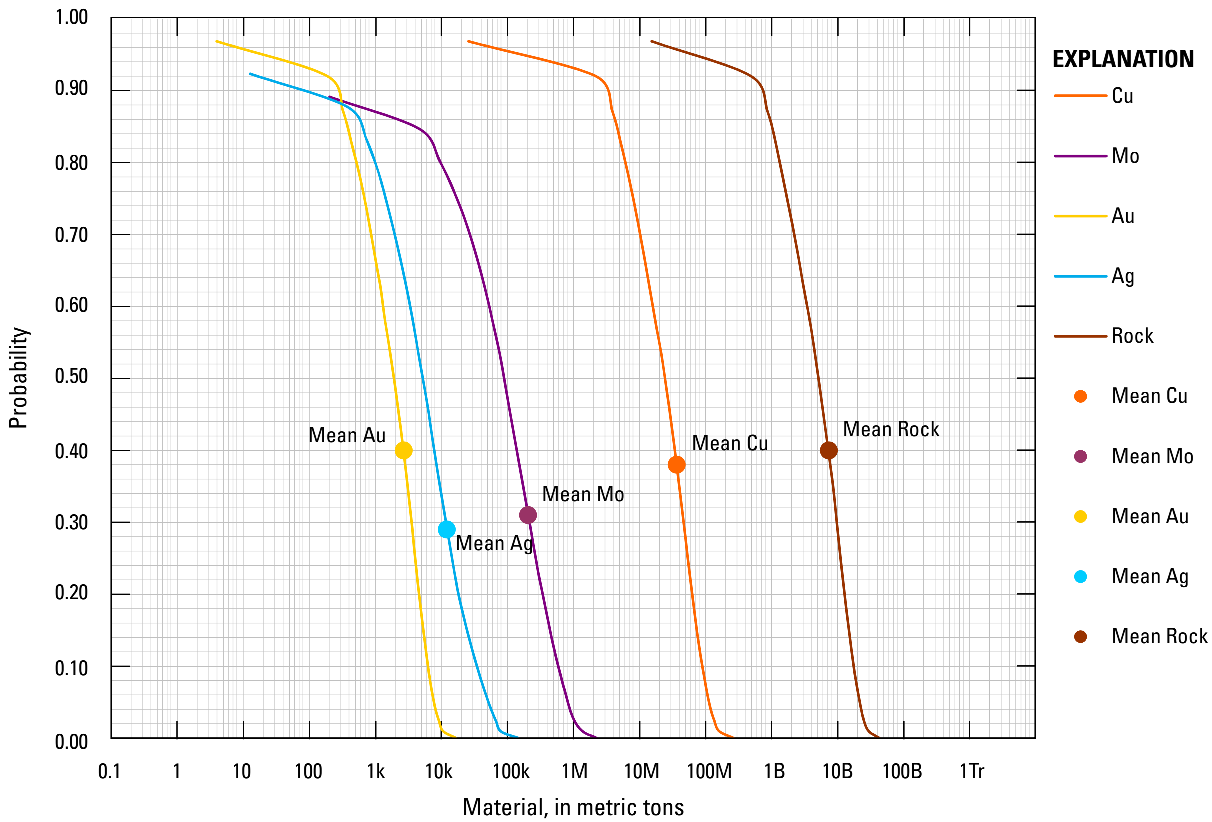

Figure A2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7021, Sukhothai—China, Thailand, Myanmar, Lao People's Democratic Republic, Cambodia, and Vietnam. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix B. Porphyry Copper Assessment for Tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia

By Steve Ludington[1], Sze Wah Alexander Yan[2], Jane M. Hammarstrom[3], and Gilpin R. Robinson, Jr.[3], with contributions from Bambang Tjahjono Setiabudi[4] and Chen Shick Pei[5]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table B1 summarizes selected assessment results.

Table B1. Summary of selected resource assessment results for tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

1:2,000,000	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	60,000	810,000	8,900,000	3,500,000

Location

The tract extends for about 700 km from the southernmost tip of Thailand, through peninsular Malaysia, and it includes the northern margin of Singapore Island and parts of two of the Indonesian Tin Islands (fig. B1).

Geologic Feature Assessed

Assemblage of Carboniferous through Triassic rocks formed as both island arcs and continental arcs by subduction of Paleotethyan oceanic crust below the East Malaya terrane.

Delineation of the Permissive Tract

Tectonic Setting

The plate tectonic history of Southeast Asia is still a matter of contention. The Carboniferous through Triassic magmatic rocks that define the Malaysia tract are, however, all related to the amalgamation of a series of microcontinents that were rifted off Gond-

[1]U.S. Geological Survey, Menlo Park, California, United States.
[2]Minerals and Geoscience Department Malaysia, Kota Kinabalu, Malaysia.
[3]U.S. Geological Survey, Reston, Virginia, United States.
[4]Geological Agency of Indonesia, Bandung, Indonesia.
[5]Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) Technical Secretariat, Bangkok, Thailand.

wana (fig. 5*A*) and drifted north as a result of subduction of the Paleotethyan ocean (Wakita and Metcalfe, 2005). The Sukhothai island-arc system, as defined by Sone and Metcalfe (2008), is the result of the eastward subduction of Paleotethyan ocean floor beneath Indochina; subduction began in the latest Carboniferous and ended in the Late Triassic, when Sibumasu collided with East Malaya (fig. 5*A*). Sone and Metcalfe (2008) assign all of the area delineated as the Malaysia tract to this island-arc system. However, Metcalfe (2008), in the same volume, suggests that only the central ranges of Malaysia are part of this arc, presumably assigning the rocks in the eastern part of the country to a continental arc. We excluded much of the eastern part of Malaysia from this tract, based primarily on the distribution of mineral prospects; in the excluded eastern part, nearly all the prospects contain major tin and (or) tungsten, and none contain copper, indicating that the rocks there, like those west of the Bentong-Raub suture (fig. 5*A*), are collision-related, and unlikely to be associated with porphyry copper deposits.

Geologic Criteria

The digital geologic map used to select the rocks that define the permissive tract is a compilation of digital maps of Thailand and Malaysia that were prepared by a group at the University of Tasmania (Khin Zaw and others, 1999). The digital geologic map does not always reflect the most recent radiometric age determinations or petrologic studies on the rocks in the tract, whose ages are not always accurately known. At the same time, many of the rocks have not been dated precisely nor have they been studied extensively petrologically. Hence, it is likely that some rocks that are not permissive for porphyry copper deposits are included, either because they are not actually Permian to Triassic in age, are peraluminous, or are otherwise not strictly part of the volcanic-arc assemblage. Ultramafic rocks, peraluminous granites, and widespread areas of dominantly silicic volcanism are excluded.

To define the area included in the permissive tract, we first classified igneous map units as permissive or not, based on the geologic criteria described above, that is calc-alkaline and alkaline volcanic and plutonic rocks of Late Carboniferous, Permian, and Triassic ages. In Malaysia, the geologic map attribution does not distinguish between I-type, arc-related igneous rocks and S-type, collision-related rocks, and we relied primarily on the maps of Cobbing and others (1992) to assign polygons as permissive or not. The maps by Cobbing and others (1992) also were used to delineate the small part of the tract on Batam and Bintan Islands, Indonesia, based on the presence of I-type granites. To the polygons (fig. B1) that represent these permissive rocks, we applied a 10-km buffer to plutonic-rock polygons and a 2-km buffer to volcanic-rock polygons; this expanded the area of the tract to include all porphyry copper deposits and significant associated prospects and accounts for uncertainties in the cartographic position of mapped boundaries, as well as possible unexposed or unmapped permissive rocks. Digital map units chosen as permissive are listed in table B2.

After buffering, the limited geophysical and geochemical information was examined to ensure inclusion of any other evidence of unmapped permissive rocks or hydrothermal systems. A smoothing routine was applied to the resulting polygons, and the tract was trimmed on the southwest by the Benton-Raub suture. The tract was compared to several maps that delineate parallel belts of granitoids of contrasting composition in Southeast Asia to be sure that the tract is restricted to the I-type calc-alkaline rocks; these maps include those of Cobbing and others (1992) and Putthapiban (2002). There are a few outcrops of Cretaceous and Tertiary volcanic rocks within the tract, but they are neither thick nor widespread. Finally, the resulting shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009). There are no known post-Triassic intrusions in the tract. The tract is shown in figure B1.

Known Deposits

The Mengapur deposit is listed by Singer and others (2008) as a porphyry copper deposit of 45,000,000 tons, a copper grade of 1.8 percent and a gold grade of 0.6 g/t, but it is better considered to be a copper-gold-iron skarn deposit (table B3). The six oxidized orebodies being exploited at present, as well as seven sulfide bodies, form a ring around a poorly-mineralized adamellite intrusion (Kiang, 2008).

Mengapur was discovered in 1979 by the Geological Survey of Malaysia through regional geochemical sampling. It was prospected during 1983–1993 by MMC, who drilled 198 holes that amounted to 58,000 m of core. In 2006, Malaco Mining began the redevelopment of the project, and production started in September 2008. The main ore mineral is chalcopyrite, but magnetite also is recovered as a byproduct. According to Wong and Lee (1986), additional ore minerals include galena, molybdenite, pyrite, and sphalerite. Another small copper-gold skarn prospect, Bukit Botak, is about 2 km northwest of Mengapur (Heng and others, 2003).

Prospects, Mineral Occurrences, and Related Deposit Types

There is a surprising lack of copper-bearing prospects in Malaysia. Pekan, located about 35 km south of Mengapur, is reported to be related to volcanogenic massive sulfide deposits nearby. Several copper-bearing prospects in the northern part of the tract include a polymetallic skarn and gold-vein deposits. None of these prospects were considered significant.

A number of gold deposits are present in the Central Gold Belt, about 100 km to the west of Mengapur. Most of them are related to intermediate-composition intrusions and are perhaps best regarded as polymetallic veins, as they commonly contain moderate amounts of copper, lead, and zinc (Hassan and Purwanto, 2002; Wong and Lee, 1986).

Exploration History

The assessment team found little information about exploration for porphyry copper deposits in Malaysia and therefore

Table B2. Map units that define tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[Map unit, age range, and principal lithologies are based on a digital compilation of geologic maps of Thailand and Indonesia (Khin Zaw and others, 1999)]

Map unit	Map symbol	Lithology	Age range
	Intrusive rocks		
30-Acid intrusives (undifferentiated) (Malaysia)	Ag	Acid intrusives	Triassic and unknown
31-Intermediate intrusives (undifferentiated)	Ig	Intermediate intrusives	Paleozoic and Mesozoic
834-Granite, granodiorite, and minor diorite (Thailand)	gr	Granite, granodiorite, and minor diorite	Triassic and unknown
	Volcanic rocks		
420-Ignimbrite	K	Ignimbrite	Triassic
421-Acid to intermedite volcanics	K	Dacite and rhyolite	Triassic
422-Intermediate to basic volcanics	K	Andesite and basalt	Triassic
520-Ignimbrite	P	Ash-flow tuff	Permian
521-Acid to intermediate volcanics	C	Dacite and rhyolite	Carboniferous
522-Intermediate to basic volcanics	P	Andesite and basalt	Permian
621-Acid to intermediate volcanics	C	Dacite and rhyolite	Carboniferous
622-Intermediate to basic volcanics	C	Andesite and basalt	Carboniferous

Table B3. Identified porphyry copper resources in tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Mengapur[1]	3.746	102.825	Cu-Au	presumed Triassic	45	1.8	n.d.	0.6	n.d.	810,000	Kiang (2008)

[1]Deposit is best considered a Cu-Au-Fe skarn deposit.

surmised that there has been little exploration. Exploration has focused on tin and, within the tract, gold and base metals in the Kuala Lipis-Raub and Jeli-Gua Musang areas in the western part of the tract.

The geologic maps of peninsular Malaysia produced by the Malaysia Geological Survey are reported to be reliable (Burrett, 1999). The assessment team found no evidence of any current exploration by non-Malaysian mining companies.

Sources of Information

Principal sources of information used by the assessment team for delineation of the tract are listed in table B4.

Grade and Tonnage Model Selection

The known copper-skarn deposits in the tract are gold-rich, and gold likely will be an important part of the resource at any undiscovered deposits in the tract. Many of the rocks that define the tract represent accreted island-arc rocks that were originally emplaced on oceanic crust. The porphyry copper-gold submodel of Singer and others (2008) was selected for the assessment of the Malaysia tract (table 6).

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The tract contains a large gold-rich skarn deposit with porphyry copper affinity (Mengapur). In addition, there are scattered copper- and gold-bearing vein and skarn prospects, as well as numerous gold-rich polymetallic vein deposits throughout the tract that are indicative of the porphyry copper environment. The tract is heavily vegetated and most historical exploration has been for alluvial tin and gold.

All these factors contributed to the assessment team's estimate that there is at least an even chance that two or more undiscovered deposits exist in the tract (table B5). The deposit density obtained from the estimate is five deposits/100,000 km^2, which is less prospective than would be predicted by the global deposit-density model of Singer and others (2005).

Table B4. Principal sources of information used for tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[NA, not applicable; MMAJ, Metal Mining Agency of Japan; AMIRA, AMIRA International Ltd (http://www.amira.com.au/); CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic maps of Myanmar, Laos, Cambodia, Thailand, Vietnam, and Yunnan Province, China	1;250,000; 1:500,000	Khin Zaw and others (1999)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	AMIRA database	NA	Khin Zaw and others (1999)
	MMAJ database	NA	Metal Mining Agency of Japan (1998)
	World Minerals Geoscience Database	NA	Natural Resources Canada (2010)

Table B5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
1	2	6	6	6	2.8	2	70	1	3.8	60,000	6

Table B6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	180,000	3,500,000	23,000,000	40,000,000	8,900,000	0.26	0.06
Mo	0	0	5,200	130,000	280,000	52,000	0.2	0.39
Au	0	20	300	1,700	2,500	640	0.3	0.06
Ag	0	0	540	6,500	13,000	2,900	0.2	0.3
Rock	0	44	760	4,700	8,100	1,800	0.28	0.06

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table B6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. B2). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

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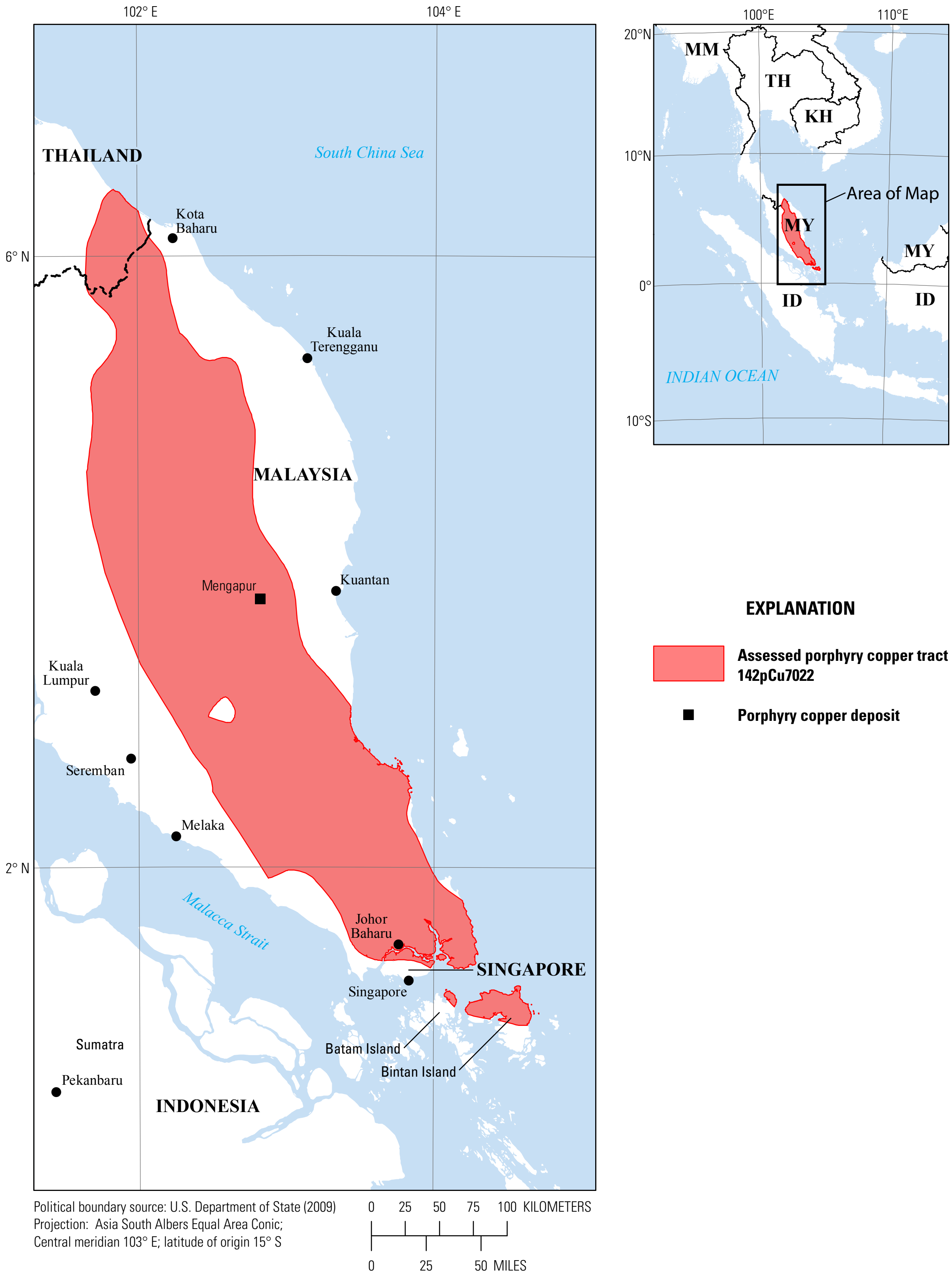

Figure B1. Map showing tract location and porphyry copper deposits for tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia. ID, Indonesia; KH, Cambodia; MM, Myanmar; MY, Malaysia; TH, Thailand.

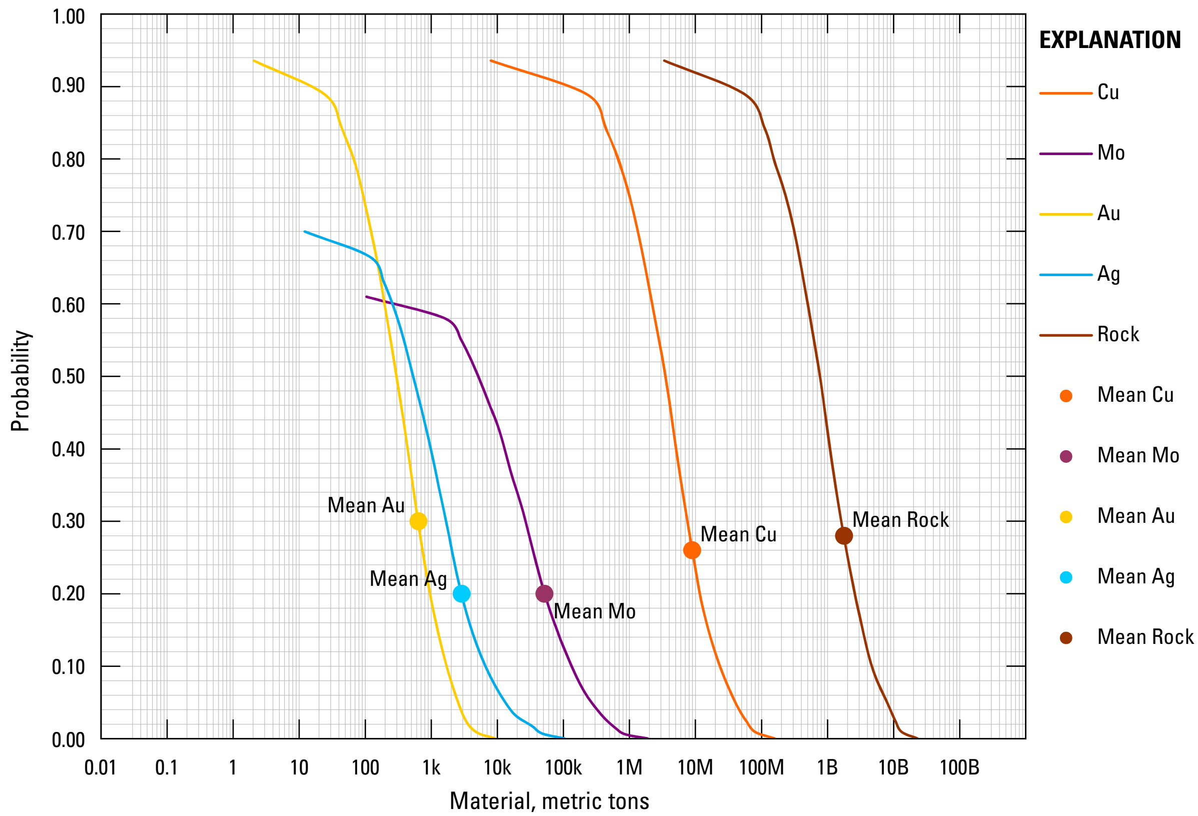

Figure B2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7022, Malaysia—Malaysia, Thailand, Singapore, and Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix C. Porphyry Copper Assessment for Tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Lao People's Democratic Republic

By Steve Ludington[1], Jane M. Hammarstrom[2], and Gilpin R. Robinson, Jr.[2], with contributions from Wudhikarn Sukserm[3], Pairatt Jarnyaharn[3], Pichai Otarawanna[3], Boonsong Yokartt[3], Sompob Wongsomasak[3], Nguyen Van Quy[4], Sieng Sotham[5], I.M. Sim[5], and Takehiro Sakimoto[3]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010)
Grade and tonnage model: Porphyry copper, general model (Singer and others, 2008)
Table C1 summarizes selected assessment results.

Table C1. Summary of selected resource assessment results for tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	91,220	n.d.	28,000,000	16,000,000

Location

The tract is within an area about 500 by 700 km in the central part of Cambodia and the southern part of Vietnam; it also includes a small area in southeast Lao People's Democratic Republic (Laos) (fig. C1).

Geologic Feature Assessed

A field of Jurassic and Cretaceous intrusive and volcanic rocks that are the result of subduction of the Pacific Plate beneath southern Indochina.

[1]U.S. Geological Survey, Menlo Park, California, United States.
[2]U.S. Geological Survey, Reston, Virginia, United States.
[3]Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.
[4]Department of Geology and Minerals of Vietnam, Hanoi, Vietnam.
[5]Department of Geology and Mines, Phnom Penh, Cambodia.

Delineation of the Permissive Tract

Tectonic Setting

Although the Paleozoic plate tectonic history of Southeast Asia is still a matter of some contention, the Jurassic and Cretaceous rocks that define the Mekong Delta tract are almost certainly related to southwest-directed subduction of the Pacific Plate beneath Indochina.

The igneous rocks that define this tract appear to be a typical calc-alkaline subduction-related suite. Intrusive rocks range in composition from diorite to granite and volcanic rocks range in composition from andesite to rhyolite. Thuy and others (2004) showed that the rocks in southern Vietnam are metaluminous I-type granitoids that vary in composition from about 56 to 76 wt. percent silica, and they attributed them to subduction of the Pacific Plate below Vietnam. Limited information indicates this to be true for the rocks in Cambodia, as well.

Outside the Mekong Delta tract there are a few igneous rocks of Jurassic and Cretaceous age that were not included in any permissive tract. The age and origin of these excluded rocks are uncertain and they do not seem to be associated with any important mineral prospects. These include a few granites, diorites, and rhyolitic volcanic rocks emplaced along the Red River Fault Zone in northern Vietnam and southern Yunnan (fig. 5*A*), a small group of granites and diorites in southernmost Yunnan that are scattered between the Red River Fault Zone and the eastern margin of a Gangdese-Tethyan tract and a few outcrops of volcanic rocks of varied composition in Malaysia. The Malaysian rocks are all within the Malaysia tract and overlie the Permo-Triassic permissive rocks there.

Geologic Criteria

The digital geologic map used to select the rocks that define the permissive tract is a compilation of digital maps of Vietnam, Cambodia, and Lao People's Democratic Republic that were prepared by a group at the University of Tasmania (Khin Zaw and others, 1999). The digital geologic map does not always reflect the most recent radiometric-age determinations or petrologic studies on the rocks in the tract, whose ages are not always accurately known. At the same time, many of the rocks have not been dated precisely, nor have they been studied extensively petrologically. Hence, it is likely that some rocks may have been included that are not permissive for porphyry copper deposits, either because they are not actually Jurassic or Cretaceous in age, or are otherwise not strictly part of the volcanic-arc assemblage. Ultramafic rocks and widespread areas of dominantly silicic volcanism are excluded.

To define the area included in the permissive tract, the assessment team first classified igneous map units as permissive or not, based on the geologic criteria described above; that is, calc-alkaline and alkaline volcanic and plutonic rocks of Jurassic and Cretaceous ages. To the polygons that represent these permissive rocks, a 10-km buffer was applied to plutonic-rock polygons and a 2-km buffer was applied to volcanic-rock polygons; this expanded the area of the tract to include all porphyry copper deposits and significant associated prospects and accounts for uncertainties in the cartographic position of mapped boundaries, as well as possible unexposed or unmapped permissive rocks. Digital map units chosen as permissive are listed in table C2.

After buffering, the limited available geophysical and geochemical information was examined to be sure that any other evidence of unmapped permissive rocks or hydrothermal systems was included in the tract. A smoothing routine was applied to the resulting polygons. Finally, the resulting shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009). There are no known Cenozoic intrusions in the tract. The tract is shown in figure C1.

Known Deposits

There are no known porphyry copper deposits within the tract.

Prospects, Mineral Occurrences, and Related Deposit Types

The only significant porphyry copper prospect identified in the tract is the Porphyry Creek project (table C3), which includes stockwork mineralization on the margins of a Jurassic pluton (Elray Resources, Inc., 2010). Whereas most of the exploration activities have been in search of gold deposits and many of the mineralized areas probably represent polymetallic veins, observations of chalcopyrite-bearing veinlets in propylitically altered quartz diorite porphyry, hydrothermal breccias, and porphyritic textures in Jurassic intrusive rocks suggest that a porphyry copper system may be present.

Southern Gold, Ltd., is exploring primarily for gold in the part of the tract that is in eastern Cambodia, and at their Snoul project they have encountered short intervals that grade 0.3–0.5 percent copper, in addition to significant gold values in an area of shallow diorite intrusions (Southern Gold, Ltd., 2010).

Olympus Pacific Minerals, Inc., also is exploring a region called Tien Thuan, in southern Vietnam, that may contain porphyry-style mineralization of the appropriate age to be included in this tract. This area was discovered by the Geological Survey of Vietnam in the 1980s and has been explored primarily for gold deposits (Olympus Pacific Minerals, 2010).

There are scattered gold- and copper-bearing skarns, polymetallic veins, and a molybdenum-rich porphyry prospect (Phnom Basset) in the tract. The team expects that with continued grassroots exploration, more prospects will be discovered.

Exploration History

Throughout much of this tract, exploration for porphyry copper deposits is at an early stage. In a 1999 review of copper and gold exploration in Southeast Asia, Feebrey (1999) did not mention a single one of the deposits and prospects included

Table C2. Map units that define tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

[Map unit, age range, and principal lithologies are based on a digital compilation of geologic maps of Thailand and Indonesia (Khin Zaw and others, 1999)]

Map unit	Map symbol	Lithology	Age range
		Intrusive rocks	
230-Intrusive rocks (Vietnam)	R2-5	Granodiorite, granite, granosyenite	Late Mesozoic to early Cenozoic
235-Intrusive rocks (Vietnam)	R1-5	Diorite, granodiorite, granite	Late Mesozoic to early Cenozoic
532-Diorite and granite (Cambodia)	6	Diorite, granite, monzonite	Cretaceous to early Tertiary
533-Dinhquan Complex (Cambodia)	5	Diorite, granodiorite, granites	Late Jurassic to Cretaceous
		Volcanic rocks	
63-Acid volcanics (Vietnam)	K	Rhyolite	Cretaceous
72-Intermediate volcanics (Vietnam)	J3-K	Andesite	Upper Jurassic to Cretaceous
510-Andesite and dacite (Cambodia)	J3-K	Andesite, dacite, tuffs	Upper Jurassic to Cretaceous
512-Undifferentiated acid volcanics (Cambodia)	J	Felsic volcanic rocks	Jurassic
513-Rhyolite and dacite (Cambodia)	J	Rhyolite and dacite	Jurassic

Table C3. Significant prospects and occurrences in tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

Name	Latitude	Longitude	Age	Comments	Reference
Porphyry Creek	13.53	105.13	Jurassic	Stockwork mineralization (chalcopyrite) on pluton margin.	Elray Resources, Inc. (2010)
Snoul	12.15	106.61	presumed Mesozoic	Cu and Au mineralization related to diorite intrusions; location approximate.	Southern Gold, Ltd. (2010)
Tien Thuan	14.03	108.55	presumed Mesozoic	Porphyry-style mineralization; location approximate.	Olympus Pacific Minerals (2010)

in this tract. Vietnam, Lao People's Democratic Republic, and Cambodia have been engulfed in war from the 1940s until very recently, and many of the countries are still in the process of developing effective mining laws that support modern mineral exploration activities. Cambodia, for example, passed its first mining law in 2001 (Wu, 2002). There is no adequate aeromagnetic map of the region, and few regional stream-sediment geochemical surveys have been done.

Burrett (1999) indicated that Lao People's Democratic Republic has only begun to be adequately mapped, mostly since the mid 1990s, whereas Cambodia and Vietnam were mapped by French geologists prior to the 1950s and 60s. Nevertheless, modern work in these two countries is limited.

There has been a steady acceleration of exploration by corporate geologists, many from China and Australia, in the

Table C4. Principal sources of information for tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

[NA, not applicable; MMAJ, Metal Mining Agency of Japan; AMIRA, AMIRA International, Ltd. (http://www.amira.com.au/)]

Theme	Name or Title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic maps of Myanmar, Laos, Cambodia, Thailand, Vietnam, and Yunnan Province, China	1:250,000 1:500,000	Khin Zaw and others (1999)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	AMIRA database	NA	Khin Zaw and others (1999)
	MMAJ database	NA	Metal Mining Agency of Japan (1998)
	World Minerals Geoscience Database	NA	Natural Resources Canada (2010)

first decade of the 21st century. The earliest outside workers may have been with CRA Exploration (now Rio Tinto), which began work in Lao People's Democratic Republic in 1989 (Feebrey, 1999).

Sources of Information

Principal sources of information used by the assessment team for delineation of the tract are listed in table C4.

Grade and Tonnage Model Selection

As there is no information about grades of porphyry-style mineralization in the tract, combined with the fact that it is a fundamentally continental arc, the team chose to use the general porphyry copper model of Singer and others (2008) for the assessment of the Mekong Delta tract (table 6).

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

There are widespread skarn and porphyry-exploration targets related to the Jurassic and Cretaceous plutons in the tract, as well as numerous pluton-related gold-bearing veins. Most of this tract was not explored between World War II and at least the mid-1980s. Modern exploration has been done only during the last decade, and the tract is considered underexplored. Much of the area is covered with surficial deposits or is strongly laterized, making grassroots exploration difficult.

All these factors contributed to the assessment team's estimate that there is at least an even chance that six or more undiscovered deposits exist in the tract (table C5). The deposit density obtained from the estimate is eight deposits/100,000 km^2, which is somewhat less prospective than would be predicted by the global deposit-density model of Singer and others (2005).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table C6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. C2). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table C5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	6	16	16	16	7.4	5.4	73	0	7.4	91,220	8

Table C6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	650,000	16,000,000	69,000,000	99,000,000	28,000,000	0.34	0.06
Mo	0	0	290,000	2,100,000	3,200,000	790,000	0.28	0.12
Au	0	0	380	1,800	2,400	710	0.34	0.12
Ag	0	0	3,500	24,000	37,000	9,200	0.27	0.17
Rock	0	150	3,600	15,000	20,000	5,700	0.35	0.06

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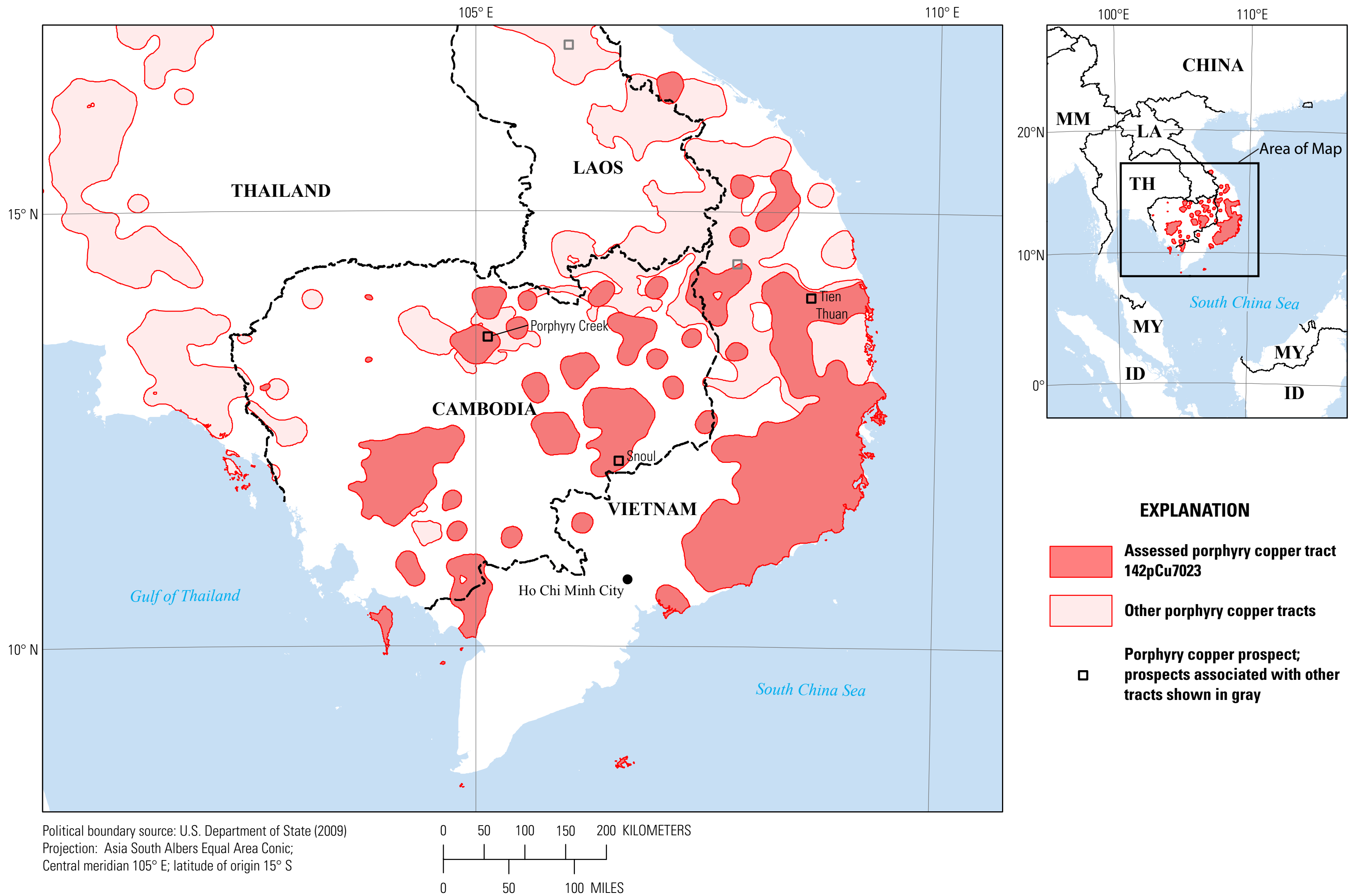

Figure C1. Map showing tract location and significant porphyry copper prospects for tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos. ID, Indonesia; LA, Lao People's Democratic Republic; MM, Myanmar; MY, Malaysia; TH, Thailand.

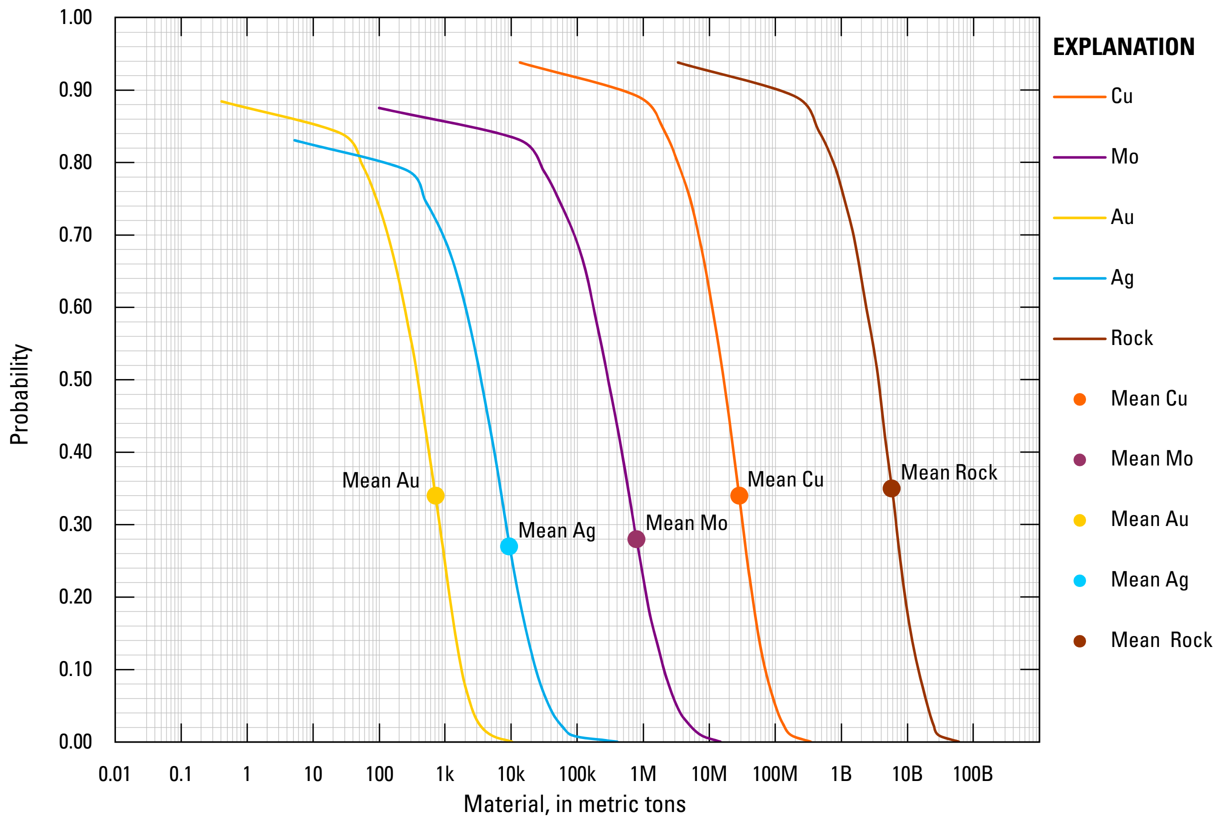

Figure C2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7023, Mekong Delta—Vietnam, Cambodia, and Laos. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix D. Porphyry Copper Assessment for Tract 142pCu7024, Wuntho-Popa—Myanmar and India

By Steve Ludington[1], Jane M. Hammarstrom[2], and Gilpin R. Robinson, Jr.[2], with contributions from Khin Zaw[3] and Dennis P. Cox[1]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010)
Grade and tonnage model: Porphyry copper, general model (Singer and others, 2008)
Table D1 summarizes selected assessment results.

Table D1. Summary of selected resource assessment results for tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	45,260	6,290,000	8,800,000	1,700,000

Location

This tract is primarily in Myanmar and although narrow, may extend for about 1,600 km from north to south, including two small volcanic islands (Barren and Narcondam) in the Andaman Sea that belong to India (fig. D1).

Geologic Feature Assessed

A linear belt of Late Cretaceous through Holocene volcanic rocks related to subduction of the Indian Ocean Plate below Indochina.

Delineation of the Permissive Tract

Tectonic Setting

The igneous rocks that define the Wuntho-Popa tract are almost certainly related to northeast-directed subduction of the Indian subcontinent and the Indian Ocean Plate beneath Indochina along the Sunda subduction zone (Mitchell, 1993; Curray, 2005; Chan-

[1]U.S. Geological Survey, Menlo Park, California, United States.
[2]U.S. Geological Survey, Reston, Virginia, United States.
[3]University of Tasmania, Hobart, Australia.

drasekharam and others, 2009). On the mainland of Myanmar, this subduction is oblique. The area is called the Wuntho-Popa magmatic arc by Mitchell and others (2008) and the Pegu Yoma volcanic arc by Fan and Ko (1994). It is the northern continuation of the Sunda Arc.

Geologic Criteria

The few igneous rocks exposed at the surface in this tract are primarily mafic calc-alkaline (Mitchell and others, 2008), although some of the younger Plio-Pleistocene rocks in this belt have alkaline affinities (Maury and others, 2004). The granodiorites exposed in the northern part of the belt are as old as about 90 Ma (Mitchell, 1993). At the same time, emplacement of some of the younger rocks also may be guided by the Sagaing Fault (fig. 5*A*), a major right-lateral structure that helps to accommodate the ongoing northward movement of the Indian Ocean Plate.

In the Andaman Sea, rocks on Barren Island (fig. D1) range in composition from basalt to andesite, whereas those on Narcondam Island (fig. D1) include andesite and dacite (Chandrasekharam and others, 2009).

Unexposed Miocene (and possibly older) volcanic rocks may be present at shallow depths along the axis of the Eastern Volcanic Line, as depicted by Myint (1994). The team used the inferred position of that line to delineate a narrow corridor as permissive. Because volcanic rocks may be present at shallow depth beneath the Irrawaddy River floodplain and delta sediments, this subjective delineation was used rather than the more conventional buffering of volcanic outcrops. The permissive map units chosen are characterized as code 29, Cenozoic volcanic rocks on the digital geologic map used (Khin Zaw and others, 1999), although some of these outcrops are older (Mitchell, 1993).

The team also examined the limited geophysical and geochemical information to be sure that any other evidence of unmapped permissive rocks or hydrothermal systems was included. Finally, the resulting shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009). There are no known Cenozoic intrusions in the tract. The tract is shown in figure D1.

Known Deposits

The single known porphyry copper deposit, Monywa (fig. D1, table D2), is atypical in that most of the ore delineated is enriched by supergene processes and it is exposed at a very shallow level. The deposit has been classified in a variety of ways (Nansatsu-type massive sulfide, transitional between Kuroko massive sulfide and porphyry copper, supergene-enriched porphyry copper, high-sulfidation (copper-rich) epithermal); the team sided with Sillitoe (United Nations, 1978) and Singer and others (2008) and considers it to be a porphyry copper deposit for the purposes of this assessment. The description of Monywa is primarily from Mitchell and others (2008), but there are also descriptions in Krisl (1975) and Winn and Kirwin (1998).

Monywa consists of four mineralized areas that are in close proximity, Sabetaung, Sabetaung South (both presently in production), Kyisintaung, and Letpadaung (both unmined). The total resource at Monywa has not been finally delineated, but it is in the neighborhood of 2,000,000,000 tons, with a copper grade of about 0.35 percent [Singer and others (2008) list it as 1,700,000,000 tons at 0.37 percent copper]. Precious metals are not recovered from the oxide material now being mined by heap-leach and processed by solvent extraction-electrowinning (SX-EW) methods. However, samples from drill core at the Kyisintaung deposit averaged 0.15 g/t gold and 23 g/t silver. The deposit appears to have been formed in the late Miocene.

Prospects, Mineral Occurrences, and Related Deposit Types

The most important prospect in the area is Shangalon (fig. D1, table D3), which is Eocene in age (Goossens, 1977, 1978; Win and Myint, 1998). This area was drilled by the Burmese government (with the help of the United Nations Development Program) in the mid-1970s, and a possible (only partly delineated) resource of about 9,000,000 t with copper grade of 0.23 percent was reported (Singer and others, 2008). Although not included in the resource, the deposit contains both molybdenum and gold. The area was further explored by Ivanhoe (who was developing Monywa at the time) in the mid-1990s before they left the country.

Most major outcrop areas of volcanic rock within the tract have either porphyry copper prospects or epithermal precious-metal mineralization, all poorly documented (Win and Myint, 1998).

Exploration History

Geologists of the British Geological Survey mapped Myanmar, but there has been little activity since 1939 (Burrett, 1999). Systematic modern geologic mapping, regional stream-sediment surveys, and airborne geophysical data are lacking.

Western mineral-exploration groups began to operate in the country in the 1980s, but this work came to an end recently because of political factors (Ivanhoe Mines, 2010). Other foreign companies, notably from China and India, continue to operate in Myanmar (Global Times, 2010).

Sources of Information

Principal sources of information used by the assessment team for delineation of the tract are listed in table D4.

Grade and Tonnage Model Selection

As there is no reliable information about gold grades of porphyry-style mineralization in the tract, we chose to use the

Table D2. Identified porphyry copper resources in tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Mo subtype, deposits that have Au/Mo ratios <3 or average Mo grades >0.03 percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data, NA, not applicable. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Monywa	22.13	95.041	NA	Late Miocene	1,700	0.37	n.d.	n.d.	n.d.	6,290,000	Mitchell and others (2008)

Table D3. Significant prospects and occurrences in tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[Ma, million years; %, percent; Mt, million metric tons]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference
Shangalon	23.71	95.52	Eocene	Partly delineated resource of about 9 Mt at 0.23% Cu; contains Mo and Au.	Win and Myint (1998)

Table D4. Principal sources of information for tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Myanmar	1:500,000	Khin Zaw and others (1999)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	AMIRA database	NA	Khin Zaw and others (1999)
	MMAJ database	NA	Metal Mining Agency of Japan (1998)
	World Minerals Geoscience Database	NA	Natural Resources Canada (2010)

general porphyry copper model of Singer and others (2008) for the assessment of the Wuntho-Popa tract (table 6). The magmatic arc in mainland Myanmar probably should be considered a continental arc. At the present day, the subduction zone in Myanmar is still continent against continent.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

There is one large deposit (Monywa) and one significant prospect (Shangalon) in the tract, along with numerous other porphyry, skarn, and epithermal prospects. Because modern geophysical methods have not been employed to search for shallow intrusions, and because there is little active exploration, this tract can be considered to be underexplored. However, the presence of porphyry copper and epithermal prospects suggests that this tract could be prospective. The assessment of this tract is problematic because there is no reliable way to estimate how thick the cover may be over any buried (and potentially mineralized) volcanic rocks and hypabyssal intrusions.

All these factors contributed to the assessment team's estimate that there is at least an even chance that an undiscovered deposit exists in the tract and that there could be as many as nine undiscovered deposits (table D5). The deposit density obtained from the team estimate is seven deposits/100,000

Table D5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
0	1	5	9	9	2.2	2.7	120	1	3.2	45,260	7

Table D6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7024, Wuntho-Popa—Myanmar and India.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	1,700,000	22,000,000	40,000,000	8,800,000	0.25	0.29
Mo	0	0	9,700	590,000	1,300,000	250,000	0.19	0.45
Au	0	0	23	620	1,000	230	0.24	0.42
Ag	0	0	0	6.900	14,000	3,000	0.19	0.52
Rock	0	0	400	4,700	8,300	1,800	0.26	0.29

km^2, which is somewhat less prospective than would be predicted by the global deposit-density model of Singer and others (2005).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table D6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. D2). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

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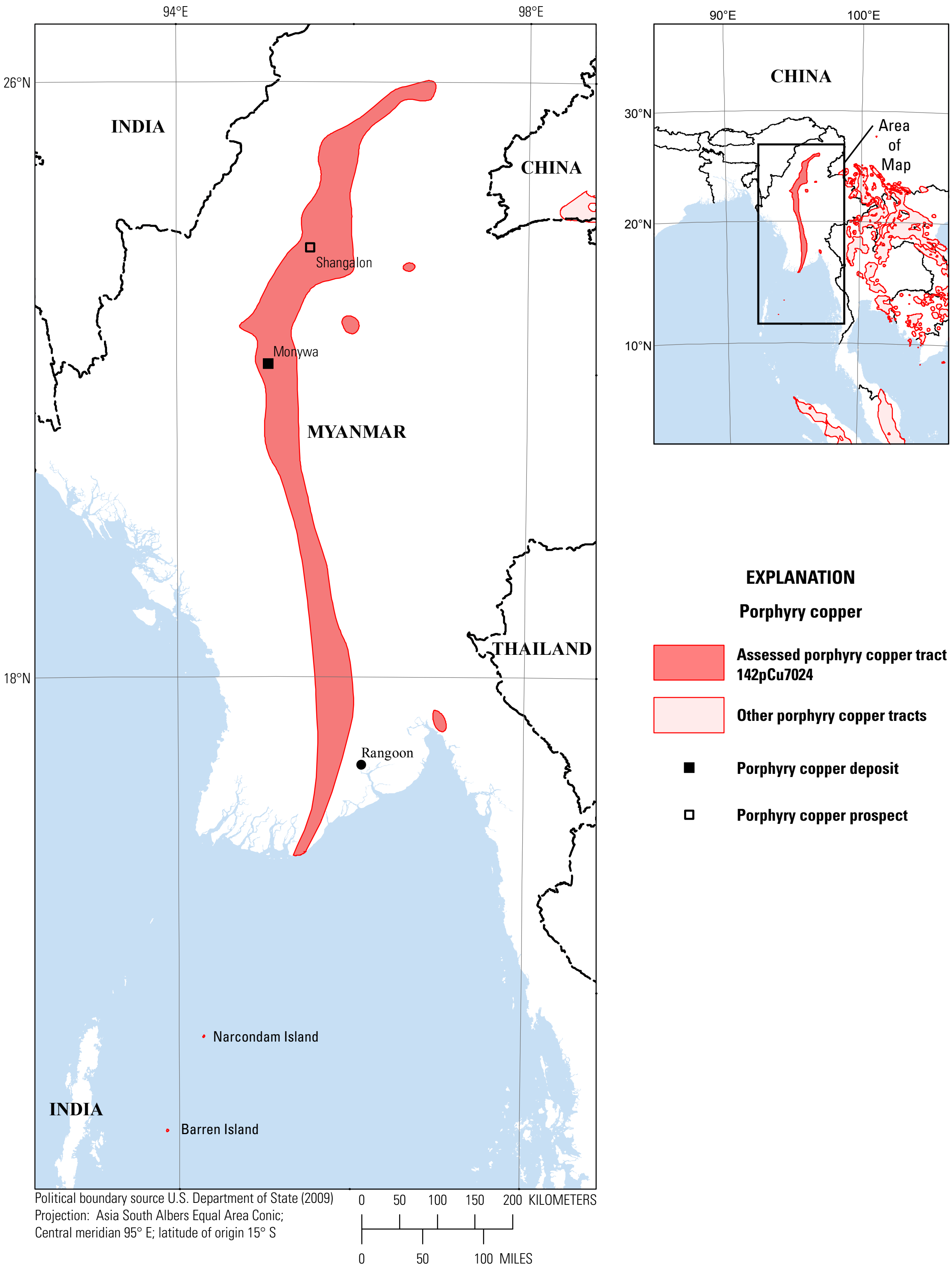

Figure D1. Map showing tract location, deposit, and significant porphyry copper prospects for tract 142pCu7024, Wuntho-Popa—Myanmar and India.

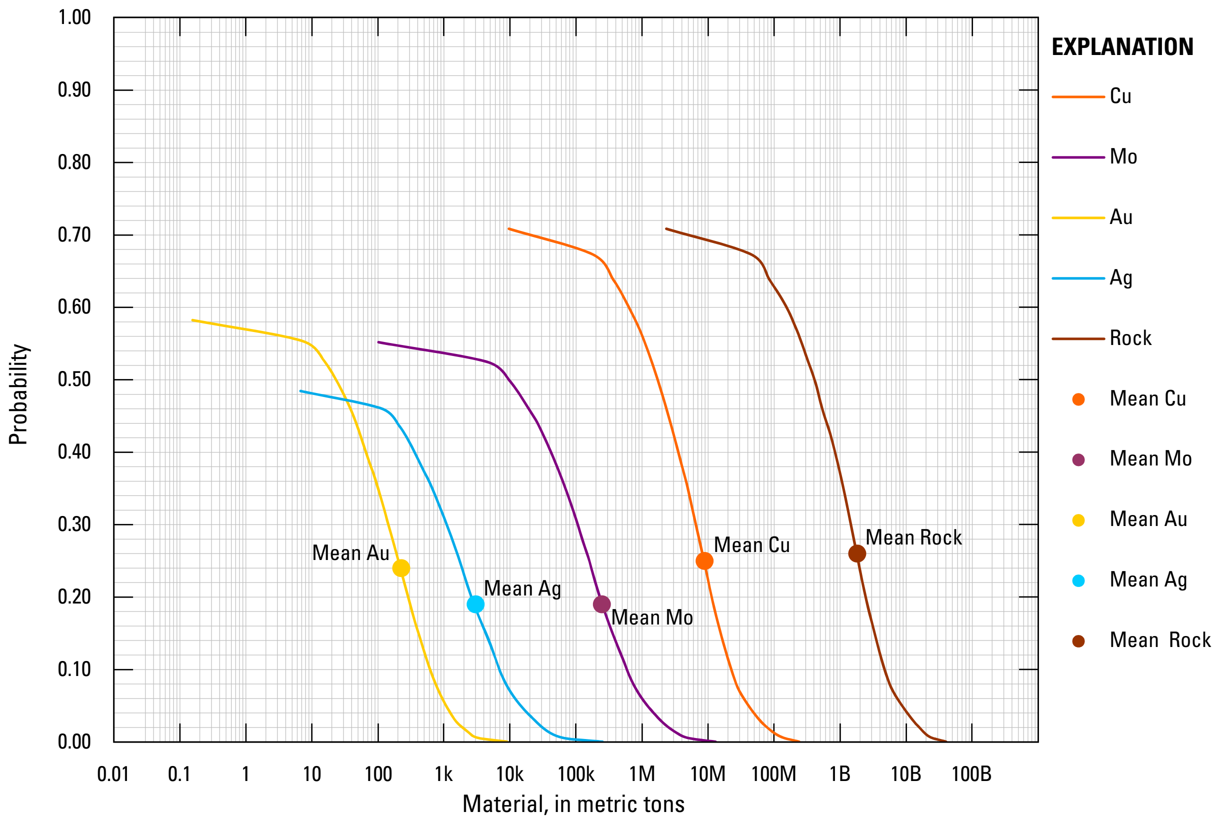

Figure D2. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7024, Wuntho-Popa—Myanmar and India. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix E. Porphyry Copper Assessment for Tract 142pCu7020, Sumatra Island—Indonesia

By Gilpin R. Robinson, Jr.[1], Jane M. Hammarstrom[1], Steve Ludington[2], Arthur A. Bookstrom[3], Alexander Yan Sze Wah[4], Bambang Tjahjono Setiabudi[5], Dwi Nugroho Sunuhadi[3], Sewit A. Yenie[1], and Michael L. Zientek[3], with contributions from Chen Shick Pei[6]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Porphyry copper, general model (Singer and others, 2008)
Table E1 summarizes selected assessment results.

Table E1. Summary of selected resource assessment results for tract 142pCu7020, Sumatra Island—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	131,030	900,000	23,000,000	13,000,000

Location

The tract includes western Sumatra Island from the northern tip to the southern tip (fig. E1).

Geologic Feature Assessed

An Eocene-Pliocene continental magmatic arc that straddles the northwest-trending Sumatran Fault Zone in western Sumatra.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]U.S. Geological Survey, Menlo Park, California, United States.
[3]U.S. Geological Survey, Spokane, Washington, United States.
[4]Minerals and Geoscience Department, Sabah, Malaysia.
[5]Directorate of Mineral Resources Inventory, Geological Agency of Indonesia, Bandung, Indonesia.
[6]Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) Technical Secretariat, Bangkok, Thailand.

Delineation of the Permissive Tract

Tectonic Setting

The mid- to late Tertiary porphyry copper tract on Sumatra Island incorporates a magmatic arc developed in response to oblique subduction of the Indian Plate under continental crust of the Sundaland part of the Eurasian Plate (Garwin and others, 2005). The tract includes Eocene to Pliocene intrusive- and volcanic-rock units but excludes thick overlying Quaternary volcanic and sedimentary units. The intrusive centers and the porphyry copper deposits and prospects are localized along the right-lateral Sumatran Fault system (fig. E2) that initiated during the Miocene in response to oblique subduction (Barber and others, 2005).

The Sumatra Island tract is the northwestern part of the 3,800-km-long Eocene to Holocene Sunda-Banda magmatic arc (fig. 5*B*,*C*). The Sunda-Banda magmatic arc stretches from Sumatra to the easternmost part of the Sunda-Banda Arc northeast of Timor (fig. 5*C*). The western boundary of the Sumatra Island tract is the Indian Ocean; the eastern boundary overlaps but is near the northwest-striking right-lateral, strike-slip Sumatra Fault system that structurally localized many of the Tertiary intrusive centers and where the tract is overlain by thick sequences of Quaternary sedimentary and volcanic rocks to the northeast. The southeastern termination of the tract occurs at the Sunda Strait that separates Sumatra Island from Java (fig. E2, fig. 5*C*). The Sunda Strait is an extensional basin formed at the transition from oblique subduction to the northwest along the Sunda Trench to frontal subduction to the east along the Java Trench (Huchon and Le Pichon, 1984).

Geologic Criteria

The geologic units that define the permissive tract, shown in figure E3, are calc-alkaline igneous rocks of Eocene to Pliocene age (most are mid-Miocene). Igneous rock map units of uncertain age, that span this age range but may be as old as Cretaceous, are included in the tract. Most of the plutonic rocks that crop out within the tract are numerous small bodies of diorite-granodiorite (some porphyritic) and a few granite-granodiorite bodies (table E2). The chemistry of these rocks is calc-alkaline, but some sodic variants known as adakites are present (Barber and others, 2005).

Calc-alkaline volcanic rocks are considered permissive for porphyry copper deposits as they are localized near and often overlie intrusive centers that may host porphyry deposits and may include small unmapped intrusive bodies within their borders. The volcanic rocks that define the tract include andesite flows and tuffs, dacite and associated dacitic tuffs and breccias, and basalt flows (table E2). Two areas of volcanoclastic sediments in northern Sumatra have been included as they delineate probable intrusive centers that are not identified by volcanic rocks alone. Mid-Tertiary bimodal rhyolite-basalt sequences and andesitic tuffs that are primarily within marine carbonate rocks (fringing reefs bordering the oceanic islands) or clastic sedimentary rocks have been excluded from the tract. These distal volcanic deposits in carbonates and sediments are interpreted to be part of the accretionary-wedge complex, and their sites of deposition were not likely to be near the intrusive centers that host porphyry copper deposits. A few high-K alkaline-series volcanic rocks occur in a back-arc setting (Barber and others, 2005).

The team used 1:250,000-scale geologic maps (table E2; Geological Research and Development Centre, 1987–2000) to identify areas of permissive rock types, based on the map legend attribute information describing map-unit rock types, composition, and age. The maps were scanned and rectified, and the areas of permissive rock units were digitized by hand to build an attributed digital GIS file used to define the permissive tract. After choosing the polygons and groups of polygons that represent the surface expressions of permissive igneous intrusions, a 10-km buffer was applied to account for a spatial uncertainty of approximately 2 km in the digitized geology and deposit location data and the possibility that deposits may be associated with intrusions that expand beneath their surface expression and are also less than 1 kilometer beneath the land surface. A 2-km buffer was applied around the permissive volcanic units, as these may be imprecisely located and partly covered. A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified polygons using an algorithm (PAEK, polynomial approximation with exponential kernel) with a tolerance of 20 km. Necking, thinning and contraction of the polygons resulting from the above processing necessitated manual cleaning of the preliminary tract (for example, polygon necks removed). Final tracts were compared to the permissive geologic features in source maps to ensure that original permissive boundaries were honored. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

These revised preliminary tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks and sedimentary deposits are greater than 1 km in thickness. The resulting tract shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The use of a polygon-aggregation distance of 50 km resulted in a tract outline consistent with the expectation of the Indonesian geologic expert, Bambang Tjahjono Setiabudi, and with the distribution of copper and gold occurrences in mineral-occurrence the Indonesia databases (Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP), 1997; Directorate of Mineral Resources and Inventory, 2004a,b). The distribution of these mineral occurrences was not used to delineate tract

Table E2. Map units that define tract 142pCu7020, Sumatra Island—Indonesia.

[Geologic map, map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Geologic map	Map unit	Age range	Rock types
		Intrusive rocks	
420	Tmiu	Pliocene to Miocene	Diorite-granodiorite
0421-0521	Tii	Oligocene	Microdiorite
0421-0521	Tir	Oligocene	Diorite-melanodiorite
0421-0521	TMi	Cretaceous to Oligocene	Granodiorite, diorite
0421-0521	TMigs	Cretaceous to Oligocene	Granodiorite, gabbro
0421-0521	Tmiu	Middle to late Miocene	Diorite-granodiorite
520	Tib	Early to late Oligocene	Bateekeubeue intrusion
520	Tibm	Middle Miocene	Granodiorite
520	Tid	Early to middle Miocene	Diorite
520	Tit	Middle Miocene	Diorite to granodiorite
618	Tmip	Middle to late Miocene	Quartz microdiorite
618	Tmit	Middle to late Miocene	Diorite, microdiorite
618	Tmvp	Middle to late Miocene	Dolerite sills
619	Tmig	Middle Miocene	Microdiorite
619	Tmis	Middle Miocene	Microdiorite
620	Til	Middle Miocene	Leucogranite
0617-0717	Tlih	Paleogene	Fine-grained granite porphyry
0617-0717	Tliu	Paleogene?	Granodiorite, diorite
0617-0717	Tmi	Miocene	Microdiorite, diorite
0617-0717	Tmisi	Miocene	Granodioritic to dioritic
0617-0717	Tmiti	Miocene	Granodiorite
715	Tgr	Eocene and Oligocene	Granite, quartz diorite
716	TMi	Eocene and Oligocene	Granodiorite-granite
716	TMiab	Eocene and Oligocene	Granodiorite, Adamellite
716	Tmibi	Miocene	Subvolcanic micrograntites
716	Tmid	Miocene	Subvolcanic porph. microdiorites
716	TMik	Eocene and Oligocene	Leucogranite, granodiorite
716	TMimn	Eocene and Oligocene	Granodiorite, granite
716	Tmipl	Miocene	Granodiorite, diorite
716	Tmisp	Miocene	Subvolcanic porph. microdiorites
716	Tmiti	Miocene	Granodiorite
716	TMiu	Eocene and Oligocene	Granodiorite
716	Tuim	Pliocene	Feldspar granite porphyry
718	Tmi	Miocene	Diorite
718	Tmitj	Miocene	Diorite
0714-0814	Tdb	Miocene	Diabase dikes and sills
0714-0814	Tgdr	Miocene	Hornblende granite-granodiorite
0714-0814	Tgr	Miocene	Biotite granite, granite porphyry
0813-0812	Tmda	Miocene	Dacite
0813-0812	Tmdi	Miocene	Diorite

Table E2. Map units that define tract 142pCu7020, Sumatra Island—Indonesia.—Continued

Geologic map	Map unit	Age range	Rock types
		Intrusive rocks	
0813-0812	Tpgdl	Pliocene	Granodiorite
0813-0812	Tpgds	Pliocene	Granodiorite
0813-0812	Tpgr	Pliocene	Granite
0911-0910	Tmdi	Middle Miocene	Diorite
0911-0910	Tmg	Middle Miocene	Granite
912	Tmdi	Middle Miocene	Diorite
912	Tmgr	Middle Miocene	Granite
912	Tpan	Pliocene	Andesite
913	Tmdi	Middle Miocene	Diorite (chloritized)
913	Tpgr	Pliocene	Granite, granodiorite
1010	Tm	Middle Miocene	Granite, granodiorite-diorite
1110	Tejg	Eocene	Granite
1110	Tmda	Oligocene to early Miocene	Dacite
1110	Tmgr	Oligocene to early Miocene	Granite, granodiorite
		Volcanic rocks	
0421-0521	Tmvc	Middle to late Miocene	Intermediate volcanics
519	Tlva	Oligocene to Miocene	Andesite, basalt
519	Tlvs	Oligocene to Miocene	Felsic, intermediate and mafic lava
520	Tmvc	Late Miocene	Felsic volcanics (reworked)
618	Tmvh	Middle to late Miocene	Andesite, dacites
618	Tmvo	Middle to late Miocene	Andesitic agglomerates
618	Tmvp	Middle to late Miocene	Andesite
618	Tmvt	Middle to late Miocene	Andesitic volcanics
619	Tlvk	Early Miocene	Andesite
619	Tmva	Middle Miocene	Andesite
619	Tmvt	Middle Miocene	Andesite
620	Tlvm	Early Miocene	Felsic to intermediate pyroclastics
715	Ta	Eocene and Oligocene	Andesite (basaltic)
716	Tlvl	Eocene and Oligocene	Porphyritic pyroxene absarokitic lavas
716	Tmv	Miocene	Undifferentiated volcanics
716	Tmvab	Miocene	Porphyritic andesites
716	Tmvam	Miocene	Intermediate volcaniclastics and lava
716	Tmvsg	Miocene	Porphyritic andesites
716	Tmvsk1	Miocene	Andesite lava
716	Tmvsk2	Miocene	Reworked volcanic deposits
716	Tuvm	Pliocene	Acid to basic lavas
0617-0717	Tlis	Late Eocene	Porphyritic andesites, microdiorite
0617-0717	Tmva	Miocene	Andesite
0617-0717	Tmvak	Miocene	Andesite, basalt
0617-0717	Tmvna	Miocene	Intermediate volcanics
0617-0717	Tmvp	Miocene	Andesite, basalt
0714-0814	Tb	Eocene to Oligocene	Ignimbrite, tuff

Table E2. Map units that define tract 142pCu7020, Sumatra Island—Indonesia.—Continued

Geologic map	Map unit	Age range	Rock types
		Intrusive rocks	
0617-0717	Tmvp	Miocene	Andesite, basalt
0714-0814	Tb	Eocene to Oligocene	Ignimbrite, tuff
0714-0814	Tomp	Miocene to Oligocene	Intermediate volcanics
718	Tmvh	Miocene	Andesite-dacite
718	Tmvo	Miocene	Andesite
718	Tuvs	Miocene to Pliocene	Andesite
718	Tuvsu	Miocene to Pliocene	Andesite
0813-0812	Tomh	Oligocene	Andesite
815	Ta	Miocene	Andesite
0911-0910	Tmba	Middle to late Miocene	Dacitic volcanic breccia
0911-0910	Tml	Middle to late Miocene	Dacitic breccia
0911-0910	Tmpl	Pliocene	Andesitic to basaltic volcanic breccia
0911-0910	Tomh	Oligocene to early Miocene	Andesite-basalt lavas
912	Tmba	Late Miocene	Dacite volcanic breccia
912	Tml	Late Miocene	Dacite breccia
912	Tmpl	Pliocene	Epiclastic volcanic breccia
912	Tomh	Oligocene to early Miocene	Andesite-basalt lavas
912	Tpok	Paleocene to Oligocene	Volcanic breccia
913	Tmba	Late Miocene	Dacite tuff
913	Tomh	Oligocene to early Miocene	Volcanic breccia
1010	Tmba	Middle to late Miocene	Dacitic volcanic breccias
1010	Tmpl	Pliocene to late Miocene	Andesite, Dacite tuffs
1010	Tomh	Oligocene to early Miocene	Volcanic breccia
1010	Tpok	Oligocene-Paleocene	Andesite breccia
1011	Tmba	Middle to late Miocene	Dacitic volcanic breccia
1011	Tmpl	Late Miocene to Pliocene	Basalt-andesite
1011	Tomh	Early Miocene-Oligocene	Andesite-basalt
1011	Tpok	Paleocene to Oligocene	Volcanic breccia
1017-1016	Tma	Miocene	Andesite
1110	Tomh	Miocene to early Oligocene	Andesite-basalt
1110	Tpv	Pliocene	Andesite

boundaries; however, the locations of (1) major and minor copper deposits, prospects, and occurrences, and (2) hydrothermal gold-copper deposits and prospects lacking lead as a secondary commodity or galena, as a prominent mineral, listed in the Indonesian mineral-occurrence database, are localized within the Sumatra Island tract. Two areas of hydrothermal gold-copper veins that list lead as a significant commodity or galena as a common vein mineral in the mineral-occurrence databases occur in sedimentary and metasedimentary rocks located outside of the tract. These lead-bearing vein occurrences are in 1:250,000-scale maps sheets (map numbers 0914 and 0915, Geological Research and Development Center, 1987–2000) that lack identified intrusive- and volcanic-rock units considered permissive for porphyry copper deposits, are located more than 60 km east of the nearest bodies of permissive volcanic rocks, and are more than 150 km east of the Sumatran Fault system that has localized the distribution of the igneous systems associated with known porphyry copper deposits and prospects in the tract. The lead-bearing veins occur in Quaternary to late Tertiary sedimentary rocks, primarily sandstones, mudstones, and marls with minor tuffaceous volcanic beds, deposited on Jurassic igneous and metamorphic rock continental basement. Based on interpretative geologic cross sections through these map areas, the sedimentary rock sections hosting the vein occurrences are greater than 1 km in thickness. The sedimentary rocks are overlain by Quaternary alluvial sediments in many areas. The lead-bearing veins probably represent polymetallic vein systems that are unrelated to porphyry systems and are not likely to be proximal to buried porphyry systems. The Sumatra Island tract includes at least five national parks and a number of nature reserves.

Known Deposits

The only known porphyry copper deposit is the Miocene Tangse porphyry copper-molybdenum deposit located in the northern part of the Sumatra Island tract (fig. E1; table E3). At Tangse, an outcrop of stockwork-altered porphyry was discovered during a British-Indonesian government sponsored regional geologic mapping and exploration geochemistry program in 1976. The discovery was followed by soil sampling, geophysical studies, and exploratory drilling between 1979 and 1981 (van Leeuwen, 1994). The exploration program identified a zone of anomalous copper concentrations in a 5-km-long and 1–2-km-wide zone of altered, fractured, and leached porphyry stock (van Leeuwen and others, 1987). The Tangse deposit is hosted in a zone of intrusive and volcanic rocks localized by the northwest-trending Sumatran Fault Zone (figs. E2 and E3) that traverses the length of Sumatra. The copper-molybdenum mineralization is hosted in a multiphase quartz diorite stock, and the development of alteration and mineralization occurred between 13 and 9 Ma (van Leeuwen, 1994). Although early potassic alteration (biotite), overprinted by phyllic alteration (sericite-quartz) and associated sulfide mineralization, in turn overprinted and surrounded by propylitic alteration (chlorite-epidote-carbonate), is continuous in the overall deposit area, subeconomic to economic copper grades are irregular in distribution (van Leeuwen and others, 1987), and the deposit has not been mined. Reserve-resource estimates are 600 million tons of low-grade material at 0.15 percent copper (table E3), including 30 million tons of ore at 0.3–0.6 percent copper and 0.02–0.03 percent molybdenum (van Leeuwen and others, 1987). Oxidation and leaching of the deposit has resulted in patchy development of supergene copper enrichment (Taylor and van Leeuwen, 1980).

Prospects, Mineral Occurrences, and Related Deposit Types

In addition to Tangse, there are four or five main clusters of additional porphyry copper prospects and occurrences representing about a dozen prospects and occurrences in the Sumatra Island tract (table E4; Directorate of Mineral Resources Inventory, Bandung, Indonesia, written commun., 2004), which contain copper, gold, molybdenum, and base metals. The Mudik copper-gold porphyry prospect was identified in the early 1970s by regional stream-sediment sampling. Prospecting in the vicinity of geochemical anomalies at Mudik found numerous brecciated pyritic boulders, spread over a 2 km^2 area, containing up to 7.5 g/t gold (Grunsky and Smee, 1999). Low-grade porphyry copper prospects at Geunteut, Dusun, Sigalagala, Danu Diatas, and Siuluk Deras (fig. E1) are associated with arc-parallel faults that are part of the Sumatran Fault system and Miocene to Pliocene diorite to granodiorite stocks emplaced within segments and jogs of the Fault system (Barber and others, 2005). A number of areas surrounding or adjacent to the porphyry prospects contain numerous prospects and anomalies of copper, gold, and base metals in soil and sediment samples, such as at the Takengon prospect in the Aceh Province, North Sumatra. The Takengon prospect includes and surrounds the epithermal gold Collins prospect. Exploration at Collins identified two 11-m drill intercepts with 22 and 15 g/t gold, respectively (East Asia Minerals Corporation, 2010). At Takengon, two areas of Tertiary porphyry-style copper mineralization and an area of Au-Cu skarn mineralization lie adjacent to the gold-bearing vein swarm and stockwork at the Collins prospect. Supergene-enriched copper porphyry mineralization adjacent to the epithermal gold Collins prospect contains 2.58 percent copper and elevated gold (East Asia Minerals Corporation, 2010). Geophysical studies suggest that the epithermal vein and stockwork systems at the Collins prospect coalesce below the surface in a larger porphyry-style system (East Asia Minerals Corporation, 2010). Some placer-gold occurrences also are present in streams draining to the west coast.

Exploration History

Minerals exploration has taken place throughout Sumatra Island at a prospect and district scale along with geochemical sampling of soils and sediments on a regional scale. The Dutch undertook systematic mineral exploration and development between the 1840s and 1930s (Van Bemmelen, 1949) that ceased during and after World War II and Indonesian independence. Revision of Indonesian mining and finance laws under President Suharto in 1967 initiated new mineral-exploration activity from the late 1960s to present. Porphyry-associated mineral occurrences at Danu Diatas, Siuluk Deras, and Danau Dipatiempat were discovered during mineral exploration during the 1960s to 1990s, and the Tangse deposit and other prospects, such as Dusun, were identified through regional geologic mapping and geochemical sampling during this period (van Leeuwen, 1994). Geochemical and geophysical surveys also were done, but this information was not available during this assessment. The individual porphyry copper prospects have received prospect-level geochemical and geological exploration and rock chip sampling. Drilling has taken place on the Tangse deposit, the Dusun prospects, the Takengon (Collins) prospect, and probably on the Mundik prospect (Barber and others, 2005; Dalimunthe and others, 1997a,b). Companies that have been active on these prospects are Rikit Atlas Minerals, Newcrest Mining, and East Asia Minerals Corporation.

Table E3. Identified porphyry copper resources in tract 142pCu7020, Sumatra Island—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; NA, not applicable. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent); n.d., no data]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Tangse	5.033	95.95	NA	11	600	0.15	0.02	n.d.	n.d.	900,000	Djaswadi (1993), Taylor and van Leeuwan (1980), van Leeuwen (1994); van Leeuwen and others (1987)

Table E4. Significant prospects and occurrences in tract 142pCu7020, Sumatra Island—Indonesia.

[g/t, grams per metric ton; Ma, million years; n.d., no data]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference
Mudik	–1.7	101.25	Miocene	Prospect, 7.5 g/t Au in pyritic boulders.	Grunsky and Smee (1999)
Takengon (Collins prospect)	4.834	96.594	Tertiary	Cu-porphyry mineralization, Au-Cu skarn, and epithermal Au vein stockworks with supergene enrichment at Collins prospect area at Takengon.	East Asia Minerals Corporation (2010)
Geunteut	5.012	95.603	14	Cu-Mo-Au in granodiorite stock.	Bennett and others (1981); Coulson and others (1988)
Dusun	4.213	97.209	n.d.	Stockwork in diorite-tonalite porphyry.	Cameron and others (1983); Miswar and Coulson (1987); Dalimunthe and others (1997a, b); Bryant and Carlile (1980)
Sigalagala	3.396	97.894	9–11	Cu-Mo stockwork in diorite porphyry.	Cameron and others (1982); Johnson and others (1987)
Danu Diatas	–1.089	100.704	Pliocene	Cu-Mo in propylitized rhyolite overlying granite porphyry.	Barber and others (2005)
Siuluk Deras	–1.952	101.206	Pliocene	Cu-Mo in propylitized diorite.	Barber and others (2005)
Danau Dipatiempat	–2.847	101.934	Miocene to Pliocene	Low-grade Cu in argillized diorite in Tertiary volcanic rocks.	van Leeuwen (1978)
Tanjung Sakti	–4.474	103.126	Mid-Miocene	Low-grade Cu in brecciated and propylitized diorite stock.	Acquino (1988)

Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7020 are listed in table E5.

Grade and Tonnage Model Selection

Tangse, the only deposit with identified resources within the tract, is a porphyry copper-molybdenum deposit with no reported gold grade. Analysis of variance tests on ore tonnage and grade data (table 6) showed that the Tangse porphyry copper deposit is consistent with the deposit populations in the general porphyry copper model for the world (Singer and others, 2008). This model was deemed the most appropriate model for estimation of undiscovered resources in the Sumatra Island tract, consistent with the reasoning and recommendations of Drew and Singer (2005).

Table E5. Principal sources of information used for tract 142pCu7020, Sumatra Island—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of Indonesia	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Systematic geologic map, Indonesia	1:250,000	Geological Research and Development Centre (1987–2000)
Mineral occurrences	Porphyry copper deposits of the world: data base, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence data base	NA	Directorate of Mineral Resources and Inventory (2004b)
	Mineral occurrence reports	NA	Djaswadi (1993), Miscellaneous company reports

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The team reviewed the results of a preliminary assessment done in February 2005; preliminary estimates were revised in 2010 (table E6) utilizing larger-scale geologic map information and incorporating the results of more recent exploration activity and geologic research in the area. The method of estimation was subjective and based on expert opinion and on analogy with geologically similar well-explored areas the team was familiar with in other regions of Southeast Asia and the world.

Takengon is one of the prospects judged to be likely to contain ore grades and tonnages consistent with the general porphyry copper deposit model, and it provides the rationale for the estimate of 1 deposit at 90-percent confidence.

Considerations that influenced estimates at 50- and 10-percent confidence levels include the presence of the Tangse porphyry copper deposit and the number of additional porphyry-copper systems, prospects and occurrences along a well- defined magmatic arc. Strike-slip faulting within the tract provides evidence for a favorable structural setting for porphyry copper emplacement. In addition, several epithermal gold (low-sulfidation) and base-metal vein deposits also are present and could indicate the presence of buried porphyry systems, especially in the areas of gold, copper, and base-metal anomalies or occurrences that cluster, sometimes in the vicinity of known porphyry prospects. Another consideration was the presence of voluminous Eocene to Miocene intrusive and volcanic rocks in the tract that might host porphyry copper deposits in areas where uplift and erosion has been less intense and extensive, and extensive areas of Quaternary volcanic rocks that may cover unexposed porphyry copper deposits that lie at depths of less than 1 km. The estimate results in a mean of 7.1 expected undiscovered porphyry copper deposits in Sumatra Island within the tract and, when combined with the known Tangse deposit gives a density of five deposits/100,000 km^2. The team did not apply the deposit density models of Singer and others (2005) directly during the assessment, however our estimate of 5 deposits/100,000 km^2 is consistent with, but at the lower end of, their reported observed range in deposit density in thoroughly explored porphyry copper tracts worldwide. This low prospectivity for porphyry copper deposits in the Sumatra tract, as assigned by the assessment team, reflects the recognition that no large porphyry systems are known in the continental-arc segment of the Sunda-Banda Arc and that the oblique nature of subduction and lack of plate reorganization during the late Tertiary in this area may decrease the likelihood of porphyry copper deposit development as compared to other prospective arcs in the region.

Probabilistic Assessment Simulation Results

Undiscovered resources for the Sumatra permissive tract 142pCu7020 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits (table E6) with the general grade and tonnage model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table E7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. E4).The cumulative frequency plot shows the estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean for each commodity and for total mineralized rock.

Table E6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7020, Sumatra Island—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; $C_v\%$, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and $C_v\%$ are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	$C_v\%$	N_{known}	N_{total}		
1	5	13	13	13	6.1	4.3	71	1	7.1	131,030	5

Table E7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7020—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	490,000	13,000,000	56,000,000	90,000,000	23,000,000	0.32	0.07
Mo	0	0	230,000	1,600,000	2,600,000	640,000	0.27	0.14
Au	0	0	300	1,500	2,200	600	0.32	0.13
Ag	0	0	2,500	20,000	32,000	7,800	0.26	0.19
Rock	0	120	2,800	12,000	18,000	4,800	0.34	0.07

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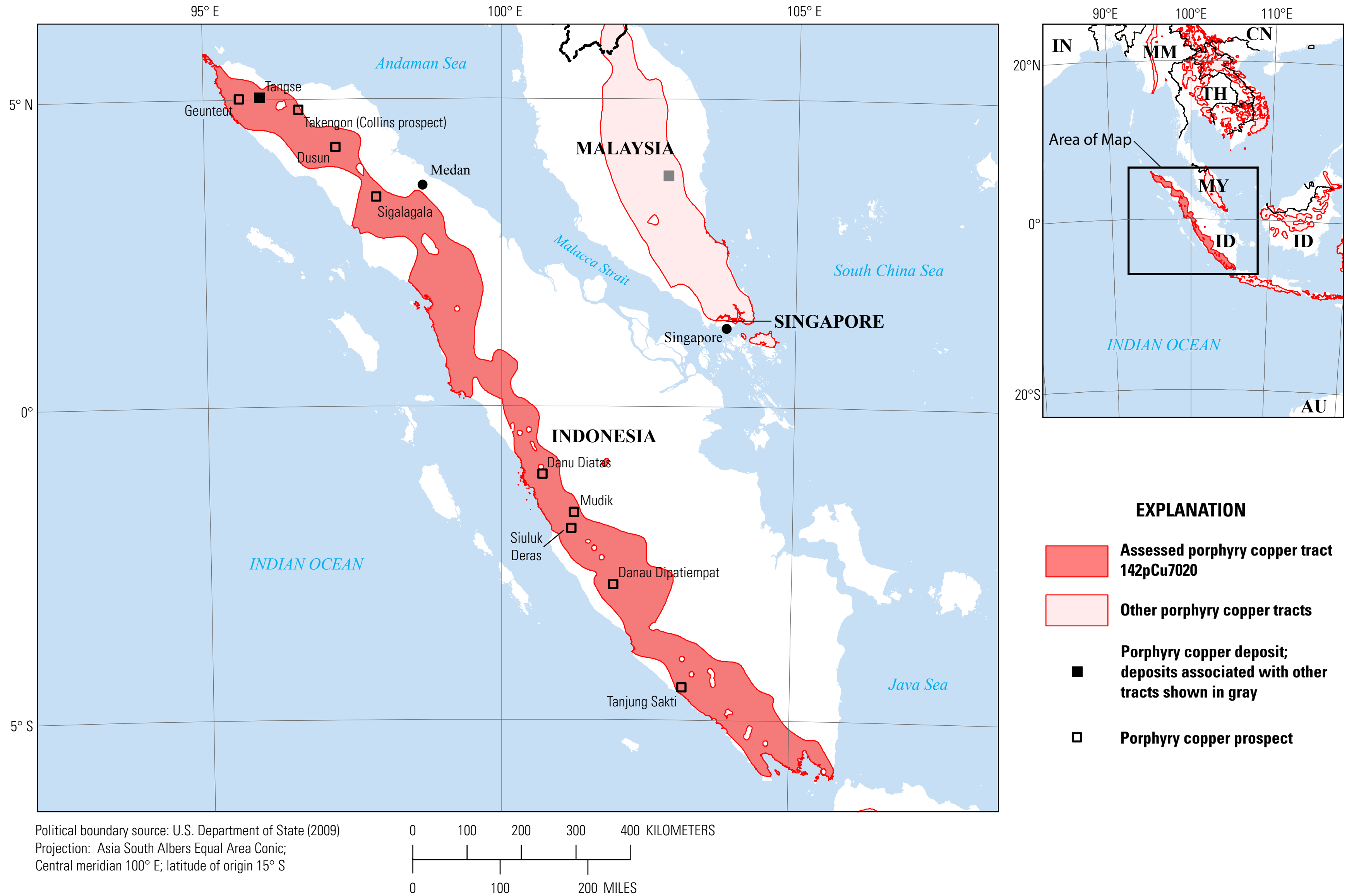

Figure E1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7020, Sumatra Island—Indonesia. AU, Australia; CN, China; IN, India; ID, Indonesia; MM, Myanmar; MY, Malaysia; TH, Thailand.

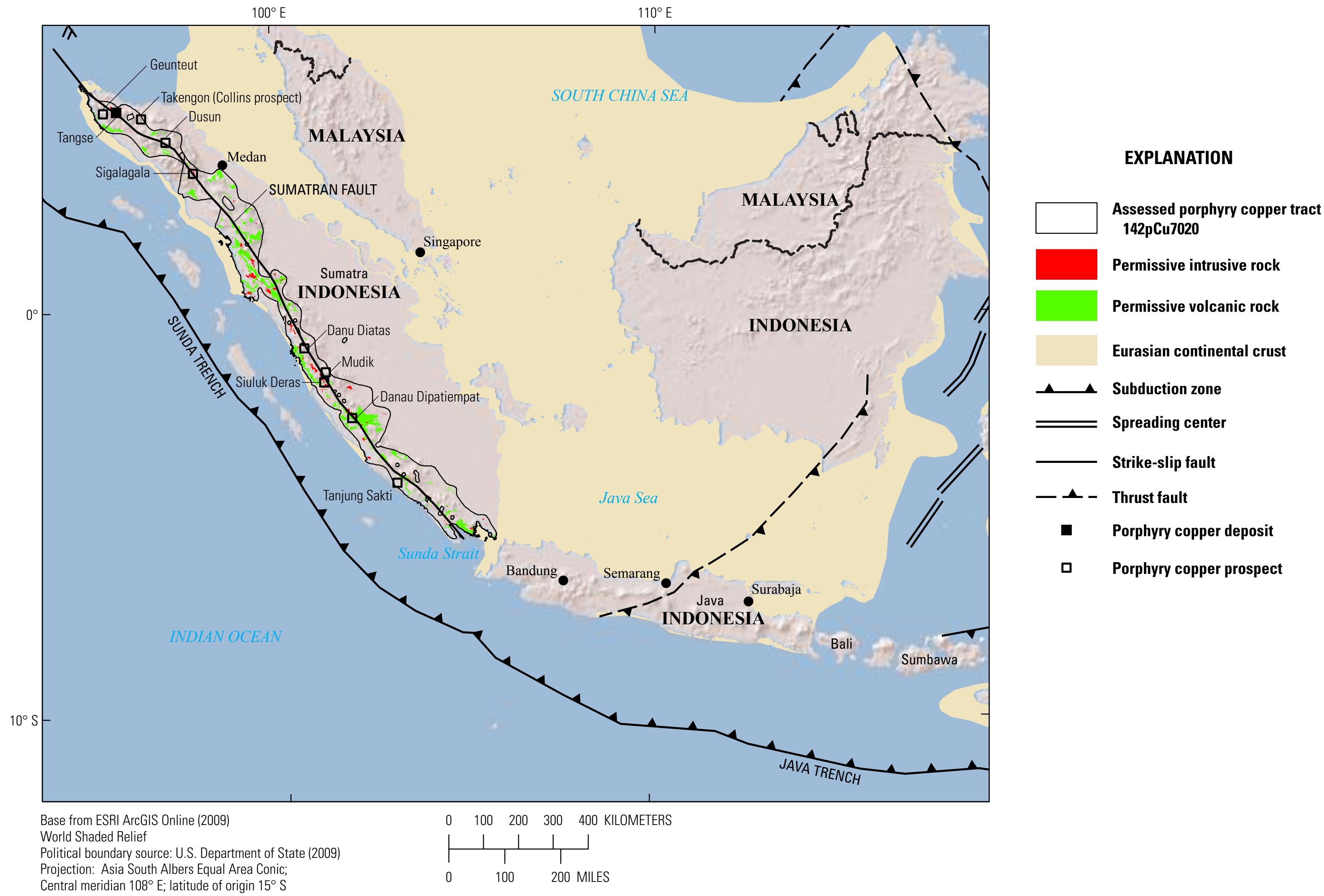

Figure E2. Map showing the regional setting for tract 142pCu7020, Sumatra Island—Indonesia.

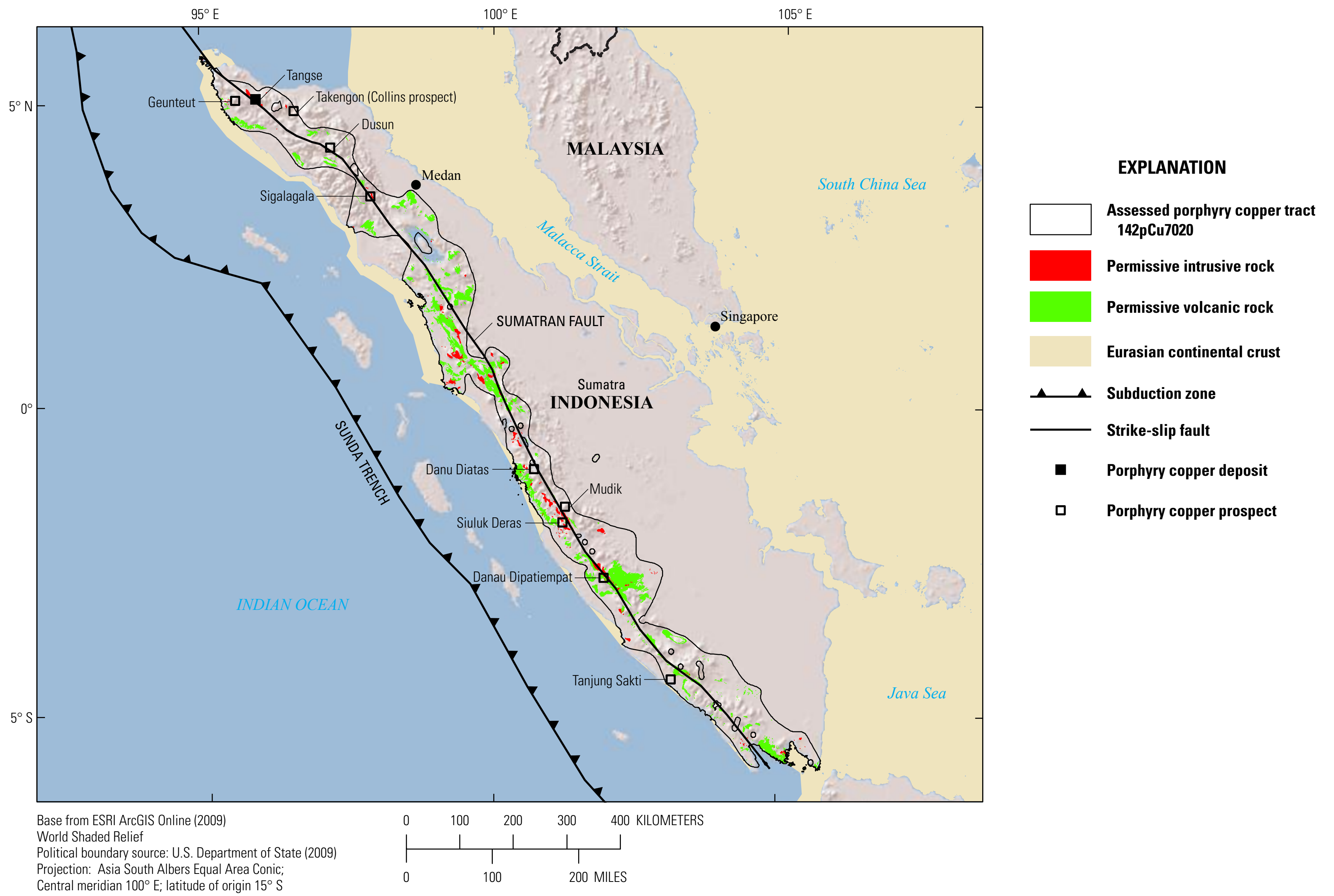

Figure E3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper deposits and prospects for tract 142pCu7020, Sumatra Island—Indonesia.

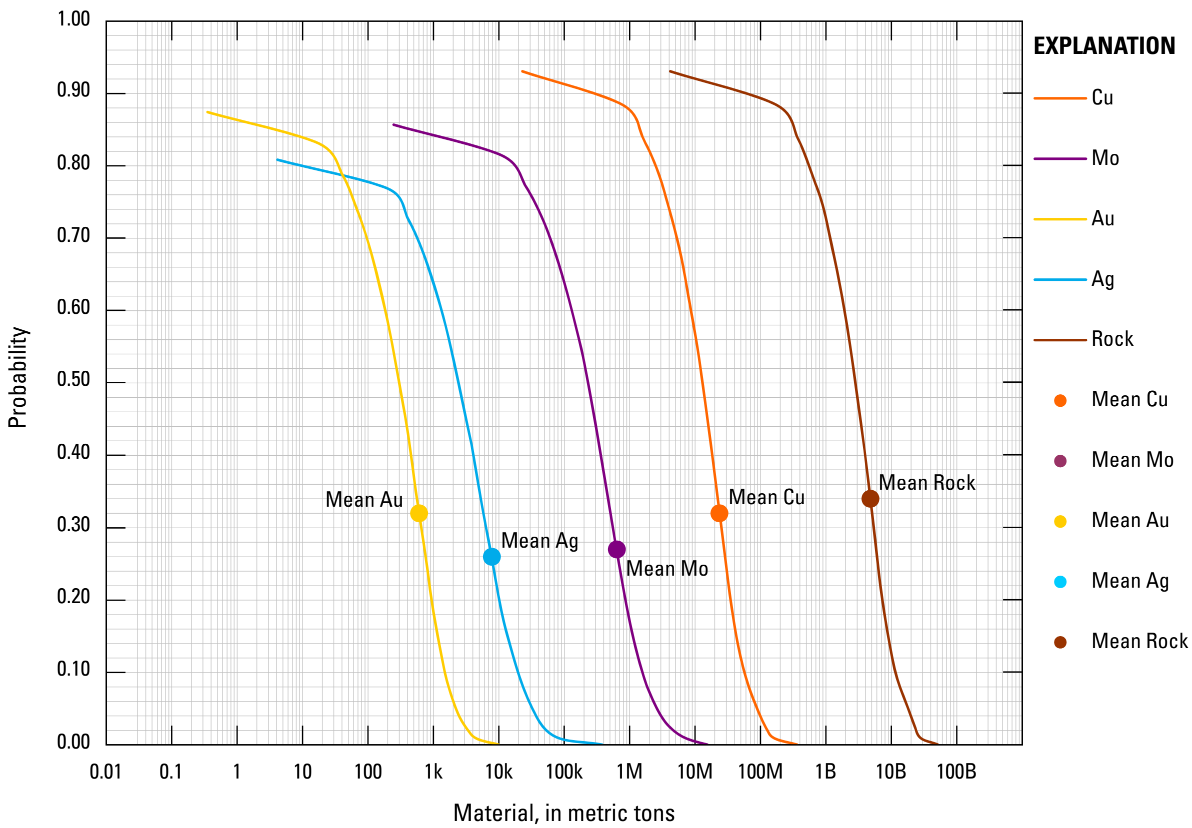

Figure E4. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7020, Sumatra Island—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix F. Porphyry Copper Assessment for Tract 142pCu7025, Sunda-Banda Arc—Indonesia

By Gilpin R. Robinson[1], Jr., Jane M. Hammarstrom[1], Steve Ludington[2], Arthur A. Bookstrom[3], Sewit A. Yenie[1], Bambang Tjahjono Setiabudi[4], Dwi Nugroho Sunuhadi[3] and Michael L. Zientek[3], with contributions from Gwaibo Kopi[5]

Deposit Type Assessed: Porphyry copper, Cu-Au subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table F1 summarizes selected assessment results.

Table F1. Summary of selected resource assessment results for tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[km, kilometers; km², square kilometers; t, metric tons; NA, not applicable; n.d., no data]

Date of assessment	Assessment depth (km)	Sub-tract	Tract area (km²)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	a	61,200	n.d.	10,000,000	4,200,000
		b	22,550	7,216,000	15,000,000	8,000,000
		c	5,670	n.d.	2,100,000	0
		Total	89,420	7,216,000	27,00,000	NA

Location

The tract includes southern Java (Jawa) extending eastward to Wetar Island, incorporating several other Greater Sunda Islands (fig. F1).

Geologic Feature Assessed

The eastern part of the Eocene to Holocene Sunda-Banda magmatic arc from Java (Jawa) to east of Wetar Island.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]U.S. Geological Survey, Menlo Park, California, United States.
[3]U.S. Geological Survey, Spokane, Washington, United States.
[4]Directorate of Mineral Resources Inventory, Geological Agency of Indonesia, Bandung, Indonesia.
[5]Geological Survey of Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

The Sunda-Banda Arc tract is the eastern part of the 3,800-km-long Eocene to Holocene Sunda-Banda magmatic arc that stretches from Sumatra to east of Damar Island (fig. 5*C*). Porphyry copper mineralization in the tract, most of which is Miocene to Pliocene age, is generally associated with bodies of andesite porphyry, dacite porphyry, breccia, and tonalite porphyry (table F2). The largest known porphyry copper deposit, Batu Hijau, is 3.7 Ma (Garwin and others, 2005).

The long, elongated tract delineates a mid-Tertiary magmatic arc developed in response to frontal subduction of the Indian Ocean Plate along the Java Trench in the west and Timor Trough to the east (fig. F2). The tract has been subdivided into 3 sub-tracts (fig. F3) based on differences in basement type, tectonics, and subduction history. The western part of the tract comprising Java (Jawa), sub-tract a, is a magmatic arc constructed on continental crust of the Eurasian Plate. Sub-tract b, east of Java (Jawa) extending from Bali to west Flores Islands, is an island arc constructed on oceanic crust (Carlile and Mitchell, 1994) and the magmatism in this area shows the smallest amount of geochemical influence from thinned continental crust or subducted continental-crust-derived sediments along the Sunda-Banda Arc trend (Elburg and others, 2004). Sub-tract c, extending from east Flores to Wetar Islands, is an island arc constructed on oceanic crust or highly thinned continental crust (Carlile and Mitchell, 1994). Magmatism in this area is geochemically influenced by Australian continental-crust materials (thinned continental crust or subducted continental-crust sediments; Elburg and others, 2004). In the late Miocene to Pliocene, collision of the Australian continent with the Sunda-Banda Arc shut off subduction along the Timor Trough and initiated a polarity shift to southward subduction of oceanic crust of the marginal Banda Sea beneath the arc in the sub-tract c area (Garwin and others, 2005).

Geologic Criteria

The entire tract includes Eocene to Pliocene intrusive- and volcanic-rock units but excludes thick overlying Quaternary volcanic and sedimentary units. The geologic units that define the permissive tract are calc-alkaline igneous rocks of Eocene to Pliocene age (most are mid-Miocene). Igneous-rock map units of uncertain age, that span this age range but may be as old as Cretaceous, have been included in the tract. Most of the plutonic rocks that crop out within the tract are small bodies of diorite-granodiorite (some porphyritic) and a few granite-granodiorite bodies (table F2). The chemistry of these rocks is calc-alkaline, but some sodic variants known as adakites are present (Elburg and others, 2004; Barber and others, 2005).

Calc-alkaline volcanic rocks are considered permissive for porphyry copper deposits because they are localized near, and often overlie, the intrusive centers where porphyry copper deposits often occur. These volcanic-rock map units may include small unmapped intrusive bodies within their borders. The volcanic rocks that define the tract include andesite flows and tuffs, dacite and associated dacitic tuffs and breccias, and basalt flows (table F2). Mid-Tertiary bimodal rhyolite-basalt sequences and andesitic tuffs that are primarily within marine carbonate rocks (fringing reefs bordering the oceanic islands) or clastic sedimentary rocks have been excluded from the tract. These distal volcanic deposits in carbonates and sediments are interpreted to be part of the accretionary-wedge complex, and their sites of deposition were not likely to be near the intrusive centers that host porphyry copper deposits. A few high-K alkaline series volcanic rocks occur in a back-arc setting (Barber and others, 2005).

The team used 1:250,000-scale geologic maps (table F2) to identify areas of permissive rock types, based on the map legend attribute information describing map-unit rock types, composition, and age. The distribution of the permissive rock units is shown in figure F3. The maps were scanned and rectified, and the areas of permissive rock units were digitized by hand to build an attributed digital GIS file used to define the permissive tract. After choosing the polygons and groups of polygons that represent the surface expressions of permissive igneous intrusions, we applied a 10-km buffer around them to account for a spatial uncertainty of approximately 2 km in the digitized geology and deposit location data and the possibility that deposits may be associated with intrusions that expand beneath their surface expression and also are less than 1 km beneath the land surface. A 2-km buffer was applied around the permissive volcanic units, as these may be imprecisely located and partly covered. The locations of (1) major and minor copper deposits, prospects, and occurrences and (2) hydrothermal gold-copper deposits and prospects listed in the Indonesian mineral-occurrence database (Directorate of Mineral Resources and Inventory, 2004a,b) correlated with the buffer polygons. In some areas, the buffer polygons were extended and modified to include the deposits and prospects in this database that were located outside of, but near, the buffer polygons. A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified polygons using an algorithm (PAEK, polynomial approximation with exponential kernel) with a tolerance of 20 km. Necking, thinning and contraction of the polygons resulting from the above processing necessitated manual cleaning of the preliminary tract (for example, polygon necks removed). Final tracts were compared to the permissive geologic features in source maps to ensure that original permissive boundaries were honored. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

Table F2. Map units that define tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[Geologic map, map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Map symbol	Lithology	Age range
		Intrusive rocks	
		142pCu7025a, Java	
1 (Western Jawa)	Tmi	Granite, granodiorite	Late early Miocene
1 (Western Jawa)	Tlmi	Porphyritic diorite, porphyritic andesite	Early Miocene
1 (Western Jawa)	Tomi	Granodiorite	Late Oligocene to early Miocene
2 (Middle Jawa)	Tpib	Diorite	Pliocene
2 (Middle Jawa)	Tmik	Plagioclase porphyry, basalt	Late Miocene
2 (Middle Jawa)	Tpi	Intrusive rocks and andesite-basalt volcanic plug	Pliocene
2 (Middle Jawa)	Tmi	Diorite	Middle to late Miocene
3 (Eastern Jawa)	Tmi	Andesite	Early to middle Miocene
		142pCu7025b. Bali to west Flores Islands	
1807	Tmi	Dacite, basalt	Middle Miocene
2007	Tdi	Diorite	Lower to middle Miocene
2007	Tsy	Syenite	Lower to middle Miocene
2007	Tt	Tonalite-trachyte	Lower to middle Miocene
2007	Tda	Dacite	Lower to middle Miocene
2107	Tmg	Granodiorite	Late Miocene
2107	Tmd	Quartz diorite	Late Miocene
2109-2108-2208	Tdi	Diorite	Middle Miocene
2109-2108-2208	Tgr	Granite, monzonite	Eocene to Oligocene
2207	Tmg	Granite, granodiorite	Middle Miocene
		142pCu7025c, east Flores to Wetar Islands	
2207	Tmg	Granite, granodiorite	Middle Miocene
2307	Tpdi	Quartz diorite	Pliocene
2307	Tmgd	Granodiorite	Upper Miocene
2508	Tmdi	Diorite	Middle Miocene
2508	Tmgd	Granodiorite	Middle Miocene
2508	Tmgr	Granite	Middle Miocene
2508	Tmda	Dacite	Middle Miocene
		Volcanic rocks	
		142pCu7025a, Java	
1 (Western Jawa)	Tmib	Andesite	Early to late Miocene
1 (Western Jawa)	Tnv	Andesite and basalt breccia and lava	Pliocene

Table F2. Map units that define tract 142pCu7025, Sunda-Banda Arc—Indonesia.—Continued

[Geologic map, map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Map symbol	Lithology	Age range
		Volcanic rocks	
1 (Western Jawa)	Tpvs	Tuff	Pliocene
1 (Western Jawa)	Tpi	Andesite	Pliocene
1 (Western Jawa)	Tmvs	Volcanic breccia, tuff	Late Miocene
1 (Western Jawa)	Tlvs	Volcanic breccia, tuff	Early Miocene
1 (Western Jawa)	Tomv	Andesite	Late Oligocene to early Miocene
1 (Western Jawa)	Temv	Volcanic breccia, tuff	Late Eocene to early Miocene
2 (Middle Jawa)	Tnvb	Andesitic to basaltic volcanic breccia, lava flow and tuff	Late Miocene
2 (Middle Jawa)	Tpv	Volcanic breccia, tuff	Pliocene
2 (Middle Jawa)	Tnv	Andesite and basalt breccia and lava	Middle Miocene to Pliocene
2 (Middle Jawa)	Tmv	Andesite and basalt lava and breccia	Early to middle Miocene
2 (Middle Jawa)	Tomv	Andesite, basalt, and dacite	Late Oligocene to early Miocene
3 (Eastern Jawa)	Tlmv	Dacite, andseite, basalt	Early to middle Miocene
3 (Eastern Jawa)	Tomv	Andesite and basalt lava, breccia, and tuff	Late Oligocene to early Miocene
3 (Eastern Jawa)	Tomw	Basalt	Late Oligocene to early Miocene
3 (Eastern Jawa)	Tmv	Andesite, basalt and dacite	Middle Miocene
		142pCu7025b, Bali to west Flores Islands	
1707	Tpvp	Andesite-basalt lava and breccia	Pliocene
1707	Tpva	Lava	Pliocene
1707	Tomu	Volcanic breccia and lava	Oligocene to early Miocene
1807	Tomp	Volcanic breccia and lava	Oligocene to early Miocene
1807-1907	Tmv	Andesitic volcanic breccia	Early to middle Miocene
1807-1907	Tmi (a,b,d,u)	Andesite, basalt	Middle to late Miocene
2007	Tmv	Dacite, porphyritic dacite	Lower to middle Miocene
2007	Tlmv	Andesite, basalt	Lower Miocene
2007	Ta	Andesite	Middle-lower Miocene
2107	Tmt	Volcanic lava and breccia	Middle to late Miocene
2109-2108-2208	Tomk	Andesite and basalt volcanic breccia and lava	Early Miocene
2109-2108-2208	Tan	Andesite	Middle Miocene
2207	Tmt	Dacitic lava	Middle Miocene
2207	Tmk	Volcanic breccia	Early Miocene

Table F2. Map units that define tract 142pCu7025, Sunda-Banda Arc—Indonesia.—Continued

[Geologic map, map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Map symbol	Lithology	Age range
		Volcanic rocks	
		142pCu7025c, east Flores to Wetar Islands	
2207	Tmt	Dacitic lava	Middle Miocene
2207	Tmk	Volcanic breccia	Early Miocene
2307	Tmpa	Volcanic lava and breccia	Upper Miocene
2508	Tmpa	Andesite and basalt lava and breccia	Late Miocene to Pliocene
2508	Tmn	Dacite lavas	Late Miocene to Pliocene
2508	Tmt	Andesite and basalt breccia	Early Miocene
2711, 2509, 2709, 2508, 2608, 2708, 2507, 2607, 2707	Tv	Andesite, basalt	Pliocene

These revised preliminary-tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks and sedimentary deposits are greater than 1 km in thickness. The final tract boundary was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The Sunda-Banda Arc tract includes the southern part of Java (Jawa), areas within and between the islands of Bali, and Sumbawa (Nusa Tenggara Barat), Flores (Nusa Tenggara Timur), and Maluku. The Sunda-Banda Arc tract includes at least 10 national parks and a number of nature reserves.

Known Deposits

The Batu Hijau porphyry copper-gold deposit (1.64 billion metric tons at 0.44 percent copper, 0.35 g/t gold) on Sumbawa Island (fig. F3), the only porphyry deposit in the overall Sunda-Banda Arc tract (table F3) with identified resources (Singer and others, 2008), is located in sub-tract b. The deposit and other prospects in the region were discovered in early 1990 as a result of a reconnaissance stream-sediment sampling program (carried out by Newmont) and the subsequent discovery of malachite-stained float and outcrop. The copper-gold mineralization is hosted by a tonalite intrusive complex with diorite and metavolcanic wallrocks. The orebody is cylindrical, with a vertical extent of more than 650 m. Potassic core-zone alteration grading outward to extensive propylitic alteration hosts most of the ore mineralization (van Leeuwen, 1994). Sulfide and ore minerals are bornite, chalcopyrite, molybdenite, pyrite, sphalerite, galena, and electrum. Supergene ore minerals include chalcocite/digenite, covellite, cuprite, and malachite (Garwin, 2002). At the beginning of the 21st century, Batu Hijau was the tenth largest copper mine in the world, accounting for approximately 2.5 percent of global production; mine production at Batu Hijau from September 2009 to September 2010 was 190,509 metric tons of copper and 15,705 kilograms of gold (Steel Guru, 2010).

Prospects, Mineral Occurrences, and Related Deposit Types

There are numerous additional prospects and anomalies of gold and copper within the Sunda-Banda Arc tract (table F4). The western part of the Sunda-Banda Arc tract contains the gold and gold-copper districts of Cikotok, Gunung Pongkor, Cikondang, Koelon Progo, and Jampang in West Java (Jawa) Island, including the Porgera and Tjibadong epithermal gold deposits. East Java (Jawa) contains the Pagergunung, Gunung Kumitir and Gunung Tumpanqpitu, Trenggalek, Muara Mandilis, Baban Timur, and Baban Timur porphyry prospects. There are also new discoveries of porphyry-style mineralization at the Gunung Tumpanqpitu, Gunung Kumitir, and Pagergunung prospects and in East Java (Jawa).

Sub-tract a: The Miocene andesite volcanic rocks along the southern coast of Java host several porphyry occurrences associated with diorite intrusions and stocks, including the Ciemas, Tujuh-Bukit (Tumpangpita), and Tirtomoyo prospects (fig. F3). The Dutch explored near the Ciemas prospect in

Table F3. Identified porphyry copper resources in tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Batu Hijau	–8.96	116.87	Cu-Au	3.7	1,640	0.44	n.d.	0.35	n.d.	7,216,000	Garwin (2002), Clode and others (1999), Imai and Ohno (2005), Maula and Levet (1996)

1922–24, and local mining for gold began in the 1980s (van Leeuwen, 1994). The gold-ore vein stockwork at Ciemas is in a Miocene dacite porphyry intruded into early Miocene andesitic volcanic rocks that display argillization and silicification (van Leeuwen, 1994). Drilling at the Tujuh-Bukit porphyry copper-gold prospect (Tumpangpita area) yielded an inferred resource of 500 Mt at 0.4 percent copper and 0.5 g/t gold at a cutoff grade of 0.2 percent copper (Intrepid Mines Limited, 2010). Resources at Tujuh-Bukit are open in all directions. The Tirtomoyo prospect is a diorite porphyry copper-gold stockwork associated with base-metal skarn in Miocene volcanic rocks. The Dutch report evidence of mining of the base-metal skarn by the Japanese during World War II (van Leeuwen, 1994). High-sulfidation alteration and epithermal mineralization is reported to overprint the porphyry copper-gold mineralization event (Arc Exploration Limited, 2010).

Sub-tract b: Sub-tract b contains the Batu Hijau porphyry deposit and a number of porphyry copper-gold prospects with recent exploration activity (table F4). The Dodo-Elang porphyry copper-gold prospect occurs in small bodies of diorite and feldspar porphyry associated with granodiorite intruded into andesitic volcanic rocks. Potassic, propylitic, phyllic, and advanced argillic alteration styles are widespread and intense. Widespread copper-gold mineralization in the alteration zones generally is low grade but is highest (>0.5 percent copper and 0.5 g/t gold) in the potassic alteration zones (van Leeuwen, 1994). Rock geochemistry of surface and drill-core samples indicates a northeast-southwest elongate copper zone more than 1.5 km long by 0.8 km wide trending into the adjacent East Elang prospect area. Inferred resources at Dodo-Elang are estimated to be greater than 1 billion tons at undisclosed grades (Southern Arc Minerals, Inc., 2010c) At the Selodong prospect, copper-gold mineralization occurs in phyllic- and propylitic- altered dacite porphyry stocks that have intruded andesitic and rhyodacitic volcanic rocks. Trenching has reported ore grades of 0.20 percent copper and 0.88 g/t gold, and rock samples have returned grades up to 0.4 percent copper, 0.4 g/t gold, and 400 ppm molybdenum (Southern Arc Minerals, Inc., 2010a). Drilling at 7 of 15 exploration targets in a 7 by 3 km area provides an inferred resource of 225 million tons at 0.24 percent copper and 0.33 g/t gold.

Sub-tract c: No porphyry copper prospects are known in the Sub-tract c area. The Weta epithermal gold deposit lies in Sub-tract c in the eastern part of the Sunda-Banda Arc tract.

Exploration History

Detailed exploration in West and East Java (Jawa) has taken place according to Directorate of Mineral Resources (Aneka Tambang) and is also documented in the private company reports residing in that agency. This exploration activity has generated a series of grouped gold and copper anomalies, many of which have led to discoveries of porphyry gold-copper prospects. Geophysical exploration in the region has been described by Turner (1993). The Batu Hijau deposit was discovered in 1990 from studies investigating gold and copper anomalies identified as a result of a stream-sediment sampling program in Sumbawa done by Newmont in the late 1980s. The history of prospect geochemical exploration at Batu Hijau is described by Meldrum and others (1994).

Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7025 are listed in table F5.

Grade and Tonnage Model Selection

The choice of the porphyry copper-gold subtype model of Singer and others (2008) to assess for porphyry copper deposits in the Sunda-Banda Arc sub-tract a area was based on the grade characteristics of the Ciemas prospect, the gold-rich nature of the related epithermal systems in the tract area, and geologic characteristics of the Sunda-Banda magmatic arc.

Table F4. Significant prospects and occurrences in tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[Ma, million years; n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers, m, meters. Rank 4=prospect in global database of Singer and others (2008) or >16,000 t contained copper; Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
				142pCu7025a, Java Island		
Ciemas	–7.22	106.56	3.1	1.5 by 0.75 km Au-Cu-Mo anomaly. 10 drill holes show ~0.2% Cu and ~0.2 g/t Au.	McInnes and others (2004)	2
Tirtomoyo	–7.93	111.088	n.d.	Reported assays of ore materials range from 1.08 to 9.6% Cu, 0.1 to 15.0 g/t Au, 27 to 96 g/t Ag. Southern Arc noted the presence of high sulfidation veining overprinting earlier porphyry Cu-Au mineralizing events.	Southern Arc Minerals Inc. (2010b)	2
Tujuh-Bukit	–8.583	114.017	n.d.	Intrepid Mines in 2010 reports drill intercepts of 118m at 0.37g/t Au and 0.36% Cu, and 455 m at 0.39g/t Au, 0.34% Cu and 72 ppm Mo. Inferred resources of 500 million tons at 0.4% Cu and 0.5 g/t Au at 0.2% Cu cutoff grade.	Intrepid Mines Limited (2010)	4
Trenggalek	–8.266	111.812	n.d.	Outcropping epithermal gold-silver veins targeted for drilling in 2010; hydrothermal breccia, silica caps.	Arc Exploration Limited (2010)	2
Pekalongan	–7.423	109.861	n.d.	Assays of mineralized diorite and andesite report up to 0.46 g/t Au and 0.47% Cu. Stream-sediment geochemical survey completed but with generally low Au and Cu results.	Austindo Resources Corporation NL (2010)	1
				142pCu7025b, Bali to west Flores Islands		
Selodong	–8.857	116.023	n.d.	Drill core assays report 0.16–0.28% Cu and 0.28–0.56 g/t Au. 7 by 3 km target area yields inferred resources of 225 million tons at 0.24% Cu and 0.33 g/t Au.	Southern Arc Minerals, Inc. (2010a)	3
Dodo-Elang	–8.872	117.318	n.d.	Rock geochemistry of surface and drill core samples indicate a NE-SW elongate copper zone more than 1.5 km long by 0.8 km wide trending into the adjacent East Elang prospect. Inferred resources of 1 billion tons at undisclosed grades.	van Leeuwen (1994), Southern Arc Minerals, Inc. (2010c)	2
Sabarati	–8.567	117.569	n.d.	Prospect	Arc Exploration Limited (2010)	1
Hulu	–8.762	118.458	n.d.	Prospect	Arc Exploration Limited (2010)	1
Bima	–8.624	119	n.d.	The geological and geochemical results from Kowo suggest the possibility of a buried porphyry copper-gold target; additional soil sampling planned.	Arc Exploration Limited (2009, 2010)	1

Table F5. Principal sources of information used for tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of Indonesia	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Systematic geologic map, Indonesia	1:250,000	Geological Research and Development Centre (1987–2000)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence data base	NA	Directorate of Mineral Resources and Inventory (2004b)
Exploration	Exxploration overview Indonesia	NA	van Leeuwen (1994), Setiabudhi (2004, 2010 written commun.)
	Commercial databases	NA	Infomine, Intierra, MEG
	Company Web sites	NA	Austindo Resources Corporation NL (2010), Southern Arc Minerals, Inc. (2010), Arc Exploration Limited (2010), Intrepid Mines Limited (2010)

The Batu Hijau deposit in sub-tract b is classified as a porphyry copper-gold deposit by Singer and others (2008). The porphyry copper-gold subtype model is used for sub-tract b based on the characteristics of the Batu Hijau deposit, the gold-rich nature of the related epithermal systems in the tract area, and geologic characteristics of the magmatic arc in this area. The arc magmatism in sub-tract b is developed on oceanic crust in a subduction setting lacking influence from continental crust or sediments derived from continental crust (Elburg and others, 2004), and the copper-gold subtype model is judged to be appropriate for this area.

No deposits or prospects are known in sub-tract c. The choice of the porphyry copper-gold subtype model of Singer and others (2008) to assess for porphyry copper deposits in the Sunda-Banda Arc sub-tract c area was based the gold-rich nature of epithermal systems in the tract area and geologic characteristics of the Sunda-Banda magmatic arc (table 6).

Rationale for the Estimate

The results of a preliminary assessment done in February 2005 were revised by utilizing larger-scale geologic map information and incorporating the results of more recent exploration activity and geologic research in the area. The assessment team reestimated the number of porphyry copper and copper-gold deposits in the Sunda-Banda Arc sub-tracts at the 90, 50, and 10 probability confidence levels during February 2010. The method of estimation was subjective and based on expert opinion and on analogy with geologically similar thoroughly explored areas in other regions of Southeast Asia and the world with which the team was familiar.

Sub-tract a: The assessment team recognized that no large porphyry-style systems are known in the continental-arc portion of the Sunda-Banda arc underlying Java (Jawa) (De Waele and others, 2009; Garwin and others, 2005). Undiscovered porphyry copper deposits are most likely to occur in Miocene andesite volcanic rocks and associated intrusive centers located along the southern coast of Java (Jawa) that host a number of porphyry copper-gold occurrences associated with diorite intrusions and stocks. This area has been explored, but the team concluded that future exploration around the Tujuh-Bukit and possibly the Ciemas and other prospects, may identify one or more deposits at 90-percent confidence and two or more deposits at 50-percent confidence, but more than eight undiscovered deposits were unlikely in the sub-tract.

Sub-tract b: Sub-tract b, a part of the Sunda-Banda Arc developed on oceanic crust, is highly prospective for porphyry copper deposits, hosting the large Batu Hijau porphyry copper-gold deposit and a number of porphyry copper-gold prospects under current exploration that have not been fully evaluated. Of these prospects, Selodong and Dodo-Elang are most likely to have grade and tonnage characteristics consistent with the porphyry copper-gold model. Ongoing exploration is likely to identify additional prospects, particularly in the vicinity of epithermal gold prospects. The team estimated that one or more porphyry copper-gold deposits are likely at 90-percent confidence and that four or more deposits are likely at 50-percent confidence, but more than 10 undiscovered deposits are unlikely in the sub-tract.

Sub-tract c: No porphyry copper prospects are known in the sub-tract c area, however, the epithermal gold deposit at Wetar may be the surface manifestation of underlying porphyry-style mineralization at unknown depth. The panel estimated a 10-percent chance that two porphyry copper-gold deposits may be present in the sub-tract. The panel concluded that there is a 10-percent chance that a subsurface porphyry copper system may be present within 1 km of the land surface at Wetar and that another potential deposit may lie under young volcanic cover. The tract area likely to host porphyry-style mineralization in sub-tract c is small (<6,000 km^2), the arc magmatism is young (mostly Pliocene to Holocene), and the estimated occurrence of undiscovered porphyry deposits at depths shallower than 1 km is likely to be low.

Tract Summary: The combined assessment results for sub-tracts a, b, and c result in a mean estimate of 9.8 expected undiscovered deposits in the overall tract. Considerations taken into account during the overall tract estimation process were the gold-rich nature of the porphyry-style prospects and that at least 20 gold and gold-copper anomalies or mineralized centers are known throughout the Sunda-Banda Arc tract and include a number of copper-gold epithermal veins and porphyry copper-gold prospects. A major additional consideration was the presence of extensive sedimentary and volcanic cover rocks and their ability to hide concealed deposits. In addition, copper and gold occurrences and anomalies cluster throughout most of the Sunda-Banda Arc tract (Directorate of Mineral Resources and Inventory, 2004a; table F4).

The mean estimate of 9.8 undiscovered deposits for all three sub-tracts, when added to Batu Hijau, result in a density of 10.9 deposits/100,000 km^2, consistent with the observed range in deposit density in thoroughly explored porphyry copper tracts worldwide as reported by Singer and others (2005).

Probabilistic Assessment Simulation Results

Undiscovered resources for the Sunda-Banda Arc tract 142pCu7025 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits (table F6) with the porphyry copper-gold subtype grade and tonnage model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table F7. Results of the Monte Carlo simulations are presented as cumulative frequency plots (fig. F4*A–C*).The cumulative frequency plots for each sub-tract show the estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table F6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[N_{XX}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation, C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). NA, not applicable]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
142pCu7025a, Java Island											
1	2	8	8	8	3.4	2.7	80	0	3.4	61,200	6
142pCu7025b, Bali to west Flores Islands											
1	4	10	10	10	4.8	3.3	68	1	5.8	22,550	26
142pCu7025c, east Flores to Wetar Islands											
0	0	2	2	3	0.63	1	160	0	0.63	5,670	11
				Total	9.8	NA	NA	1	10.8	89,420	12

Table F7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7025, Sunda-Banda Arc—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons; NA, not applicable. Quantiles are not additive; means are additive]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
				Sub-tract a, Java Island				
Cu	0	170,000	4,200,000	28,000,000	44,000,000	10,000,000	0.28	0.07
Mo	0	0	6,900	160,000	340,000	59,000	0.21	0.37
Au	0	18	350	2,100	3,100	770	0.31	0.07
Ag	0	0	700	7,600	17,000	3,500	0.2	0.28
Rock	0	40	900	5,800	9,300	2,100	0.3	0.07
				Sub-tract b, Bali to west Nusa Tenggara Islands				
Cu	0	410,000	8,000,000	41,000,000	59,000,000	15,000,000	0.31	0.07
Mo	0	0	19,000	270,000	470,000	91,000	0.24	0.27
Au	0	40	650	2,800	3,800	1,100	0.34	0.07
Ag	0	0	1,500	12,000	25,000	5,000	0.22	0.2
Rock	0	93	1,700	8,500	11,000	3,100	0.33	0.07
				Sub-tract c, east Nusa Tenggara to Wetar Islands				
Cu	0	0	0	4,700,000	9,800,000	2,100,000	0.18	0.59
Mo	0	0	0	15,000	50,000	12,000	0.11	0.8
Au	0	0	0	360	760	150	0.2	0.59
Ag	0	0	0	1,100	2,600	690	0.13	0.75
Rock	0	0	0	940	2,200	420	0.19	0.59
				Summary of undiscovered resources for combined sub-tracts a, b, and c				
Cu	NA	NA	NA	NA	NA	27,00,000	NA	NA
Mo	NA	NA	NA	NA	NA	160,000	NA	NA
Au	NA	NA	NA	NA	NA	2,000	NA	NA
Ag	NA	NA	NA	NA	NA	9,200	NA	NA
Rock	NA	NA	NA	NA	NA	5,600	NA	NA

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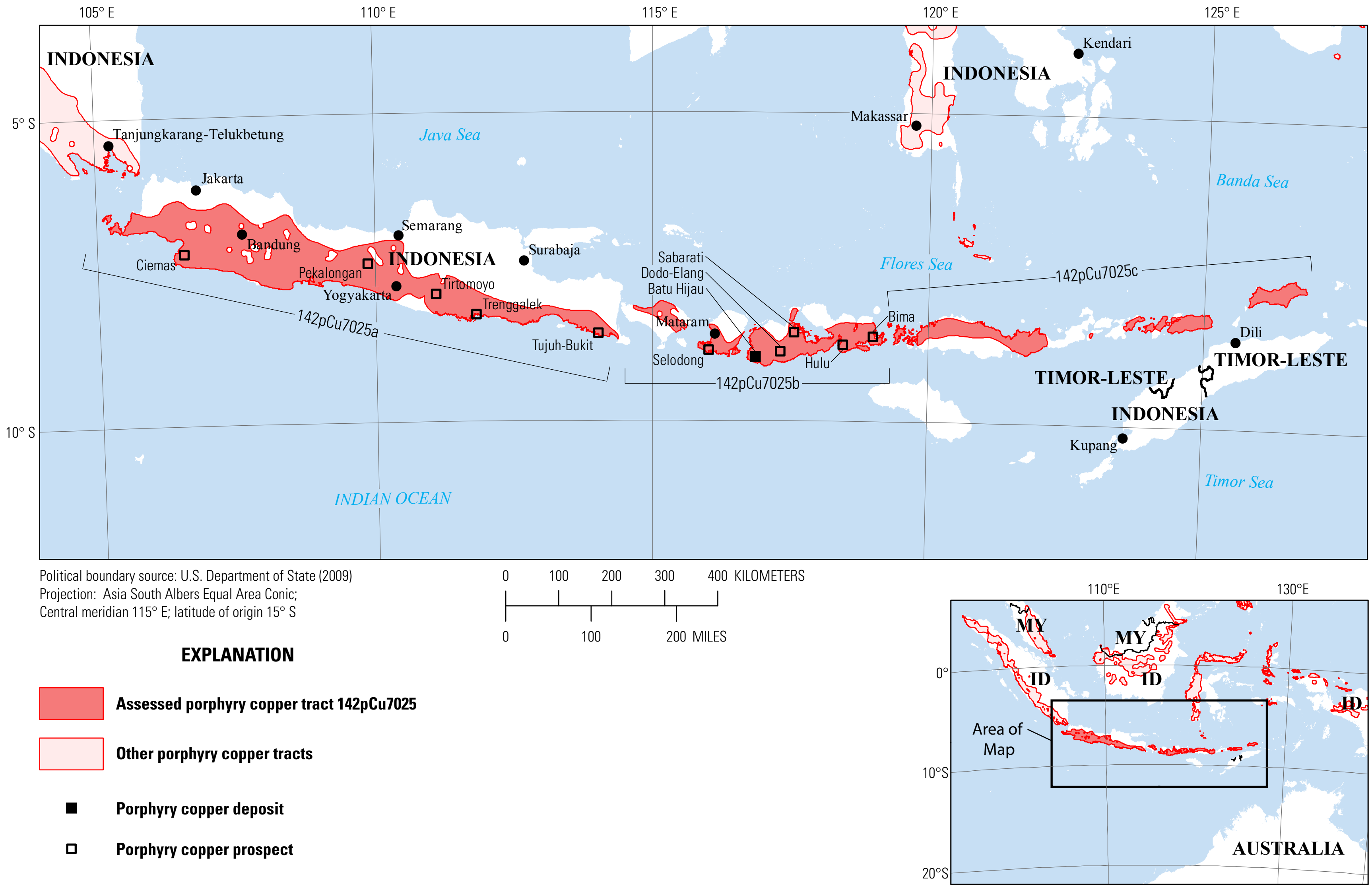

Figure F1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7025, Sunda-Banda Arc—Indonesia. ID, Indonesia; MY, Malaysia.

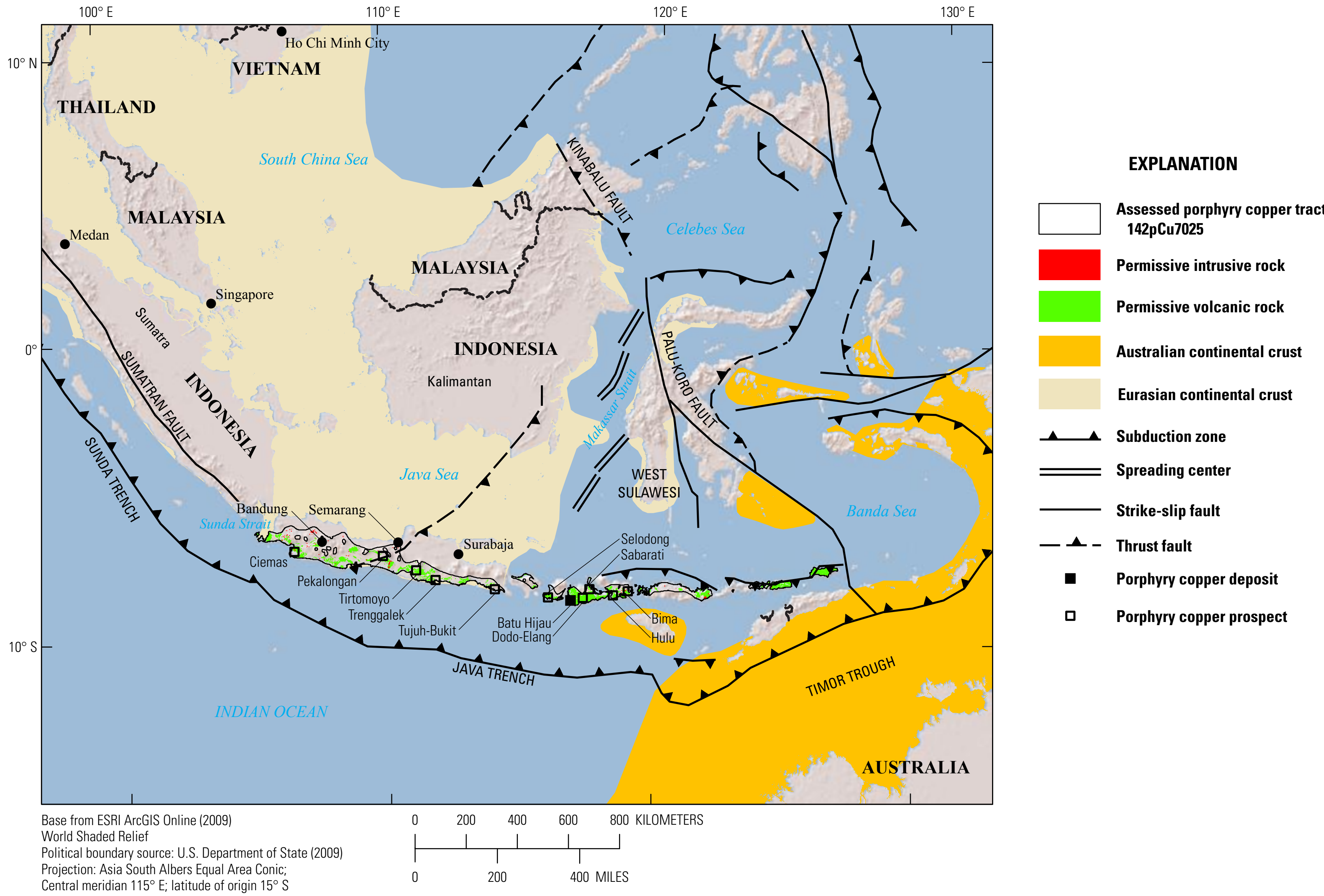

Figure F2. Map showing the regional setting for tract 142pCu7025, Sunda-Banda Arc—Indonesia.

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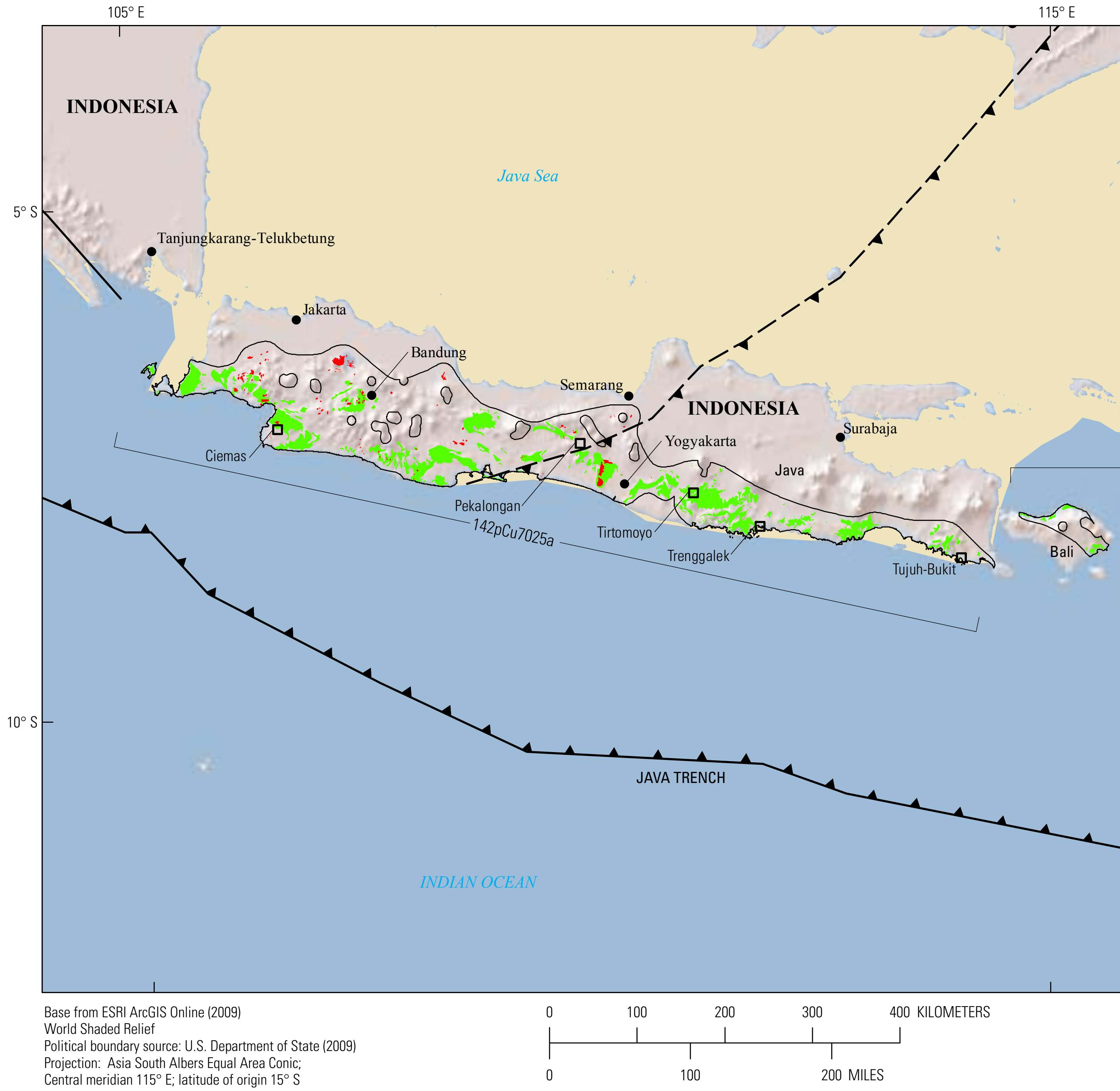
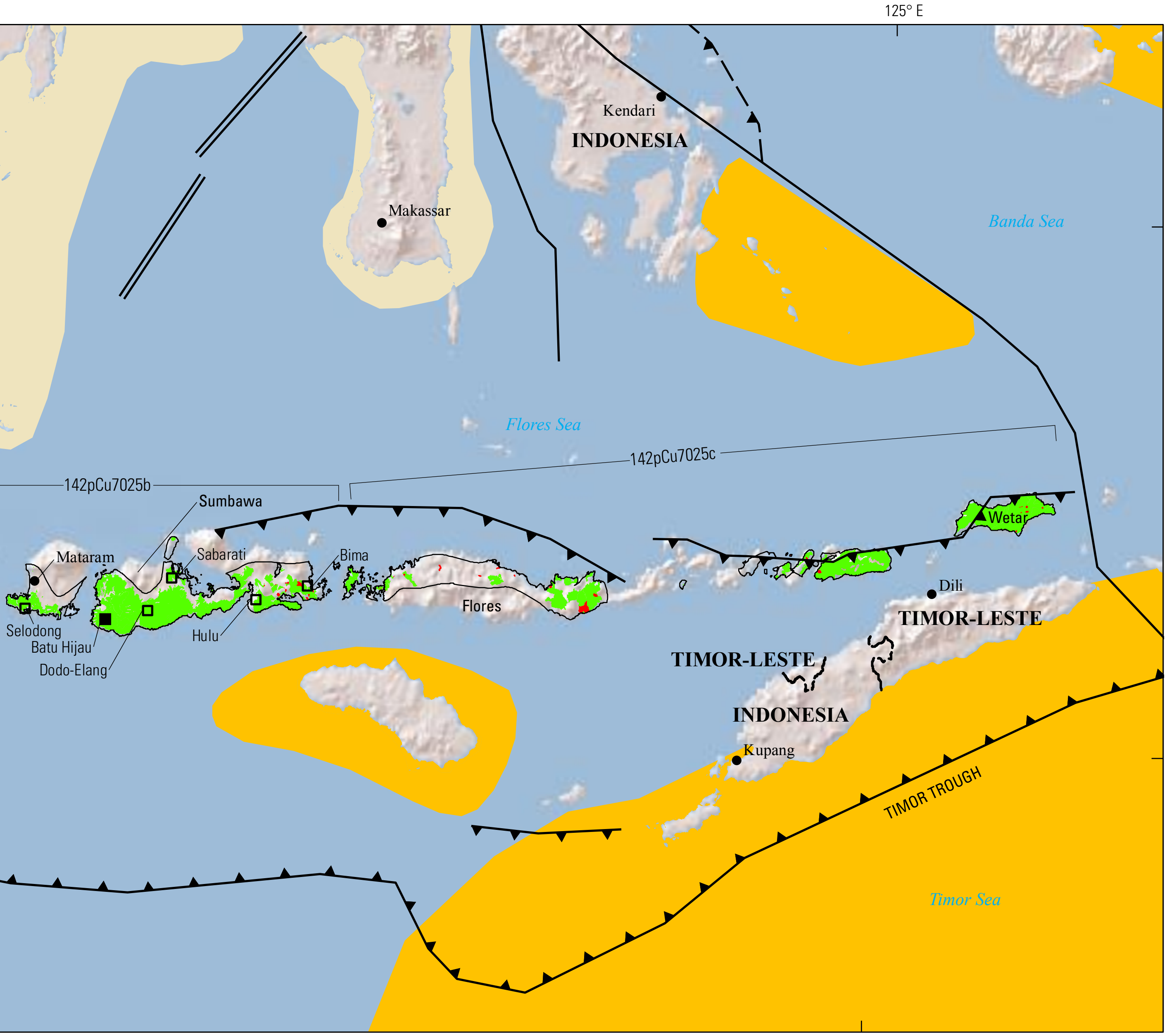
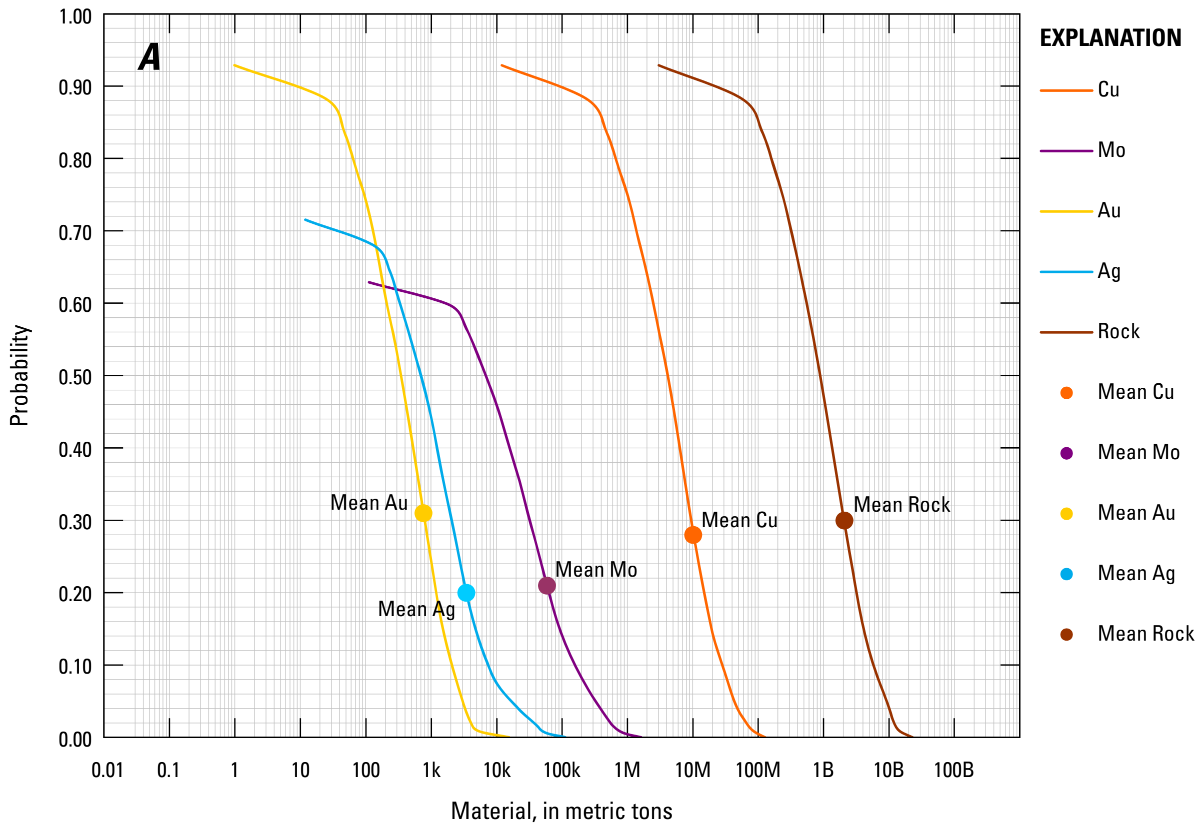


Figure F3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper deposits and prospects for tract 142pCu7025, Sunda-Banda Arc—Indonesia. 142pCu7025a, Java (Jawa) Island. 142pCu7025b, Bali to west Flores Islands. 142pCu7025c, east Flores to Wetar Islands.



EXPLANATION

Assessed porphyry copper tract 142pCu7025	Subduction zone
Permissive intrusive rock	Spreading center
Permissive volcanic rock	Strike-slip fault
Australian continental crust	Thrust fault
Eurasian continental crust	Porphyry copper deposit
	Porphyry copper prospect



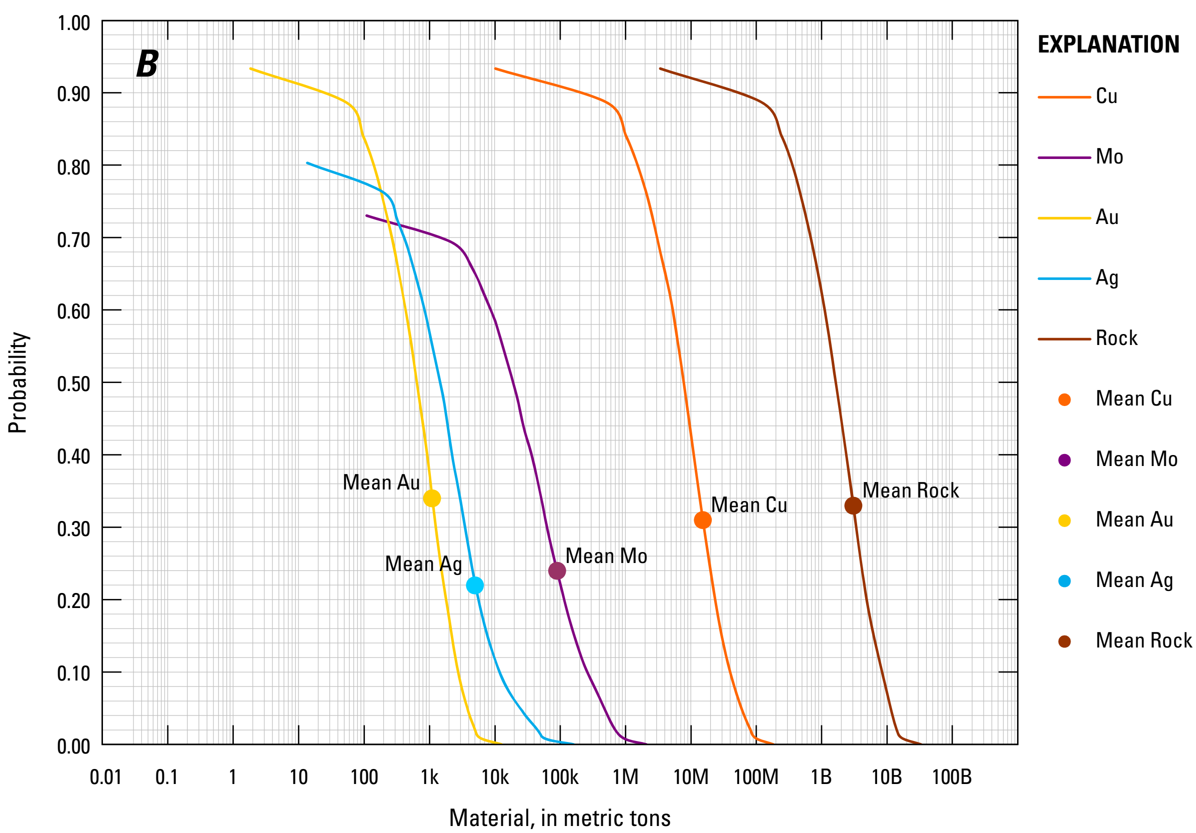


Figure F4. Cumulative frequency plots showing the results of Monte Carlo computer simulations of undiscovered resources in tract 142pCu7025, Sunda-Banda Arc-Indonesia. A,142pCu7025a, Java (Jawa) Island. B, 142pCu7025b, Bali to west Flores Islands. C, 142pCu7025c, east Flores to Wetar Islands. k, thousands; M, millions; B, billions; Tr, trillions.

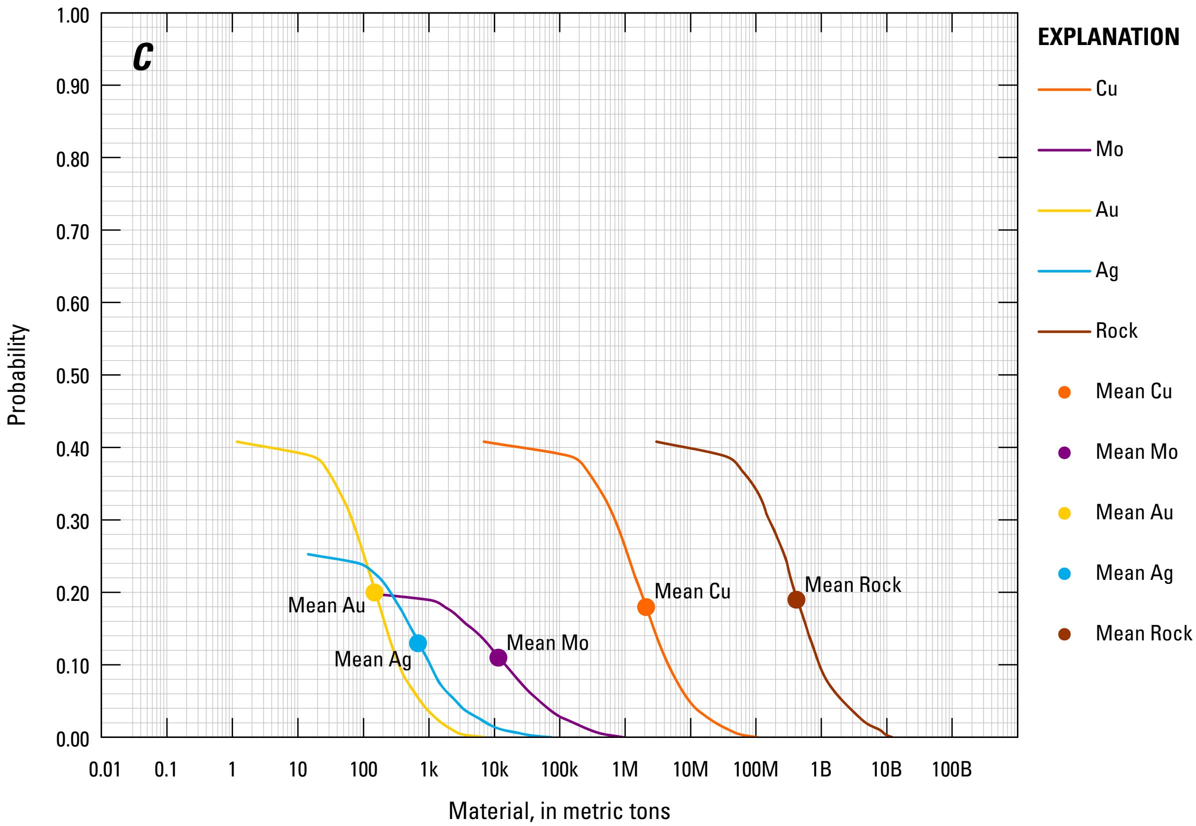


Figure F4.—Continued

Appendix G. Porphyry Copper Assessment for Tract 142pCu7026, West Sulawesi—Indonesia

By Gilpin R. Robinson, Jr.[1], Bambang Tjahjono Setiabudi[2], Dwi Nugroho Sunuhadi[2], Jane M. Hammarstrom[1], Steve Ludington[3], Arthur A. Bookstrom[4], Sewit A. Yenie[1], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table G1 summarizes selected assessment results.

Table G1. Summary of selected resource assessment results for tract 142pCu7026, West Sulawesi—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	60,270	n.d.	3,400,000	650,000

Location

The tract occupies most of the west half of the Island of Sulawesi in Indonesia (fig. G1).

Geologic Feature Assessed

Tract 142pCu7026 includes Miocene to Pliocene igneous rocks in the southern portion of the 1,200 km long Sulawesi-Sangihe magmatic arc, located in southwestern Sulawesi.

Delineation of the Permissive Tract

Tectonic Setting

The West Sulawesi magmatic arc is part of the 1,200-km-long Sulawesi-Sangihe magmatic arc, which has been active since the Miocene. The regional geologic and tectonic setting of the West Sulawesi tract is shown in figure G2. The West Sulawesi Arc

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Directorate of Mineral Resources Inventory, Geological Agency of Indonesia, Bandung, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S. Geological Survey, Spokane, Washington, United States.
[5]Geologic Survey of Papua New Guinea.

is partly developed on continental crust containing pre-Tertiary polymetamorphic rocks and Cretaceous plutons, and it has a complex history including three overlapping volcanic-arc events (Taylor and van Leeuwen, 1980; Garwin and others, 2005):

1. Cretaceous to Paleocene subduction over a west-dipping subduction zone resulted in the development of a north-northwest-trending calc-alkaline volcanic arc as West Sulawesi was accreted to the Sundaland continental-crust block bordering Kalimantan during a late Cretaceous orogenic event. Arc volcanism ceased in the Eocene as West Sulawesi rifted away from Kalimantan with the development of oceanic crust in the Makassar Straits (fig. G3).

2. A middle Miocene to early Pliocene volcanic arc developed over a west dipping subduction zone. Western Sulawesi formed an island arc east of its present position accompanied by andesitic volcanism and diorite to granodiorite intrusions.

3. Displacement of the arc system over the Makassar Straits and Celebes Sea occurred in response to collision of the Banggai-Sula continental fragment of the Australian Plate (fig. G3) with the Sulawesi Arc (Carlile and others, 1990). This collision and displacement resulted in Pliocene to Pleistocene uplift of the composite arc system. Rapid erosion associated with this uplift exposed many of the Cretaceous to Paleocene intrusions at depth levels greater than depths at which porphyry copper deposits are likely to occur.

Geologic Criteria

Based on local geologic history, including tectonics, uplift, and erosion, porphyry copper deposits in the tract are likely to be restricted to Miocene to Pliocene igneous rocks in this magmatic arc. Nearby porphyry copper deposits in the western part of the adjacent North Sulawesi-Sangihe tract, including Tombuliato and Tapadaa, are dated at 3 and 3.75 Ma, respectively (van Leeuwen, 1994). These deposits are thought to have formed in an island-arc setting above two opposed subduction zones, in contrast to the continental-arc setting of the West Sulawesi tract (van Leeuwen, 1994). The Malala low-fluorine molybdenum deposit located in the northern part of the West Sulawesi tract is associated with intrusions dated at about 4 Ma. Malala is interpreted to have formed in a postsubduction continental-arc setting following the collision of several continental microplates with Sulawesi (tectonic event 3, above; van Leeuwen and others, 1994).

The geologic units that define the permissive tract are calc-alkaline and potassic calc-alkaline to alkaline igneous rocks of Miocene to Pliocene age. Some igneous-rock map units of uncertain Tertiary age, that span this age range but may be as old as Eocene, have been included in the tract. Most of the plutonic rocks that crop out within the tract are numerous small bodies of diorite-granodiorite (some porphyritic) and a few granite-granodiorite bodies in the calc-alkaline rock series, and bodies of monzonite (map unit Tgr), monzodiorite, and syenite (monzodiorite and syenite not shown at map scale) and leucite-bearing volcanic rocks (map unit Tma) in the potassic calc-alkaline and alkaline rock series (table G2). The distribution of permissive intrusive and volcanic rocks is shown in figure G3.

Calc-alkaline volcanic rocks are considered permissive for porphyry copper deposits as they are localized near and often overlie intrusive centers that may host porphyry deposits and may include small unmapped intrusive bodies within their borders. The volcanic rocks that define the tract include andesite flows and tuffs, dacite and associated dacitic tuffs and breccias, and basalt flows (table G2). Mid-Tertiary basalt and basalt-dike complexes (oceanic crust), bimodal rhyolite-basalt sequences, and andesitic tuffs that are primarily within marine carbonate rocks (fringing reefs bordering the oceanic islands) or clastic sedimentary rocks have not been used to define the tract but are incorporated locally in the tract because of proximity to other permissive rock units. These basaltic dike complexes and the distal volcanic deposits in carbonates and sediments are interpreted to be part of the accretionary-wedge complex and their sites of deposition were not likely to be near the intrusive centers that host porphyry copper deposits. A K-calc-alkaline intrusive and volcanic province occurs in the northern part of the West Sulawesi tract, and a K-alkaline-shoshonitic volcanic province occurs in the southern part of the tract (Soeria-Atmadja and others, 1999), possibly in a back-arc tectonic setting (Taylor and van Leeuwen, 1980) or postsubduction magmatic-arc setting (Soeria-Atmadja and others, 1999).

Data used to construct the tract included 1:1,000,000-scale geology and local and regional mineral occurrence databases (Directorate of Mineral Resources and Inventory, 2004a,b) and 1:250,000-scale published geologic maps (table G2) to identify areas of permissive rock types, based on the map legend attribute information describing map unit rock types, composition, and age. The 1:250,000-scale maps were scanned and rectified and the areas of permissive rock units were digitized by hand to supplement the partial digital geology coverage at 1:1,000,000-scale provided by the Indonesian Directorate of Mineral Resources and Inventory (2004a). This enhanced GIS file was used to define the permissive tract. After choosing the polygons and groups of polygons that represent the surface expressions of permissive igneous intrusions, a 10-km buffer was applied to account for a spatial uncertainty of approximately 2 km in the digitized geology and deposit location data and the possibility that deposits may be associated with intrusions that expand beneath their surface expression and are also less than 1 kilometer beneath the land surface. A 2-km buffer was applied around the permissive volcanic units, as these may be imprecisely located and partly covered.

A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise

Table G2. Map units that define tract 142pCu7026, West Sulawesi—Indonesia.

[Map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Lithology	Age range
	Intrusive rocks	
d, di	Diorite	Late Miocene
gd	Granodiorite	Early Miocene
gr	Granite, granodiorite	Miocene
Tdi	Diorite	Middle Miocene
Tgr	Granite, monzonite	Eocene to Oligocene
Tmpg	Granite	Pliocene
Tmpi	Granite, granodiorite, diorite	Middle Miocene to Pliocene
Tpkg	Granite, granodiorite	Pliocene
	Volcanic rocks	
t	Trachyte or andesite	Pliocene
Tan	Andesite	Middle to late Miocene
Tma	Leucite-basaltic tuff	Middle to late Miocene
Tmav	Volcanic tuff	Late-middle Miocene
Tmb	Volcanic tuff	Middle Miocene
Tmcv	Volcanic breccia	Pliocene to late Miocene
Tmkv	Lava	Middle Miocene
Tml	Andesite	Middle to late Miocene
Tmpv	Basalt, andesite	Pliocene to late Miocene
Tmrt	Volcanic tuff	Early to middle Miocene
Tmtv	Andesite, basalt	Middle Miocene to Pliocene
Tolv	Andesite, basalt	Oligocene
Tomk	Andesite, basalt	Early Miocene
Toml	Andesitic-basaltic tuff	Oligocene
Tpbc	Eruptive center	Pliocene
Tpbl	Lava	Pliocene
Tpbv	Lava	Pliocene
Tplv	Andesite, basalt	Eocene to Pliocene
Tppl	Trachyte	Pliocene
Tppv	Trachyte, andesite	Pliocene

the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified polygons using an algorithm (PAEK, polynomial approximation with exponential kernel)with a tolerance of 20 km. Necking, thinning, and contraction of the polygons resulting from processing required a subsequent manual cleaning step (for example, to remove polygon necks). Final tract boundaries were compared to the permissive geologic features in source materials to ensure that original permissive boundaries were honored. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

These revised preliminary-tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks or sedimentary deposits are greater than 1 km in thickness. As a last step, the tract boundary was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The West Sulawesi tract encompasses the western part of Sulawesi Island. The tract includes the southern Miocene to Pliocene portion of the 1,200-km-long North Sulawesi-Sangihe magmatic arc located in the southwestern part of Sulawesi, bounded by the coast of Sulawesi along the west and south boundary of the tract; the extent of Miocene to Pliocene volcanic and intrusive rocks define the eastern boundary, and the northern border of the West Sulawesi tract is delineated by a set of northwest-striking faults that follow a rotation hingeline extending from the intersection of the north Sulawesi Trench with regional Palu-Koro Fault Zone (fig. G3; Walpersdorf and others, 1998). Neogene plate motions, magma chemistry types, and the migration trend of volcanism differs across this rotation hingeline that delineates the West Sulawesi tract from the North Sulawesi tract (142pCu7027). Potassic calc-alkaline volcanism is restricted to the West Sulawesi tract (Walpersdorf and others, 1998).

The West Sulawesi tract defines an area where the estimated number of undiscovered deposits was expected to be significantly different than in the adjacent North Sulawesi tract because of differences in the geology, plate-tectonic settings, extent and depth of cover, number of known prospects and deposits, and thoroughness of exploration. A number of gold and base-metal occurrences and prospects associated with Tertiary intrusive and volcanic rocks, including volcanogenic massive sulfide deposits, are located in the West Sulawesi tract (Djaswadi, 1993). A few national parks and nature reserves are located in the tract.

Known Deposits

No porphyry copper deposits are known to be present in the West Sulawesi tract, however the tract does contain the Malala porphyry molybdenum deposit (dated at 4.14 Ma) in the northern part of the tract. The Malala deposit is a low-fluorine molybdenum-rich porphyry system in quartz monzonite in a composite Miocene to Pliocene granite-quartz monzonite-granodiorite batholith (Soeria-Atmadja and others, 1999). The Malala deposit contains 100 Mt of ore resources at 0.14 percent MoS_2. The molybdenum mineralization is associated with a late-stage quartz monzonite stock in the roof zone of a composite pluton emplaced during an arc-continent collision magmatic event in the late Miocene to Pliocene (Taylor and van Leeuwen, 1980).

Prospects, Mineral Occurrences, and Related Deposit Types

The Sassak prospect (table G3) lies in the central part of the tract associated with an intrusive complex of shoshonitic affinity (Soeria-Atmadja and others, 1999). Although gold grades are not reported for the prospect, Sassak was identified as a Cu-Au porphyry deposit by Soerai-Atmadja and others (1999) and Singer and others (2008). The porphyry-style mineralization at Sassak occurs in a series of small Miocene (10.6 Ma) alkaline stocks, including monzodiorite, monzonite, and syenite, that are satellite intrusions near the southern margin of the Mamasa monzonite batholith (Soeria-Atmadja and others, 1999). These stocks intruded early Miocene andesitic lavas and breccias. Porphyry-style mineralization probably occurred at about the time of emplacement of a series of northeast-trending intermediate and alkaline dikes. The prospect has little economic significance because of its small size and low grade (Taylor and van Leeuwen, 1980). Near Sassak, occurrences of gold-base metal vein and gold-bearing quartz veins are widespread along the northern margin of the Mamasa batholith (Soeria-Atmadja and others, 1999).

The medium-sized gold deposit at Awak, in the middle of the tract, occurs in quartz veins, breccias, and stockworks emplaced along a series of shallow-dipping shear zones in Cretaceous metamorphic rocks (fig. G3; Sillitoe, 1995). Additional base-metal and copper occurrences lie in the northern and southern parts of the tract.

Exploration History

There was regional- and prospect-scale exploration by the Dutch in the colonial period between the 1840s and 1930s and deposit-scale exploration around mines and occurrences that began in the 1960s and continued episodically through the 1990s (van Leeuwen, 1994). Exploration geochemistry and mapping in the late 1960s through 1970s was initiated in Sulawesi based on recognition of widespread Tertiary calc-alkaline rocks in an island-arc or continental-arc setting, a few known copper occurrences, and the possibility that the porphyry copper districts in the Philippines might extend southward into Sulawesi. The Sassak porphyry prospect was discovered during the late 1960s during a reconnaissance geological survey of West Sulawesi by geologists of the Geological Survey of Indonesia. Stream-sediment sampling and trenching was used to delineate the prospect area followed by a detailed mapping and drilling program in the 1970s. Exploration activity in the region was mostly by RTZ, Kennecott, and Newmont joined by other junior exploration companies based in the Southeast Asia region, such as Tropic Endeavour Indonesia (TEI) (van Leeuwen, 1994).

Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7026 are listed in table G4.

Grade and Tonnage Model Selection

The porphyry Cu-Au subtype model (Singer and others, 2008) was selected to assess the undiscovered resources associated with porphyry copper deposits in the West Sulawesi tract (table 6). The model selection for the tract is based on the geological, mineralogical, and geochemical features of

Table G3. Significant prospects and occurrences in tract 142pCu7026, West Sulawesi—Indonesia.

[Ma, million years; %, percent]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference
Sassak	–3.158	119.48	10.6	Explored 1969–1976. 0.1 to 0.6% Cu reported. Prospect has little economic significance.	Djaswadi (1993), Taylor and van Leeuwan (1980)

Table G4. Principal sources of information used for tract 142pCu7026, West Sulawesi—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of Indonesia	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Systematic geologic map, Indonesia	1:250,000	Geological Research and Development Centre (1987–2000)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)

the Sassak prospect, which is considered a porphyry Cu-Au deposit type by Soeria-Atmadja and others (1999) and Singer and others (2008), the gold-rich nature of the related epithermal systems in the tract area, and the K-alkaline nature of the intrusive and volcanic rocks in the tract area.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The numbers of undiscovered porphyry copper deposits in West Sulawesi tract were estimated at 90, 50, 10, and 5 probability percentiles in February 2010 on the basis of subjective estimation (table G5). The method of estimation was based on expert opinion and on analogy with geologically similar areas the in other regions of Southeast Asia and the world with which the team was familiar.

The estimate results in a mean of 1.1 expected undiscovered deposits yielding an estimated density of 1.8 porphyry copper deposits/100,000 km^2. Considerations that influenced the estimate were the presence of several centers of gold and copper occurrences throughout the tract, including the Awak gold deposit and gold-copper occurrences north of the Mamasa batholith. There was discussion about the significance of the Sassak prospect, with the conclusion that it is likely to be a porphyry copper-gold system, but is of little economic significance because of its small size. A small number of mineral occurrences in the tract are compatible with the porphyry copper-gold models and rocks types, such as diorite, granodiorite, and monzonite. These calc-alkaline to alkaline intrusive rocks are considered potential host rocks for porphyry copper-gold deposits; however, significant porphyry copper prospects are lacking in the tract. Cessation of westward dipping subduction under the tract in the late Miocene followed by extensive uplift and erosion during the Pliocene to Pleistocene in the tract may limit the likelihood of undiscovered porphyry copper deposits. The tract may have some potential for porphyry copper-gold deposits formed in a postsubduction setting (Richards, 2009); postsubduction tectonics may have stimulated the generation of the Pliocene potassic calc-alkaline to alkaline igneous rocks in the tract (Soeria-Atmadja and others, 1999). A postsubduction tectonic setting is postulated for the Pliocene Malala molybdenum porphyry deposit located in the northern part of the tract (van Leeuwen and others, 1994). The uncertainty associated with the assessment results for this tract reflects the uncertain porphyry potential in the tract with subduction probably ending around or slightly before the Pliocene, rapid post-Pliocene uplift and erosion, large areas of intrusions lacking associated volcanic rocks in the northern half of the tract, and the potential that a portion of these intrusive rocks in the north are collision-related rather than subduction related. The team did not apply the deposit

Table G5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7026, West Sulawesi—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und} expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}; total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed]

Consensus undiscovered deposit estimates						Summary statistics				Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
0	1	2	3	3	1.1	0.98	91	0	1.1	60,270	1.8

Table G6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7026, West Sulawesi—Indonesia.

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	650,000	7,900,000	15,000,000	3,400,000	0.21	0.3
Mo	0	0	0	33,000	81,000	19,000	0.14	0.68
Au	0	0	66	610	1,100	240	0.24	0.3
Ag	0	0	0	2,000	4,300	1,100	0.15	0.59
Rock	0	0	150	1,600	3,200	680	0.22	0.3

density models of Singer and others (2005) directly during the assessment; however, the estimate of 1.8 deposits/100,000 km^2 is low compared to the observed deposit-density range reported by them. This is consistent with the assessment team's evaluation that this relatively well-explored tract is not likely to be highly prospective for undiscovered porphyry copper-gold or porphyry copper deposits.

Probabilistic Assessment Simulation Results

Undiscovered resources for the West Sulawesi permissive tract 142pCu7026 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits (table G5) with the copper-gold subtype grade and tonnage model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table G6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. G4). The cumulative frequency plot shows the estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

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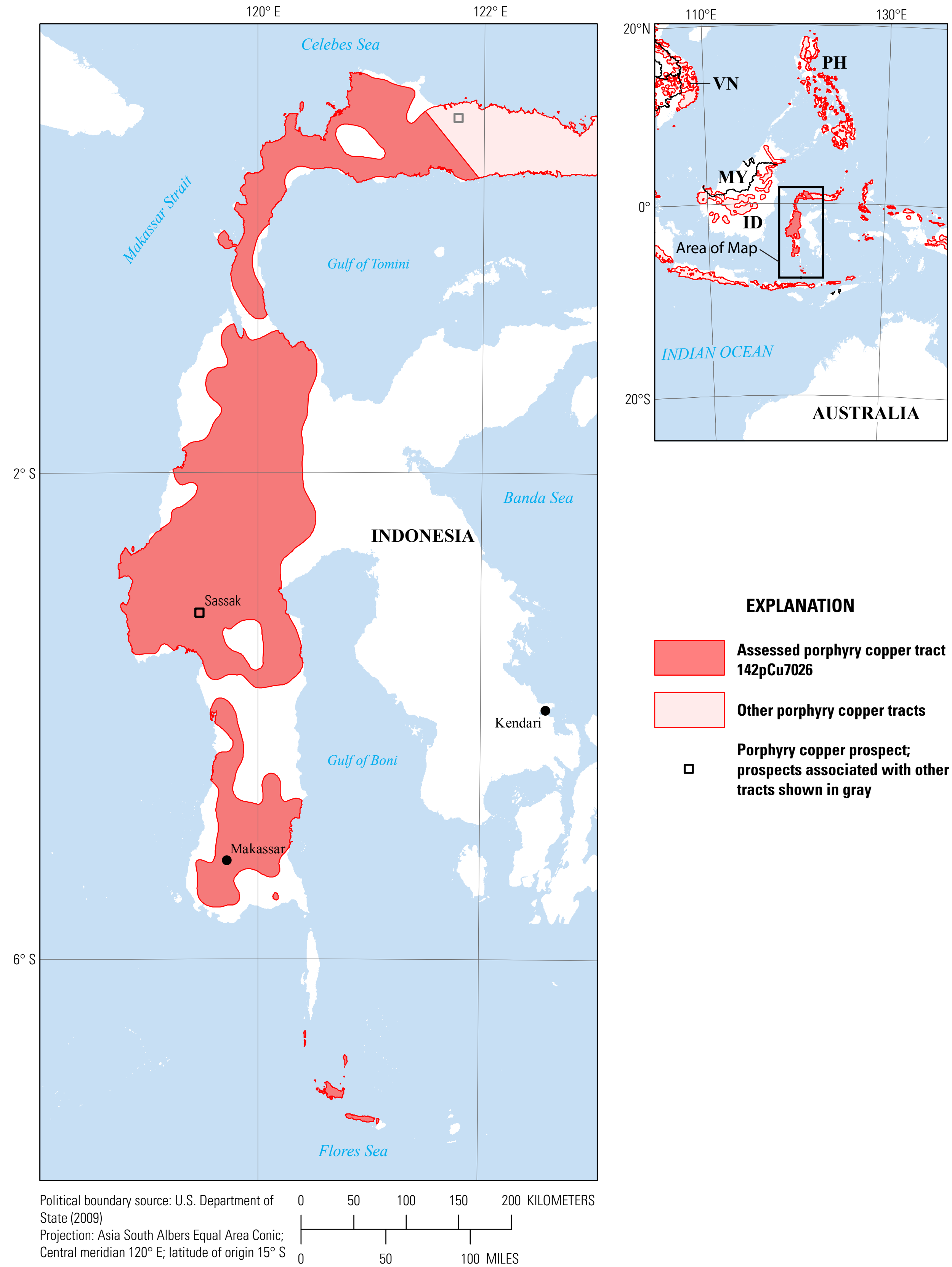

Figure G1. Map showing tract location and significant porphyry copper prospects for tract 142pCu7026, West Sulawesi—Indonesia. ID, Indonesia; MY, Malaysia; PH, Philippines; VN, Vietnam.

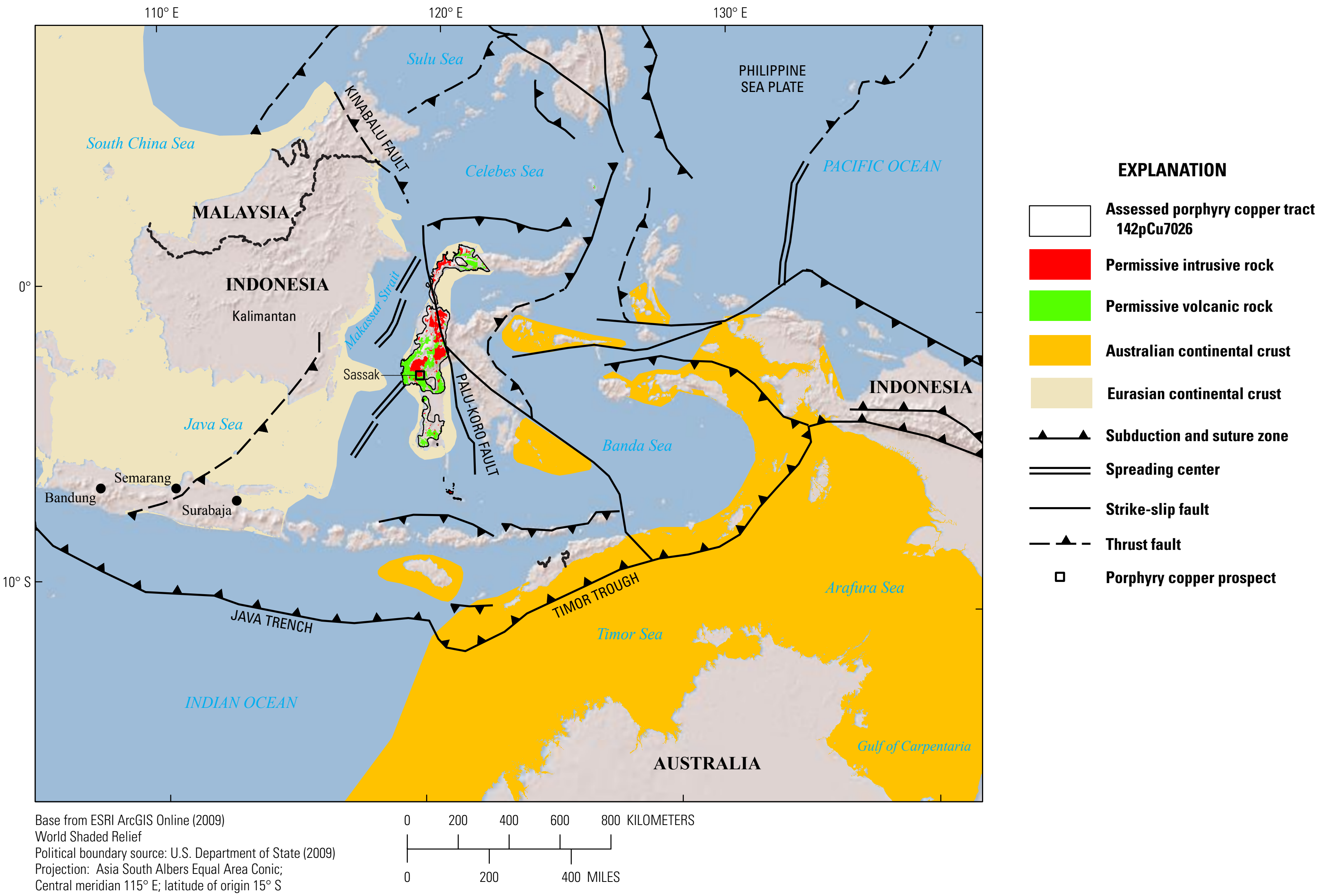

Figure G2. Map showing the regional setting for tract 142pCu7026, West Sulawesi—Indonesia.

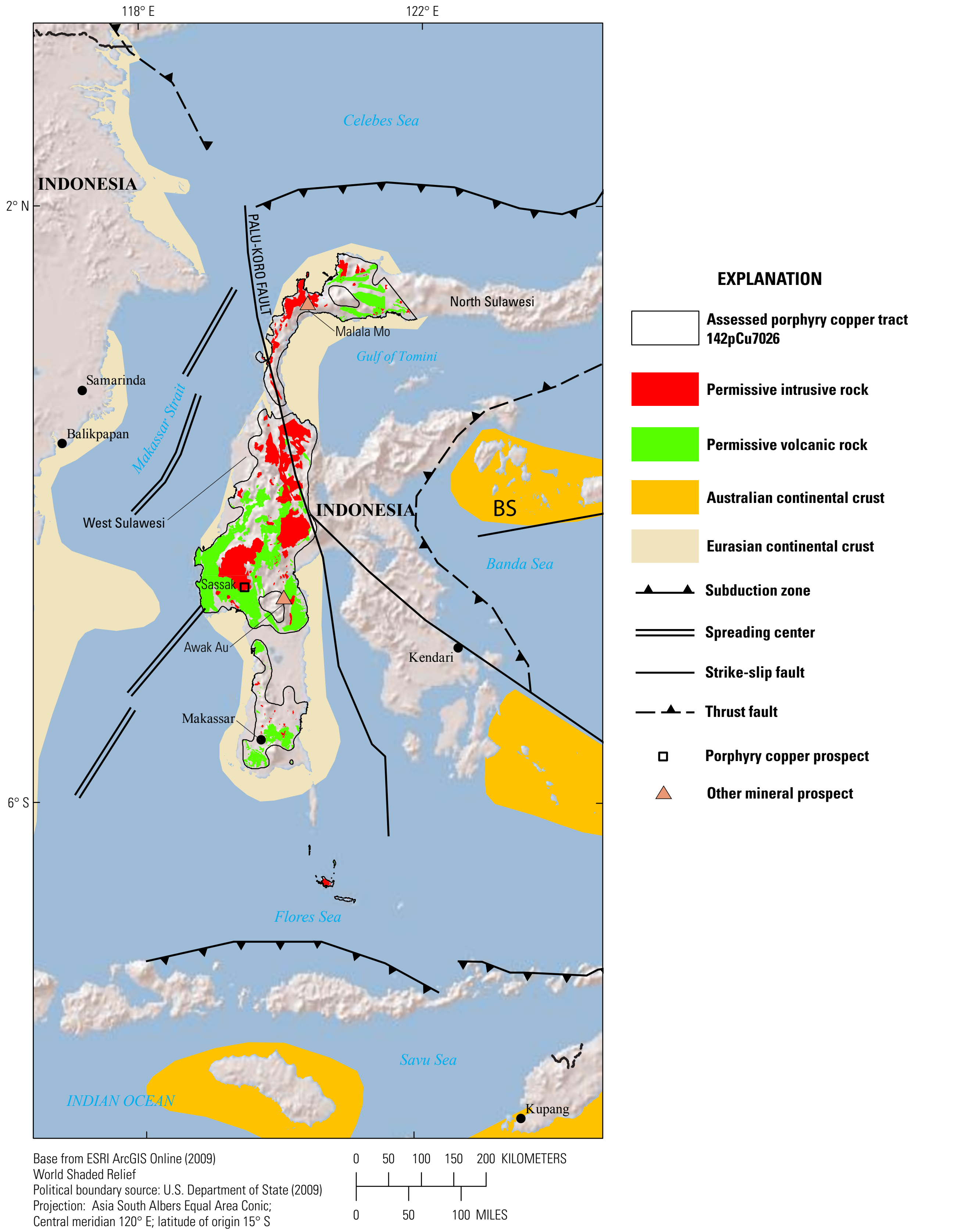

Figure G3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper prospects for tract 142pCu7026, West Sulawesi—Indonesia. BS, Banggai-Sulu continental fragment.

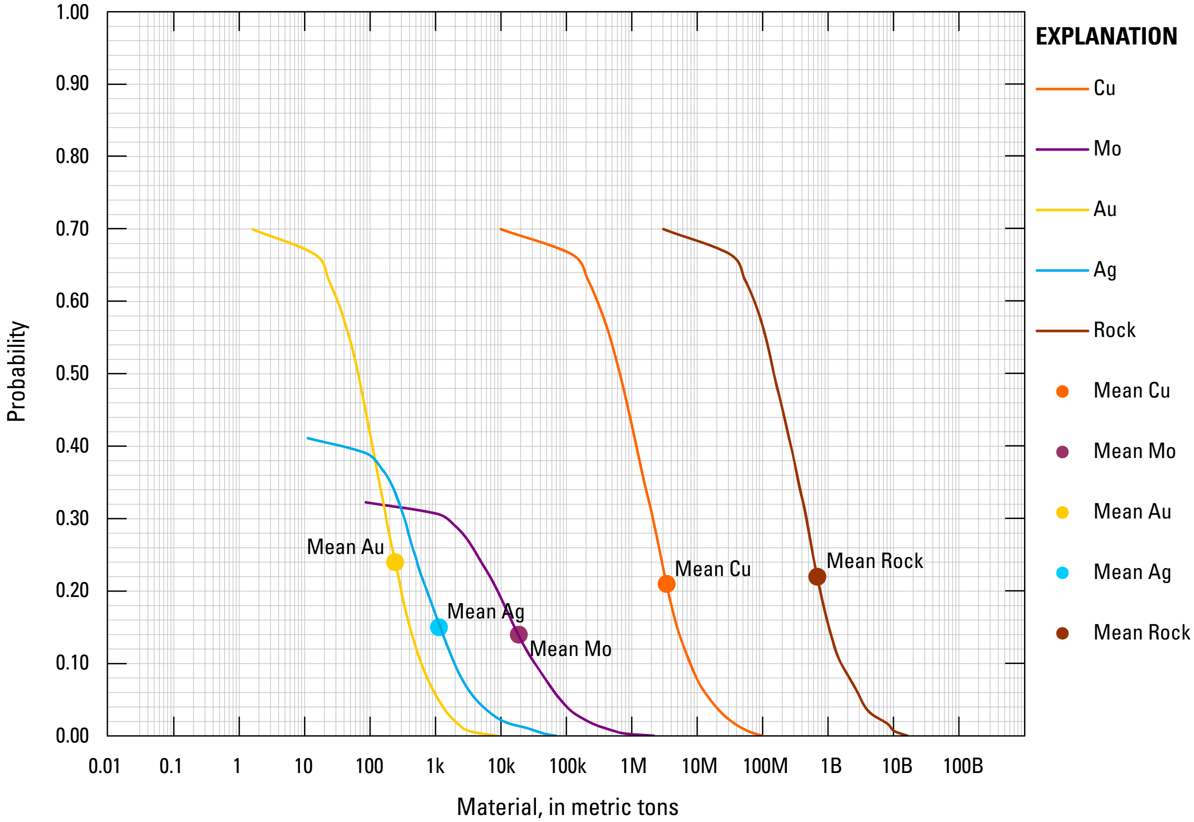

Figure G4. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7026, West Sulawesi—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix H. Porphyry Copper Assessment for Tract 142pCu7027, North Sulawesi-Sangihe—Indonesia

By Gilpin R. Robinson, Jr.[1], Bambang Tjahjono Setiabudi[2], Dwi Nugroho Sunuhadi[2], Jane M. Hammarstrom[1], Steve Ludington[3], Arthur A. Bookstrom[4], Sewit A. Yenie[1], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010), Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table H1 summarized selected assessment results.

Table H1. Summary of selected resource assessment results for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	20,330	2,040,300	8,900,000	3,800,000

Location

The tract includes almost all of North Sulawesi (areas not included in tract 142pCu7026) and the southeastern part of Sangihe Island (fig. H1).

Geologic Feature Assessed

This tract includes the Miocene to Pliocene volcanic- and intrusive-rock part of the North Sulawesi-Sangihe magmatic arc.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Directorate of Mineral Resources Inventory, Geological Agency of Indonesia, Bandung, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S. Geological Survey, Spokane, Washington, United States.
[5]Geologic Survey of Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

The North Sulawesi magmatic arc is part of the 1,200-km-long North Sulawesi-Sangihe magmatic arc, which has been active since the Eocene. The porphyry copper deposits in North Sulawesi are late Miocene to Pliocene in age. They formed in an island-arc setting developed on oceanic crust above two opposing subduction zones that formed as a result of northward displacement of Sulawesi over a developing south-dipping subduction zone in the Celebes Sea that initiated in response to late Tertiary interaction of the Australian and Pacific Plates (Carlile and others, 1990; Kavalieris and others, 1992; Perello, 1994). The regional geologic and tectonic setting of the tract is shown in figure H2 and is described in more detail below.

The North Sulawesi magmatic arc is an island-arc complex developed on Cretaceous to Paleogene oceanic crust (Carlile and others, 1990). It developed during multistage and multidirectional subduction from the Eocene to present (Kavalieris and others, 1992; Hall, 1996, 2002; Pearson and Caira, 1999; Simandjuntak and Barber, 1999) in the complex convergence zone of the Eurasian, Pacific, and Australian Plates (Carlile and others, 1990). Collision of the Banggai-Sula continental crust fragment of the Australian Plate with Sulawesi displaced Sulawesi westward resulting in the 90 degree clockwise rotation of the North Arm to its present east-west orientation and displacement of the North Sulawesi Arc northward over the Celebes Sea (fig. H2; Carlile and others, 1990; Walpersdorf and others, 1998). This westward displacement and rotation of the volcanic arc developed a series of extensional basins; volcanism tends to young progressively eastward along the North Arm of Sulawesi toward the Sangihe Trench that is the locus of Holocene volcanism (Carlile and others, 1990). Formation of the calc-alkaline volcanic rocks, porphyritic diorite intrusions, and related porphyry copper deposits, occurred during magmatic-arc activity from 11 to 2.5 Ma that has been related to the subduction of oceanic-rise microplates under North Sulawesi along the Sulawesi and Sangihe Troughs. Displacement of the arc system over the Celebes Sea has resulted in Pliocene to Pleistocene uplift of the composite-arc system. Rapid erosion associated with this uplift (Kavalieris and others, 1992; Perello, 1994) exposed many of the Paleogene to early Miocene intrusions at depths greater than depths at which porphyry copper deposits are likely to occur.

Geologic Criteria

The geologic units that define the permissive tract are calc-alkaline igneous rocks of Miocene to Pliocene age (fig. H3). Some igneous-rock map units of uncertain Tertiary age, that span this age range but may be as old as Paleogene, have been included in the tract. Most of the plutonic rocks that crop out within the tract are numerous small bodies of Miocene to Pliocene diorite, quartz diorite, granodiorite, and granite (table H2).

Calc-alkaline volcanic rocks are considered permissive for porphyry copper deposits as they are localized near and often overlie intrusive centers that may host porphyry deposits and may include small, unmapped intrusive bodies within their borders. The volcanic rocks that define the tract are late Tertiary andesite flows and pyroclastics, andesite, lapilli tuff, trachyandesite, andesite porphyry, volcanic breccia, dacite, and basalt (table H2). Tertiary bimodal rhyolite-basalt sequences and andesitic tuffs that are primarily within marine carbonate rocks (fringing reefs bordering the oceanic islands) or clastic sedimentary rocks were not used to define the tract but are incorporated locally in the tract based on proximity to other permissive rock units. These distal volcanic deposits in carbonates and sediments are interpreted to be part of the accretionary-wedge complex, and their sites of deposition were not likely to be near the intrusive centers that host porphyry copper deposits (Taylor and van Leeuwen, 1980).

Data used to construct the tract include 1:1,000,000-scale geology (Directorate of Mineral Resources and Inventory, 2004a) and published 1:250,000-scale geologic maps (table H2) to identify areas of permissive rock types, based on the map legend attribute information describing map unit rock types, composition, and age. The regional mineral occurrence database (Directorate of Mineral Resources and Inventory, 2004b) was used to evaluate how the distribution of mineral occurrences corresponded to the prototract area. The 1:250,000-scale maps were scanned and rectified, and the areas of permissive rock units were digitized by hand to supplement the partial digital geology coverage at 1:1,000,000-scale provided by the Indonesian Directorate of Mineral Resources (2004a). This enhanced GIS file was used to define the permissive tract. After choosing the polygons and groups of polygons that represent the surface expressions of permissive igneous intrusions, we applied a 10-km buffer around them to account for a spatial uncertainty of approximately 2 km in the digitized geology and deposit location data and the possibility that deposits may be associated with intrusions that expand beneath their surface expression and are also less than 1 km beneath the land surface. A 2-km buffer was applied around the permissive volcanic units, as these may be imprecisely located and partly covered.

A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified

Table H2. Map units that define tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[Map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Age range	Rock types
	Intrusive rocks	
gd	Miocene	Granodiorite
gr	Miocene	Granite
Tmb	Early to middle Miocene	Diorite, quartz diorite
Tmbo	Miocene	Diorite, granodiorite
Tpb	Pliocene	Granodiorite, granite
QTi(d)	Pliocene to Pleistocene	Diorite
	Volcanic rocks	
Tmv	Miocene	Andesite, basalt
Tmvl	Miocene	Andesite, basalt
Tppv	Pliocene	Dacite, andesite
Tpwv	Pliocene	Andesite, basalt
tr	Miocene	Trachyte
Ttv	Miocene	Volcanic breccia
Tnbv	Miocene to Pliocene	Volcanics
QTi(a)	Pliocene to Pleistocene	Andesite

polygons using an algorithm (PAEK, polynomial approximation with exponential kernel) with a tolerance of 20 km. Necking, thinning, and contraction of the polygons resulting from processing required a subsequent manual cleaning step (for example, to remove polygon necks). Final tract boundaries were compared to the permissive geologic features in source materials to ensure that original permissive boundaries were honored. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

These revised preliminary-tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks or sedimentary deposits are greater than 1 km in thickness. As a last step, the tract boundary was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The outer boundary of the tract largely follows the coast line of the island chain in North Sulawesi and extends to the north to the island of Sangihe. The western border of the North Sulawesi tract is delineated by a set of northwest-striking regional faults that follow a rotation hingeline extending from the intersection of the north Sulawesi Trench with regional Palu-Koro Fault Zone (fig. H2; Walpersdorf and others, 1998). This fault zone marks the transition from dominantly Eurasian continental-crust basement to the west to dominantly oceanic crust to the east underlying the volcanic-arc system (fig. H2; Carlile and others, 1990). Neogene plate motions and the migration trend of volcanism differ across this rotation hingeline that delineates the North Sulawesi tract from the West Sulawesi tract. The eastern border of the tract is delineated by Quaternary stratovolcanoes, some active, along the eastern tip of North Sulawesi (Hall, 2002; Kavalieris and others, 1992; Simandjuntak and Barber, 1999). Much of the tract is covered with Quaternary and Neogene sedimentary and volcanic rocks. The North Sulawesi tract contains a number of national parks and nature reserves.

Known Deposits

Two porphyry copper-gold deposits with identified resources lie in the south-central part of the North Sulawesi tract (table H3). They are the Tapadaa (3.75 Ma, containing estimated resources of 43 Mt at 0.54 percent copper and 0.075 g/t gold) and Tombulilato (3.0 Ma, containing estimated resources of 287 Mt at 0.63 percent copper and 0.47 g/t gold) deposits, which include the Cabang Kiri East (132 Mt), Sungai Mak (82 Mt), and Kayubulan Ridge (73 Mt) deposits (Singer and others, 2008). The primary copper mineralization at the Tapadaa and Tombulilato deposits occurs in small high-level quartz diorite bodies with local supergene enrichment (Lowder and Dow, 1976, 1978). The Tapadaa deposits are localized within northwest-striking structurally controlled blocks in a

Table H3. Identified porphyry copper resources in tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Tapadaa	0.517	123.21	NA	3.75	43	0.54	n.d.	0.075	n.d.	232,200	Singer and others (2008), Djaswadi (1993), Lowder and Dow (1976), Lowder and Dow (1978), Taylor and van Leeuwan (1980),van Leeuwen (1994)
Tombuli-lato	0.345	123.4	Cu-Au	3	287	0.63	n.d.	0.47	n.d.	1,808,100	Singer and others (2008), Carlile and Kirkegaard (1985), Carlile and others (1990), Djaswadi (1993), Lowder and Dow (1978), Pearson and Caira (1999), Perello (1994)

Table H4. Significant prospects and occurrences in tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[Ma, million years; %, percent; n.d., no data]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference
Bulagidun	0.952	121.77	8.75	14.4 Mt at 0.61% Cu and 0.68 g/t Au; ≤0.2% Mo reported.	Carlile and others (1990), Djaswadi (1993), Lubis and others (1994), Pearson and Caira (1999), Taylor and van Leeuwan (1980)
Sangihe	3.433	125.567	n.d.	Includes Bawone prospect.	East Asia Minerals Corporation (2010)

few small multistage intrusions of quartz diorite of Pliocene age (van Leeuwen, 1994).

At Tombulilato, eight mineralized intrusive bodies of quartz diorites to dacite porphyries of late Pliocene age occur within an area of 20 km^2 (van Leeuwen, 1994). Ore-grade mineralization occurs in both argillic and advanced argillic alteration. The intrusions vary from cylindrical stocks to dikes and subhorizontal sills, often with hydrothermal breccias, emplaced into volcanic rocks (Lowder and Dow, 1978). The Tombulilato district was included in a national park in 1991.

Prospects, Mineral Occurrences, and Related Deposit Types

The Bulagidun porphyry prospect, in the northwestern corner of the tract, was discovered in 1987 by BHP-Utah (table H4). The copper-gold mineralization at Bulagidun occurs in breccia bodies that border a potassically altered diorite to quartz-diorite stock intruded into andesitic volcanic rocks dated at 9.4 Ma. The mineralization at Bulagidun differs from the other porphyry deposits in North Sulawesi by being slightly older, and it is hosted exclusively in breccias with tourmaline and potassium feldspar alteration. Trenching, soil and rock sampling, and exploratory drilling identified inferred resources of 14.4 Mt at 0.61 percent copper and 0.68 g/t gold (van Leeuwen, 1994). Bulagidun is not considered a known deposit as resources are likely open at depth (Singer and others, 2008).

The tract contains several epithermal gold deposits and sediment-hosted gold deposits that may have an association with porphyry systems. A number of epithermal gold occurrences in the Pani volcanic complex (Kavaleris and others, 1990) are south of Bulagidun near the southwestern corner of the tract. Several epithermal gold deposits lie in the northeastern part of the tract on Sangihe Island. The Sangihe prospect is hosted by diorite and andesite plugs that have intruded a sequence of andesite flows and minor associated volcani-

Table H5. Principal sources of information used for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of Indonesia	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Systematic geologic map, Indonesia	1:250,000	Geological Research and Development Centre (1987–2000)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)

clastic rocks that emanated from the Taware volcano in the southeastern part of Sangihe Island (table H4). Xenoliths of gabbro and diorite in the andesites suggest that mafic oceanic basement underlies the island. Epithermal gold mineralization exploration targets (both high- and low-sulfidation types) in volcanic rocks are related to copper and gold-bearing quartz-vein stockworks associated with a diorite stock in andesitic volcanic rocks. Porphyry-copper-style mineralization occurs within the diorite stock and andesite with stockwork-vein systems, potassic alteration (biotite-magnetite) at depth grading upwards into phyllic (sericite) alteration, and late quartz-carbonate veins (Carlile and others, 1990). Although the exploration program is focused on epithermal gold deposits, the intrusion-hosted stockwork, outcrops of porphyry copper mineralization on Taware Ridge (Carlile and others, 1990), porphyry-style alteration, association of gold mineralization with magnetic lows at depth, and drill-core results all indicate potential for porphyry copper-gold mineralization at the prospect (East Asia Minerals Corporation, 2010).

Exploration History

There was regional- and prospect-scale exploration by the Dutch in the colonial period from the 1860s through the 1930s and deposit-scale exploration around mines and occurrences that began in the 1960s and continued episodically through the 1990s (van Leeuwen, 1994). Exploration geochemistry and mapping in the late 1960s through 1970s was initiated in North Sulawesi based on recognition of widespread Tertiary calc-alkaline rocks in an island-arc setting, a few known copper occurrences, and the possibility that the porphyry copper districts in the Philippines might extend southward into Sulawesi. The tract area is thoroughly explored on a district, regional, and deposit scale. The Tapadaa, Tombulilato, and Cabang Kiri deposits were discovered in the early 1970s based on stream-sediment exploration geochemistry followed by geologic mapping, rock geochemistry sampling, and drilling by Kennecott. The Tombulilato district was further explored in the early 1980s by TEI and Utah International that outlined inferred resources of 295 Mt averaging 0.57 percent copper and 0.47 g/t gold in three main mineralized areas (van Leeuwen, 1994). The Bulagidun prospect was discovered in 1987 during an exploration geochemistry-sampling program searching for gold deposits. Exploration by BHP-Utah during the late 1980s followed up on geochemical anomalies identified in the early 1970s. Drilling has taken place at the porphyry copper deposits and occurrences and at the larger gold prospects (Garwin and others, 1995).

Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7027 are listed in table H5.

Grade and Tonnage Model Selection

The porphyry copper-gold subtype model (Singer and others, 2008) was selected to assess the undiscovered resources associated with porphyry copper deposits in the North Sulawesi tract (table 6). The model selection for the tract is based on the ore grade and tonnage characteristics of the Tampakan, Tombulilato, and Tapadaa deposits and Bulagidun prospect, the gold-rich nature of the related epithermal systems in the tract area, and geologic characteristics of the magmatic arc in this area. Based on the gold-grade classification criteria of Singer and others (2008), the Tombulilato deposit and Bulagidun prospect are classified as porphyry copper-gold type deposits. The arc magmatism is developed on oceanic crust in a subduction setting that lacks influence from continental crust or sediments derived from continental crust, and the copper-gold subtype model is judged to be appropriate.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

There has been a high level of exploration dating from the Dutch period (1840s to 1930s) and from the 1960s by private mining companies. The tract area is thoroughly explored on a district, regional, and deposit scale, although areas with Quaternary volcanic or sediment cover are likely to be less well explored. Drilling has taken place at the porphyry copper deposits and occurrences and at the larger gold prospects (Garwin and others, 1995).

The number of undiscovered porphyry copper deposits in the North Sulawesi tract in the 90, 50, and 10 probability percentiles was estimated in February 2010 (table H6). The method of estimation was subjective and based on expert opinion and on analogy with geologically similar areas in other regions of Southeast Asia and the world.

The estimate in the North Sulawesi tract results in a mean of 2.8 expected undiscovered deposits, and when combined with the Tapadaa and Tombolilato deposits, results in a density of 23.5 deposits/100,000 km^2. One consideration used in the estimation processes was that a number of porphyry copper-gold deposits cluster in small areas (Singer and others, 2005), such as the Cabang Kiri East, Sungai Mak, and Kayubulan Ridge deposits, which were included in the grade and tonnage for Tombolilato. In addition, there are a number of epithermal gold occurrences throughout the tract that may have an association with porphyry systems. Sillitoe (1994) speculates that the epithermal gold mineralization in the Pani volcanic complex may be related to a deeper porphyry system. The estimate was based on a high degree of exploration known to have taken place within the tract, with consideration of a possibility that additional deposits might be hidden under the extensive sedimentary and volcanic cover on the island, particularly in the Sangihe area (table H2). The Sangihe prospect, located on the less explored Sangihe Island, is judged to be likely to contain ore grades and tonnages consistent with the porphyry copper-gold deposit subtype model and, together with the incompletely delineated resources at Bulagidun, provides part of the rationale for the a team's estimate of 1 deposit at 90-percent confidence in this otherwise thoroughly explored tract. The team did not apply the deposit density models of Singer and others (2005) directly during the assessment, however the estimate of 23.5 deposits/100,000 km^2 is consistent with, and slightly above, the average of the observed range in their deposit- density model.

Probabilistic Assessment Simulation Results

Undiscovered resources for the North Sulawesi permissive tract 142pCu7027 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits (table H6) with the porphyry coper-gold subtype grade and tonnage model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table H7. Results of the Monte Carlo simulation are presented as a cumulative-frequency plot (fig. H4). The cumulative-frequency plot shows the estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table H6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
1	2	6	6	6	2.8	2	70	2	4.8	20,330	24

Table H7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver, in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	220,000	3,800,000	23,000,000	38,000,000	8,900,000	0.26	0.06
Mo	0	0	4,900	120,000	280,000	51,000	0.21	0.39
Au	0	22	310	1,700	2,600	650	0.3	0.06
Ag	0	0	590	6,000	12,000	2,900	0.19	0.29
Rock	0	52	790	4,900	8,000	1,800	0.28	0.06

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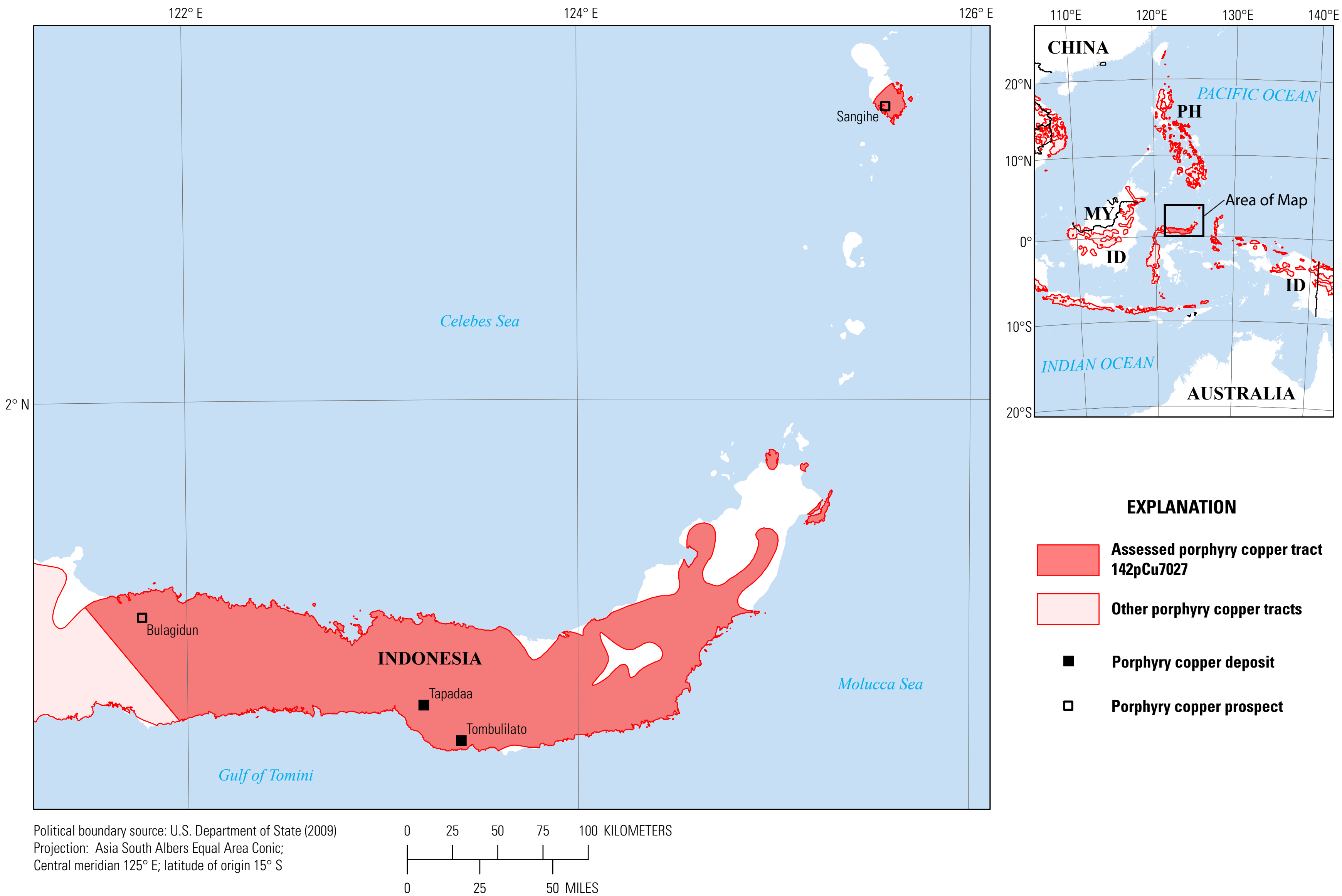

Figure H1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia. ID, Indonesia; MY, Malaysia; PH, Philippines.

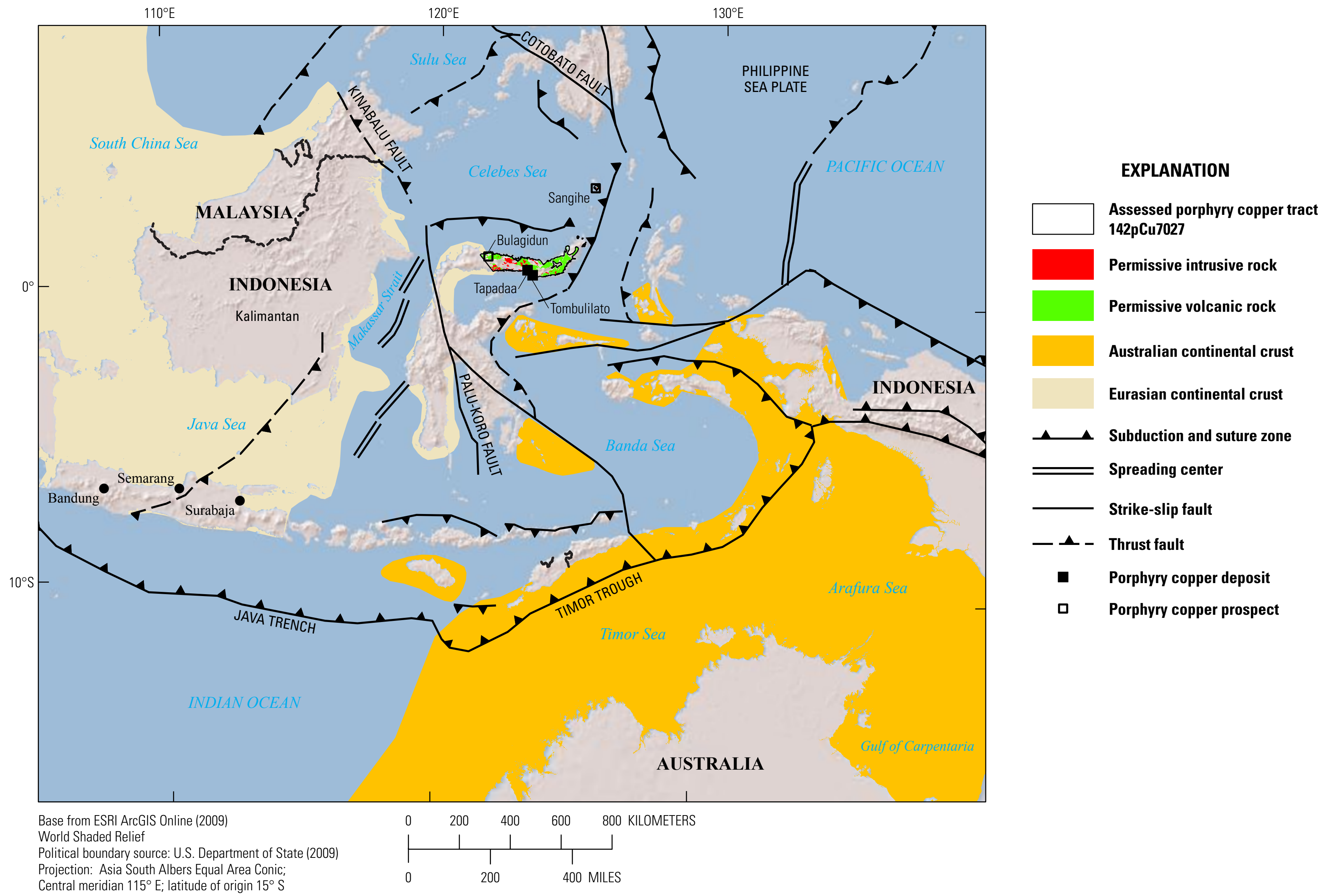

Figure H2. Map showing the regional setting for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

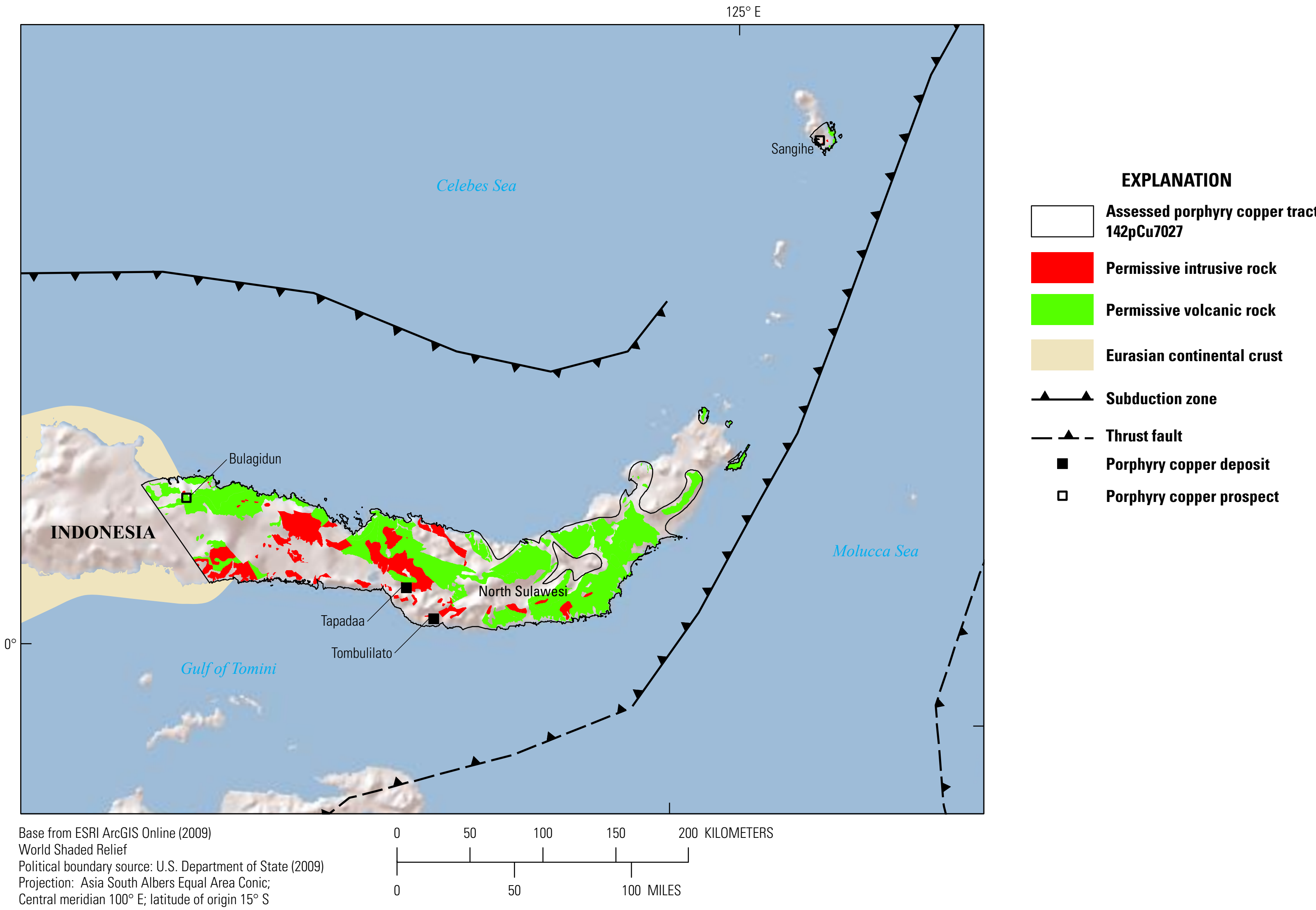

Figure H3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper deposits and prospects for tract 142pCu7027, North Sulawesi-Sangihe—Indonesia.

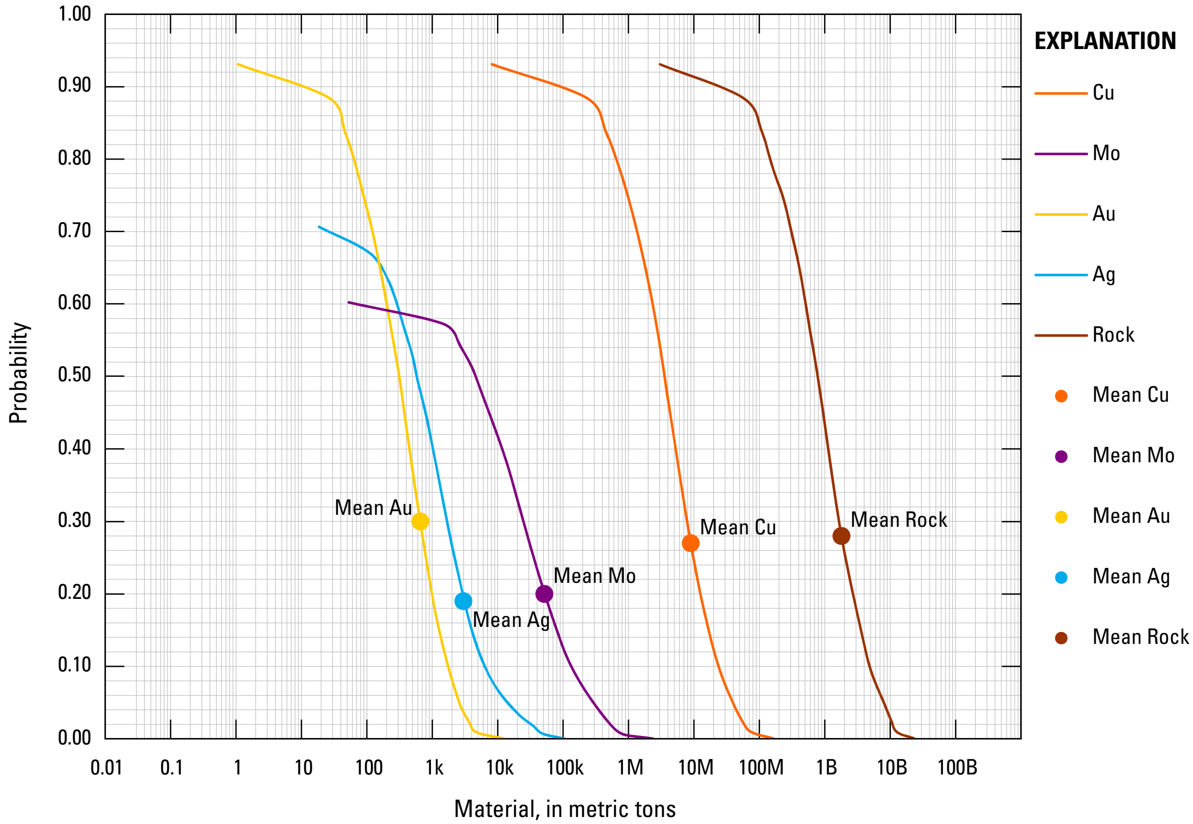

Figure H4. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources 142pCu7027, North Sulawesi-Sangihe—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix I. Porphyry Copper Assessment for Tract 142pCu7019, Central Kalimantan—Indonesia and Sabah and Sarawak, Malaysia

By Gilpin R. Robinson Jr.[1], Alexander Yan Sze Wah[2], Bambang Tjahjono Setiabudi[3], Dwi Nugroho Sunuhadi[3], Jane M. Hammarstrom[1], Steve Ludington[4], Arthur A. Bookstrom[5], Sewit A. Yenie[1], and Michael L. Zientek[5], with contributions from Chen Shick Pei[6] and Gwaibo Kopi[7]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998); Postsubduction porphyry copper-gold (Richards, 2009)
Grade and tonnage model: Porphyry copper, Cu-Au subtype (Singer and others, 2008)
Table I1 summarizes selected assessment results.

Table I1. Summary of selected resource assessment results for tract 142pCu7019, Central Kalimantan—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	144,580	940,800	40,000,000	25,000,000

Location

The tract incorporates several irregular elongated belts that trend from eastern Sabah and northeastern Kalimantan southwards through central to west Kalimantan into Sarawak, generally south of, but roughly parallel to, the Indonesia-Malaysia border in Borneo (fig. I1).

Geologic Feature Assessed

A dispersed belt of Tertiary intermediate intrusive and volcanic rocks that postdate pre-Eocene subduction and deformation, uplift, and erosion of pre-Miocene rocks and continental basement in Kalimantan.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Minerals and Geoscience Department, Sabah, Malaysia.
[3]Directorate of Mineral Resources Inventory, Geological Agency of Indonesia, Bandung, Indonesia.
[4]U.S. Geological Survey, Menlo Park, California, United States.
[5]U.S. Geological Survey, Spokane, Washington, United States.
[6]Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) Technical Secretariat, Bangkok, Thailand.
[7]Geologic Survey of Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

The tract encloses a dispersed belt of late Oligocene to Pliocene intermediate intrusive and volcanic rocks that postdate folding, thrusting, uplift, and erosion of pre-Miocene rocks and continental basement in Kalimantan. The relation of these mid- to late Tertiary intrusive rocks to subduction is unclear, and the tectonic setting for the porphyry copper deposits that occur in this tract likely is related to the postsubduction porphyry copper-gold deposit model described by Richards (2009). The regional geologic and tectonic setting of the tract is shown in figure I2.

Geologic Criteria

The igneous rocks that define the tract occur as a dispersed belt of small-volume erosional remnants of high-level andesitic to trachy-andesitic volcanic centers of late Oligocene to Pliocene age, many of them associated with gold deposits and prospects (fig. I3). These calc-alkaline stocks and volcanic rocks are part of an elongated magmatic belt developed on continental crust that overlaps geographically, and partly overlaps but mostly postdates in time, with widespread uplift and erosion, folding of pre-Miocene sequences, and development of a regional unconformity in Borneo (Hutchison, 2005; Moss and others, 1998). This deformation, uplift, and rapid erosion is interpreted to record collision between the extended passive continental margin of South China that underthrust the northern part of the Eurasian Sundaland continental margin in Borneo and ended Cretaceous to Paleogene subduction of the proto-South China Sea (Hutchison, 2005; Hall and Wilson, 2000). Slab-pull forces, together with plate reorganization and rotation associated with the impact of the Australia Plate with the Philippine Plate to the east, likely drove the South China-Borneo continent-continent collision in the Paleogene (Hall and Wilson, 2000).

The Cretaceous I-type calc-alkaline plutonic and volcanic rocks that occur in the Schwaner Mountains (fig. I3) in West Kalimantan and elsewhere within and bordering the tract are associated with the Cretaceous to Paleocene subduction event (Hutchison, 2005). These rock units have been excluded from the tract as they are associated with an earlier tectonic event. Porphyry copper deposits may have developed during this Cretaceous subduction event, but are unlikely to be preserved in central Kalimantan because of post-intrusion uplift and erosion. Copper and gold mineralization generally is not recognized in these rocks; however, the Ibu porphyry copper prospect in the western part of the tract has an uncertain age and may be related to this older subduction event (Viaene and others, 1981).

The late Oligocene to Pliocene intrusive and volcanic rocks in the tract have calc-alkaline to mildly alkaline chemistry. Some of the calc-alkaline intrusive rocks are low in potassium and enriched in sodium and are classified as adakites (Hutchison, 2005). Adakites are associated with gold mineralization at Bau and other prospects in the tract. In addition, shoshonitic basaltic-andesite volcanic rocks occur at some intrusive centers and host gold mineralization at Muyup and Masupa Ria (Abidin, 1996; Thompson and others, 1994). Although the limited chemical data for these rocks indicate a calc-alkaline to mildly alkaline (high K±Na calc-alkaline) arc-like chemical signature, regional data and reconstructions suggest that these rocks are unlikely to be related to active subduction as no convergent plate margins of this age have been identified in the area (Moss and others, 1998; Hutchison, 2005). In contrast to the other Tertiary subduction-related magmatic arcs in Indonesia, the central Kalimantan magmatic belt and surrounding Borneo are aseismic for earthquakes of magnitude 5 or greater, and geophysical evidence for a subducted slab under the arc is not apparent (Garwin and others, 2005). The dispersed belt of calc-alkaline magmatism may be related to counter-clockwise rotation of Borneo in response to plate reorganization following Australia's collision with the Philippine Sea Plate (Hall, 1996) causing a thickening of the crust and mantle instability, possibly involving an older (Cretaceous?) subducted slab (Moss and others, 1998). Any porphyry copper deposits likely to occur in this tract probably are related to the postsubduction porphyry copper-gold deposit model described by Richards (2009). Based on geologic history in this tract, including tectonics, uplift and erosion, all porphyry copper deposits are likely to be of Miocene to Pliocene age.

Data used to construct the Central Kalimantan tract include the Geological Map of Borneo (1:1,500,000; Tate, 2002), Digital Geological Map of Malaysia (1,1,000,000; Minerals and Geoscience Department, 2004), Geological Map of Sabah, Malaysia (1:500,000; Director-General Geological Survey of Malaysia, 1985), and digital GIS files for Indonesia, provided from the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) at a scale of 1:1,000,000 (table I5). The CCOP developed these GIS files using the 1:1,000,000 Preliminary Geologic Map, Kalimantan (Pieters and Supriatna, 1989) These maps and map-based GIS databases were used to identify permissive rock types, based on the map legend attribute information describing map-unit rock types, composition, and age (table I2). In addition, the Kinabalu Fault Zone of Tokuyama and Yoshida (1974) has been used to define part of the tract in central Sabah, Malaysia because a series of small Tertiary porphyritic diorite and acidic dikes and sills (not shown at map scale) are localized along a series of northwest-trending faults in the Kinabalu Fault Zone. The Kinabalu Fault Zone includes serpentinites, peridotites, ophiolitic rocks, and cherts that mark a tectonic boundary interpreted as a continent-island arc collision zone in the Cretaceous to Paleogene in Sabah (Kosaka and Wakita, 1978).

After choosing the polygons and groups of polygons that represent the surface expressions of permissive igneous intrusions, a 10-km buffer was applied to account for a spatial uncertainty of approximately 2 km in the digitized

Table I2. Map units that define tract 142pCu7019, Central Kalimantan—Indonesia.

[Map unit, geologic-age range, and principal rock types from 1:1,000,000 scale geologic maps, compiled by the Geological Research and Development Centre, Indonesia, (Pieters and Supriatna, 1989) and 1:500,000 scale geologic maps compiled by the Geological Survey of Malaysia (Minerals and Geoscience Department, 2004; Tate, 2002)]

Map unit	Age range	Rock types
	Intrusive rocks	
Toms	Oligocene to Pliocene	Granodiorite, diorite, porphyritic dacite
Toni	Oligocene to Pliocene	Intrusive center
Intrusive [Sabah Pr.]	Late Miocene to Pliocene	Quartz monzonite, granodiorite
Intrusive [Sabah Pr.]	Pliocene	Diorite, micrograpodiorite, microgranite
Nmi (Tate, 2002); IgWS (Minerals and Geoscience Department, 2004a) [Sarawak Pr.]	Miocene	I-type intrusive bodies and centers, including andesite and basalt plugs
	Volcanic rocks	
Toma	Oligocene to Pliocene	Andesite
Tomj	Oligocene to Pliocene	Andesitic volcanics
Tomv	Oligocene to Pliocene	Intermediate volcanics
Extrusive [Sabah Pr.]	Pliocene	Dacite, andesite, porphyritic andesite

geology, deposit location data, and the possibility that deposits may be associated with intrusions that expand beneath their surface expression and are also less than 1 km beneath the land surface. A 2-km buffer was applied around the permissive volcanic units, as these may be imprecisely located and partly covered. A 15-km buffer was applied around the Kinabalu Fault Zone in central Sabah to delineate an area of mid- to late Tertiary dikes and sills (not shown at map scale) that might host porphyry copper deposits.

A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified polygons using an algorithm (PAEK, polynomial approximation with exponential kernel) with a tolerance of 20 km. Necking, thinning, and contraction of the polygons resulting from processing required a subsequent manual cleaning step (for example, to remove polygon necks). Final tract boundaries were compared to the permissive geologic features in source materials to ensure that original permissive boundaries were honored. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

These revised preliminary-tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks or sedimentary deposits are greater than 1 km in thickness. The final tract boundary was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The plutonic rocks that crop out within the entire tract include numerous small bodies and intrusive centers of granodiorite, diorite, porphyritic dacite, and adamellite of late Oligocene to Pliocene age. Quartz monzonite bodies of late Miocene to Pliocene age also are present in Sabah. The volcanic rocks include high-level andesitic and trachy-andesitic intrusive centers and areas of basaltic andesite, andesite, and dacite. The distribution of the intrusive and volcanic rocks that define the tract is shown in figure I3. The Central Kalimantan tract includes at least 5 national parks and a number of nature reserves.

Known Deposits

The Mamut deposit (Kosaka and Wakita, 1978), the only known porphyry copper deposit with identified resources in the tract (table I3), is located within a cluster of porphyry prospects in the northeastern limb of the elongated magmatic belt in Sabah. It consists of disseminated copper sulfide minerals in

Table I3. Identified porphyry copper resources in tract 142pCu7019, Central Kalimantan—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Mamut	6.033	116.46	Cu-Au	7	196	0.48	0.001	0.5	2.5	940,800	Singer and others (2008),Clark (1993), Imai (2000), Kirk (1967), Kosaka and Wakita (1978), Nagano and others (1977), Tarkian and Stribrny (1999), Taylor and van Leeuwan (1980), United Nations (1985)

brecciated, quartz-veined, granodiorite porphyry. The ore metals include copper, gold, silver, and zinc with small quantities of molybdenum and mercury. Mineable ore reserves are about 83 million metric tons at 0.59 percent copper. Tonnage and grade estimates for the identified resources reported in Singer and others (2008) are 196 Mt at 0.48 percent copper, 0.001 percent molybdenum, 2.5 g/t silver, and 0.5 g/t gold.

Prospects, Mineral Occurrences, and Related Deposit Types

The late-Oligocene to Pliocene Kalimantan magmatic belt (termed central Kalimantan Arc by Garwin and others, 2005) is known principally for its epithermal gold deposits (Garwin and others, 2005). Many of the epithermal gold deposits in the tract are postulated to be the near-surface manifestations of porphyry copper systems (Corbett and Leach, 1998; Sillitoe and Bonham, 1990) and porphyry-style copper-gold and associated deposit types (table I4) are increasingly being recognized during ongoing exploration around the known epithermal gold deposits and associated volcanic centers in the tract (Geiger and others, 2002).

The Ibu porphyry copper occurrence (0.2 percent copper; 0.4 to 96 ppm molybdenum; 0.41 g/t gold) lies in the western part of Central Kalimantan tract in Indonesia. Intrusive rocks associated with the Ibu porphyry copper occurrence are aplite and granodiorite porphyry, and nearby intrusive rocks are composed of diorite, quartz diorite, and tonalite. The Ibu prospect has an uncertain age, but may be as old as Cretaceous if it is related to the nearby dated diorite-quartz diorite pluton. In this association it would represent a porphyry system preserved in a shallow erosional remnant of the calc-alkaline intrusions emplaced during Cretaceous-Paleogene subduction of the proto-South China Sea. However, the Ibu prospect may be Tertiary age in a similar setting to other porphyry copper-gold prospects, such as at Beruang Trengah, where small mid-Tertiary igneous centers have intruded into the contact zone between older Cretaceous plutons and adjacent metasedimentary rocks. Alteration minerals associated with the Ibu porphyry copper prospect include biotite, sericite, albite, carbonate minerals, magnetite, chlorite, and epidote, as well as tourmaline and zeolite. Sulfide and ore minerals include bornite, chalcopyrite, molybdenite, pyrite, galena, gold, sphalerite, bournonite, and cosalite ($Pb_2Bi_2S_5$). Supergene minerals and associated ore minerals include chalcocite, covellite, digenite, and limonite (Viaene and others, 1981).

All other known gold and gold-copper prospects in the tract are mid-Tertiary or younger in age, such as the Tertiary Bau epithermal gold deposit that lies north of Ibu in Malaysia. Bau is considered to be a sediment-hosted or Carlin-type disseminated gold deposit associated with the outlying alteration surrounding and overlying porphyry intrusion centers (Sillitoe and Bonham, 1990). At least four porphyry stocks in the 30 km by 8 km Bau District exhibit porphyry-style mineralization, including potassic and sericitic alteration with quartz stockworks carrying low-grade copper-molybdenum-gold mineralization (Sillitoe and Bonham, 1990). Gold has been mined in the Bau District since at least the last century with a recorded output of about 44,688 kg gold. Mining first started from 1899 to 1921 where nearly 31,104 kg of gold was produced. Other areas of weak porphyry type copper-gold mineralization are present in West Sarawak along with surrounding gold deposits in the region (Viaene and others, 1981; Singer and others, 2005).

The large Kelian, Indomuro, Muyup, and Manparia epithermal gold deposits are associated with felsic to intermediate porphyritic bodies in the south-central part (Banjarmansin) of the Central Kalimantan tract (Setiabudi, 2001). The Mount Muro deposit is a quartz-alunite gold deposit in a diatreme breccia pipe. The Masuparia porphyry copper-gold prospect borders the Mount Muro gold mine and the Mount Muro deposit is likely a near-surface manifestation of the deeper porphyry copper system exposed at Masuparia (Prosperity Resources Limited, 2010). Kelian is a disseminated, low sulfidation, epithermal gold deposit. Similar to Mount Muro, the epithermal gold mineralization at Kelian was preceded by and is hosted in a maar-diatreme breccia complex (Davis and others, 2008). The Kelian mine ceased its primary mining operations in 2004. The Baroi gold prospect is operated by Kalimantan Gold Corporation, Ltd., and is interpreted as related to a porphyry system (Directorate of Mineral Resources and

Table I4. Significant prospects and occurrences in tract 142pCu7019, Central Kalimantan—Indonesia.

[Rank 4=Prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; n.d., no data; Ma, million years; Mt, million meteric tons]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Kalimantan Gold (KGC CoW)	–0.583	113.333	n.d.	Includes the following prospects: Beruang Tengah, Beruang Kanan, Tumbang Huoi, Mamuring, Kalang. Surface sampling at Beruang Kanan has defined a 1,100 m long by 400–600 m wide zone of >0.1% Cu and broad spaced drilling had delineated 80–90 Mt at 0.5–0.6% Cu to a depth of about 200 m; 167 m at 0.59% Cu in porphyry style alteration; Grade 0.89% Cu from a 79 m drill hole interval on the Beruang Kanan prospect. The broad elements of porphyry system are present at Beruang Tengah, but grades encountered in the shallow drilling to date are not economic.	Geiger and others (2002), Management Report (2009), Kalimantan Gold Corporation, Ltd. (2008, 2010)	4
Masuparia	–0.56	114.022	n.d.	Drill core intercepts in porphyry Cu-Au mineralization identified in Phelps Dodge Corp. prospect bordering the Mount Muro gold deposit. Drill core assays report 0.18–0.26% Cu and 0.32–0.50 g/t Au. Geophysical studies indicate a larger porphyry system than has been drill tested	Corbett and Leach (1998), Prosperity Resources Limited (2010)	4
Baroi gold prospect	–0.5	113.18	n.d.	Drill hole intersections 5 to 24 m at 0.12 to 2.16% Cu, 0.02 to 0.11 g/t Au, 2 to 37.4 g/t Ag. Exposed. Prospect was 83 m at 2.64% Cu and 0.22g/t Au	Kalimantan Gold Corporation, Ltd. (2003, 2004, 2008)	4
Nungkok	6.1	116.466	8	0.42 to 0.57% Cu. In drill core 0.008 to 0.025% Mo.	Saigusa (1973), Nagano and others (1977), Taylor and Van Leeuwen (1980), Singer and others (2008)	4
Bongkud	6.033	116.75	n.d.	A 5 km long WNW porphyry Cu zone, intersects: 331 m at 0.31% Cu, 0.7 g/t Au; 169 m at 0.4% Cu and 0.9 g/t Au; 123 m at 0.43% Cu, 0.95 g/t Au; 74 m at 0.57% Cu, 0.95 g/t Au. Oxidized zone 45 m thick at 3.5% Cu.	Feebrey (2001), Imai (2000), Perilya (2007), United Nations (1985), Singer and others (2008)	4
Mansur	–0.533	113.2	n.d.	A review of prospects in the immediate area suggests the present level of erosion has exposed the upper levels of the Mansur porphyry system. The deeper seated magnetic anomaly represents a valid porphyry Cu target at depth. Drill intercepts below soil Cu anomaly area report low grade (0.2% Cu) porphyry-style mineralization.	Geiger and others (2002), Management Report (2009)	3
Ibu	0.833	109.25	105?	Porphyry copper prospect of uncertain age.	Viaene and others (1981), Singer and others (2008)	2
Sungai Imbak	5.267	117.117	n.d.	Sulfide veins genetically related to diorite porphyry sills and dikes.	[Malaysia] Task Force 4 (1998)	1
Ruwai	–1.367	111.167	n.d.	Porphyry Cu-Au prospect with adjacent skarn/replacement mineralization.	Scorpion Mineral (1998)	1

Inventory, 2004b). The Mansur porphyry copper-gold prospect was identified during exploration activity in the early 1990s following stream-sediment gold anomalies identified in the area during the 1980s. The Mansur prospect is located within a large circular feature that has an associated strong magnetic anomaly, coinciding with a mid-Tertiary diorite intrusion and younger feldspathic porphyry dikes intruded into clastic metasedimentary rocks. A halo of high copper concentrations in soils is localized along the western diorite-hornfels contact (Geiger and others, 2002). Epithermal gold mineralization hosted by a diatreme-dacite dome complex occurs at Lakapoi, located 10-km south-southwest of Mansur, and it likely formed at a shallower level than the porphyry system at Mansur. Porphyry copper-gold prospects at Beruang Tengah (including the nearby Beruang Kanan prospect) are located in a 10–12-km-wide circular feature that lies at the intersection of northeast and northwest trending structures. The copper-gold mineralization occurs in a number of andesite-to-dacite and quartz-diorite intrusions that have been emplaced at the contact between metasedimentary rocks to the west and older granodiorites to the east (Geiger and others, 2002). The Bukit Mantri and Nagos epithermal gold deposits are present in the south part of the tract (Yan, 1991; United Nations, 1985). A number of gold placer deposits also are present within the tract.

A few porphyry copper-gold prospects and occurrences are present in the northeast part of the tract in Sabah. The Mamut deposit and the Nungkok and Bungkud (Bukit Tampang) are nearby porphyry copper-gold prospects. Five of the porphyry copper-gold prospects in table I4 are in the Singer and others (2008) porphyry copper database (rank=4; table I4) and seven of the prospects have been drilled or trenched during exploration (rank>1; table I4).

Exploration History

Exploration for gold and porphyry copper deposits was done in the Western Kalimantan tract on a regional scale and some prospect exploration and sampling was done at the more significant mineral occurrences. Gold mining has taken place at Bau since the early 1900s. The Ibu porphyry copper occurrence was discovered in the 1970s. Geochemical and airborne geophysical surveys were done by both mineral-exploration companies and government agencies in West Sarawak and West Kalimantan in the 1980s.

The Mamut porphyry copper deposit was discovered in 1966. The mine ceased operation in mid-1999 after operating for about 24 years. Exploration took place in the tract in the late 1960s with geochemical prospecting over the entire area with some airborne geophysics on regional- and district-scales. Bongkud was discovered in 1999. The major exploration in the Sabah Central belt tract was done by the UNDP Labuk Valley Project (1964–1967), Malaysian-German Mineral Exploration project (1980–1985) and MMAJ-GSM Supra Regional Project Central Sabah Project (1990–1996). The Mamut copper deposit was mined out after 24 yrs of operation, producing a total of 2.4 million metric tons of copper concentrate (600,000 t of copper), 44.55 t of gold, and 294.49 t of silver.

The area within the North Central Kalimantan tract in the area of the Kalimantan Gold Corporation, Ltd. (KGC), contract of work (COW) area has been explored extensively by private mining companies, particularly in the 1980s and 1990s. Specific prospect-scale exploration has taken place at the Mount Muro deposit. Exploration activities by the KGC since 1990 used regional geochemical, geophysical, and field-mapping methods to identify more than 30 porphyry and porphyry- related copper-gold prospects in central Kalimantan, few of which had any detailed exploration as of 2002 (Geiger and others, 2002). Preliminary exploration targets have been identified from large circular features that are evident on satellite, Landsat radar, and aerial-photo images. These features commonly coincide with mid- to late Tertiary intrusions and are associated with circular and donut-shaped aeromagnetic anomalies (Geiger and others, 2002). Targeted field mapping and geochemical surveys have been used to further define exploration targets in the KGC prospect area.

Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7019 are listed in table I5.

Grade and Tonnage Model Selection

The grade and tonnage model used in this assessment was the porphyry copper-gold subtype described by Singer and others (2008), and this subtype is the target of most current exploration for porphyry copper deposits in the tract (table 6). The geologic characteristics and reported ore grades and tonnages are consistent with the porphyry copper-gold subtype as described by Singer and others (2008). The reported average gold grade of 0.5 g/t for Mamut is greater than the gold-grade criteria (>0.2 g/t), and the Au/Mo ratio of 500 is greater than the Au/Mo-ratio criteria (Au/Mo>30) used by Singer and others (2008) to classify deposits as copper-gold subtype. The geologic features and tectonic setting of the tract also is consistent with the postsubduction tectonic model for porphyry copper-gold deposits described by Richards (2009).

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The results of a preliminary assessment done in February 2005 for porphyry copper tracts in Borneo were reviewed

Table I5. Principal sources of information used for tract 142pCu7019, Central Kalimantan—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Preliminary geologic map, Kalimantan	1:1,000,000	Pieters and Supriatna (1989)
	Geological map of Borneo	1:1,500,000	Tate (2002)
	Digital geologic map of Malaysia	1:1,000,000	Minerals and Geoscience Department (2004)
	Digital geologic map of Indonesia	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Geological map of Sabah	1:500,000	Director-General Geological Survey of Malaysia (1985)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Mineral resource map of Asia	1:35,000,000	Kamitani, and Naito, eds. (1998)
	Digital mineral occurrences database	NA	Minerals and Geoscience Department (written commun., 2004)
	Digital mineral occurrences database	1:1,000,000	Directorate of Mineral Resources and Inventory (2004a,b)
	Atlas of mineral resources of the ESCAP region, v. 1, Malaysia	NA	United Nations (1985)

in 2009 and 2010. Revised estimates were developed using larger-scale geologic map information and incorporating the results of more recent exploration activity and geologic research on porphyry copper-gold deposits in the area. The assessment team redefined the 2005 preliminary tract boundaries and reestimated the number of porphyry copper-gold deposits in the Central Kalimantan tract at the 90, 50, and 10 probability confidence levels during February 2010 on the basis of one known porphyry copper or porphyry-related deposit and a number of prospects and exploration targets (table I6). The method of estimation was subjective and based on expert opinion and on analogy with geologically similar areas.

The estimate was influenced by an identified porphyry copper occurrence in the western part of the tract at Ibu and mid-Tertiary intrusions in West Sarawak that have petrologic characteristics and alteration consistent with porphyry copper-style (potassic, phyllic) alteration. Geochemical surveys have identified soil copper anomalies at Sebemban, Bukit Punda, Mudieng and Bukit Nimong.

Exploration for porphyry copper-gold deposits is ongoing in the south-central part of the tract (Geiger and others, 2002),

Table I6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7019, Central Kalimantan—Indonesia.

[N_{XX}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
3	8	30	30	30	13	10	78	1	14	144,580	10

Table I7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7019, Central Kalimantan—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	1,000,000	2,800,000	25,000,000	100,000,000	130,000,000	40,000,000	0.38	0.03
Mo	0	0	95,000	640,000	890,000	230,000	0.31	0.11
Au	100	250	1,900	6,900	8,600	2,900	0.39	0.03
Ag	0	230	5,400	38,000	56,000	13,000	0.29	0.07
Rock	240	640	5,200	20,000	24,000	8,100	0.39	0.03

and new porphyry copper-gold discoveries may occur in this area. The estimate was influenced by the nature and occurrence of porphyry and epithermal copper-gold prospects in this area, such as the Baroi, Beruang Kanan, Mansur, and Masuparia prospects, as well as several epithermal gold prospects that may be surface manifestations of porphyry copper-gold-related systems (Corbett and Leach, 1998). Also taken into consideration for the estimate was the fact that from 1987 to 2002 more than 30 prospective porphyry copper-gold exploration targets were identified in the south-central part of the tract and that few of these have been explored in any detail (Geiger and others, 2002). A number of gold and copper occurrences or prospects occur in the overall tract area, and at least four major epithermal gold districts within the tract are considered to have some relationship to porphyry-style systems. Seven prospects included in table I4 have been drilled or trenched during exploration reporting intercepts with grades exceeding 0.2 percent copper (rank>1; table I4); five of the prospects are in the Singer and others (2008) database.

Other factors taken into consideration for the estimation were (1) the recognition that exploration for porphyry-style copper-gold deposits in the tract mostly began in the 1980s; (2) that more than 750 small intrusive centers of appropriate age, chemistry, and setting to potentially host porphyry deposits occur in the tract; (3) that most of these centers are in remote areas in the central part of the tract where few have received even reconnaissance exploration; and (4) that if even a small proportion of these intrusive centers host porphyry-style systems, a number of undiscovered porphyry copper-gold deposits may occur in the tract. The 90-percent confidence-level estimate of three undiscovered deposits is consistent with the underexplored nature of the tract and the large number of identified porphyry prospects. Eight undiscovered deposits at 50-percent confidence level was judged appropriate based on the exploration status of the tract and the large number of small intrusive centers of appropriate age, chemistry, and setting that potentially could host porphyry deposits.

The estimate resulted in a mean of 13 expected undiscovered deposits and when added to the Mamut deposit resulted in a density of 10.0 deposits/100,000 km^2 (table I6), consistent with the observed range, but on the low-range side, of porphyry deposit density as reported by Singer and others (2005).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits (table I6) with the copper-gold porphyry subtype model (Singer and others, 2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table I7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. I4). The cumulative frequency plot shows the estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

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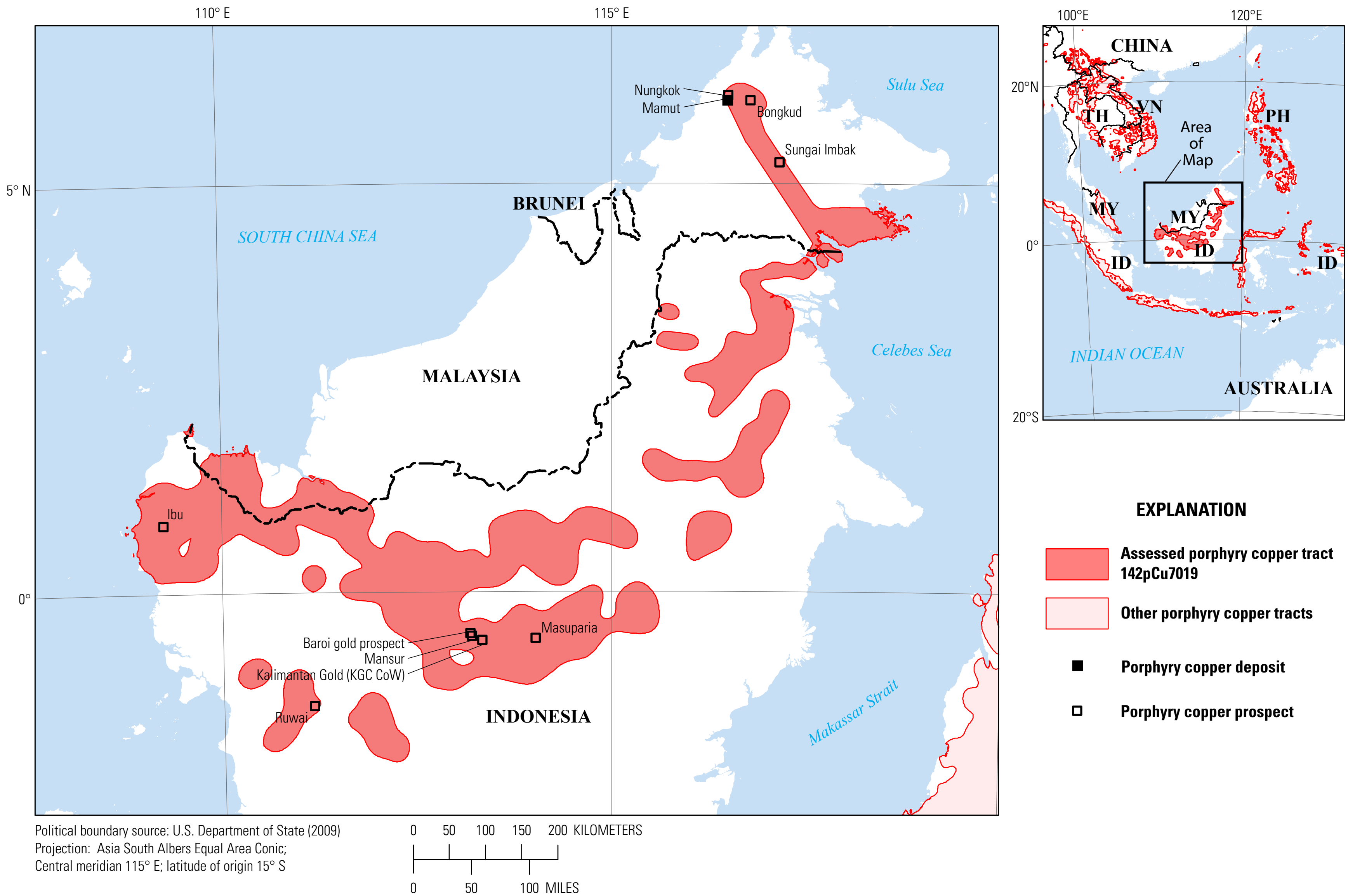

Figure I1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7019, Central Kalimantan—Indonesia. ID, Indonesia; MY, Malaysia; PH, Philippines; TH, Thailand; VN, Vietnam.

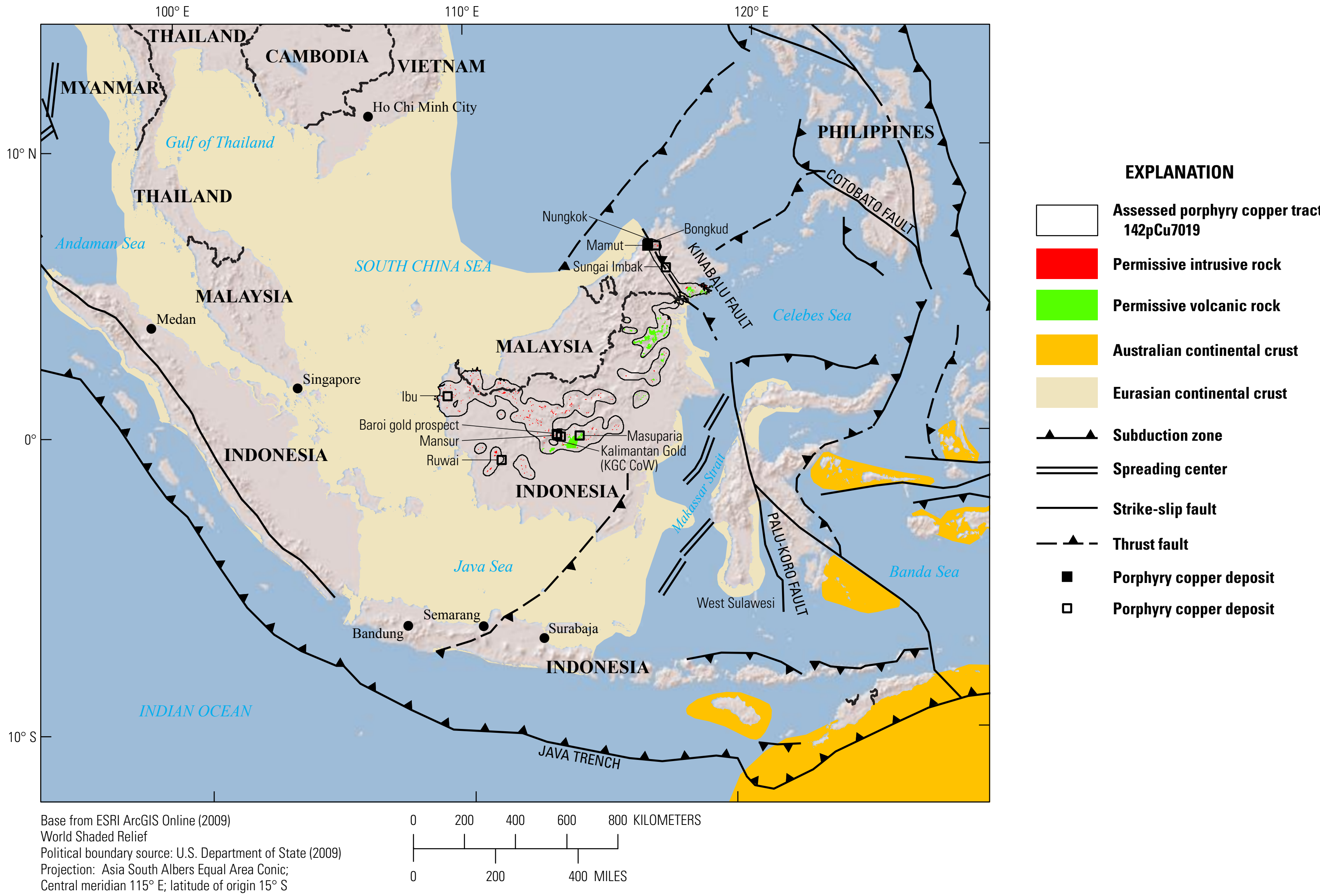

Figure I2. Map showing the regional setting for tract 142pCu7019, Central Kalimantan—Indonesia.

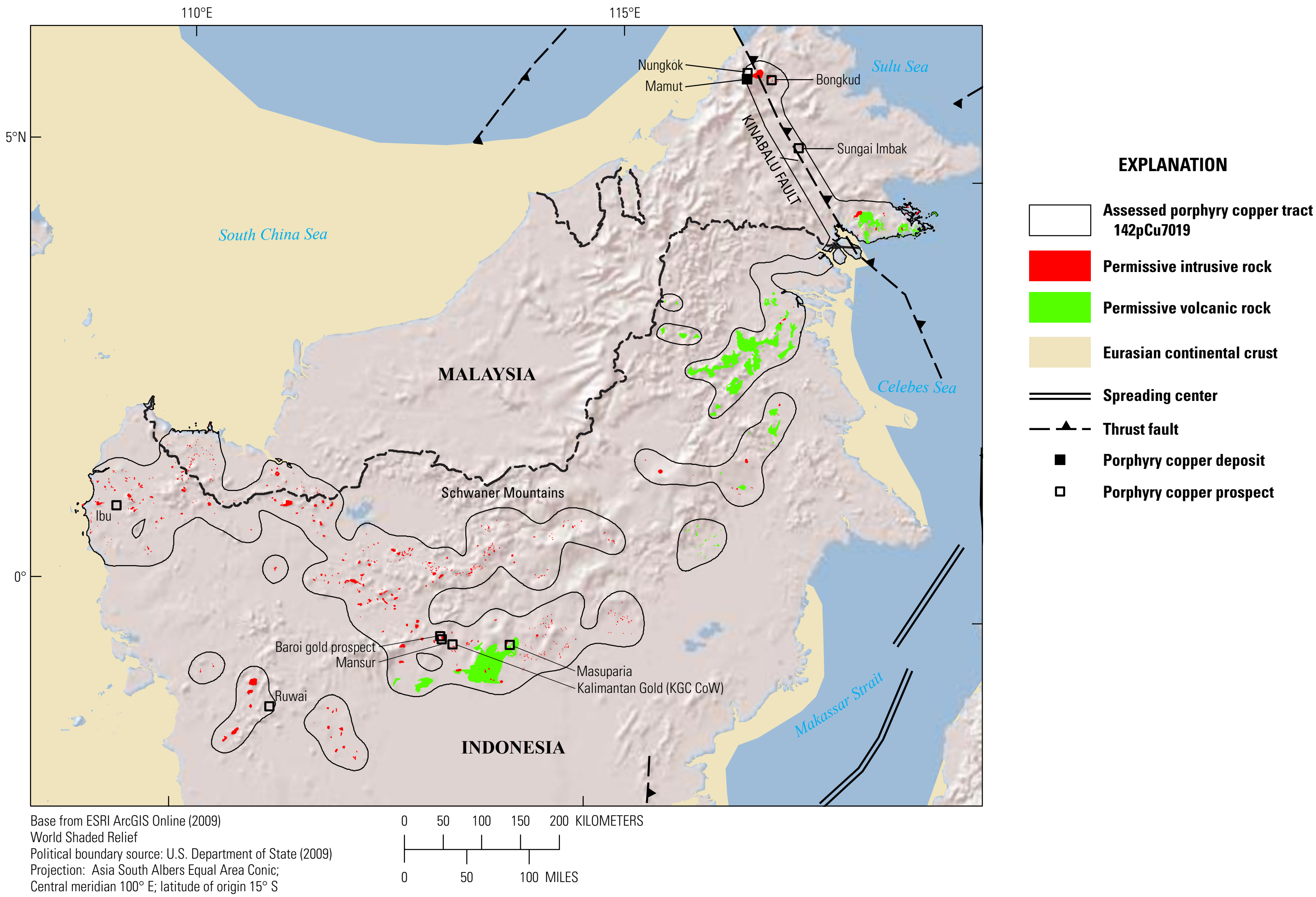

Figure I3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper deposits and prospects for tract 142pCu7019, Central Kalimantan—Indonesia.

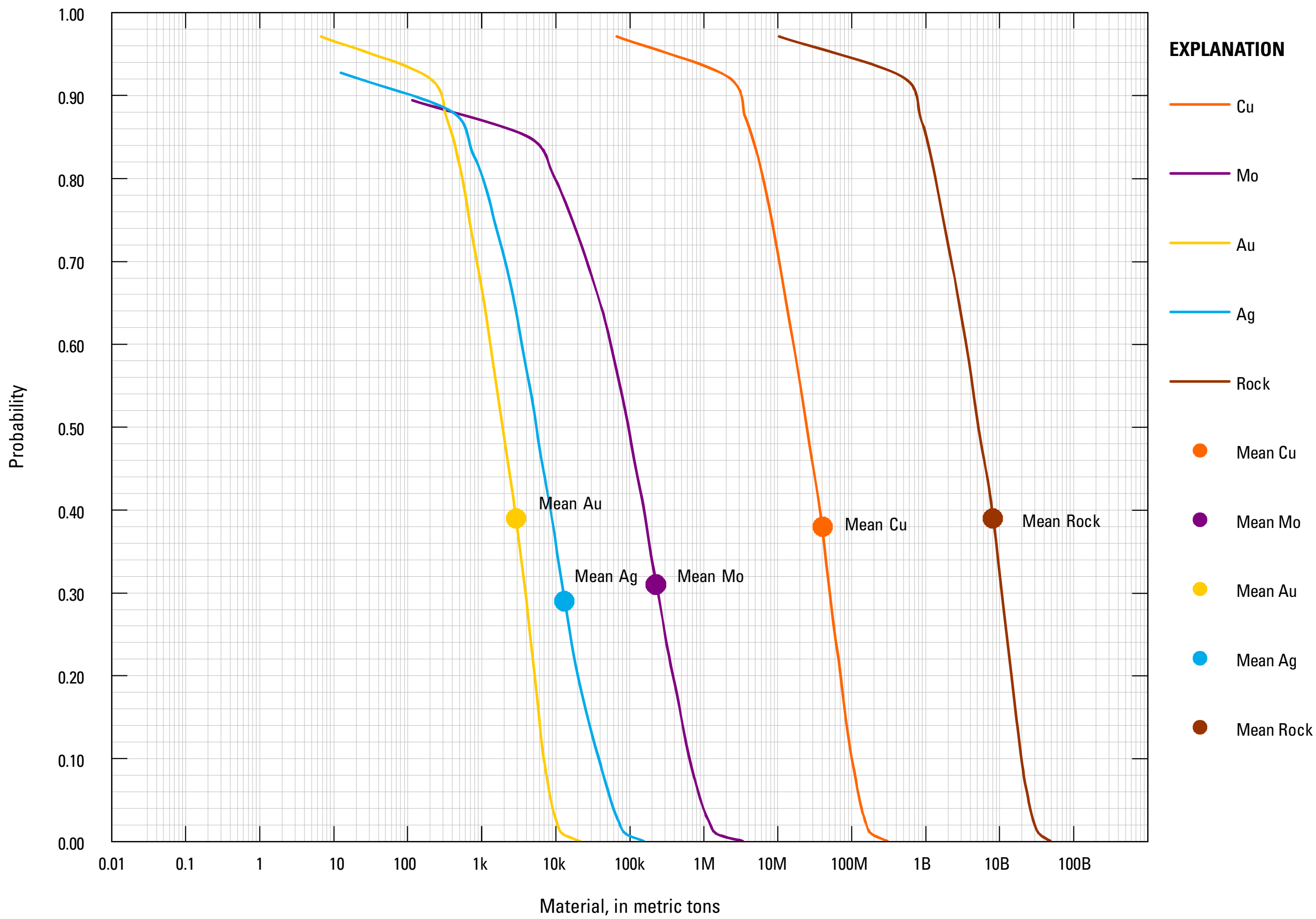

Figure I4. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7019, Central Kalimantan—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix J. Porphyry Copper Assessment for Tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5] and Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage models: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table J1 summarizes selected assessment results.

Table J1. Summary of selected resource assessment results for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	1,540	n.d.	3,100,000	660,000

Location

The tract includes Ambelau, Ambon, Haraku, Saparua, Nusa Luat, Kelang, Manipa, and western Seram Islands, Indonesia (fig. J1).

Geologic Feature Assessed

Pliocene-Quaternary Ambon island arc (northern Outer Banda Arc), eastern Indonesia.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S Geological Survey, Spokane, Washington, United States.
[5]Mineral Resources Authority, Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

The tract outlines igneous rocks that are permissive for porphyry copper deposits within the Pliocene-Quaternary Ambon Arc. The Ambon Arc extends from Ambelau Island across western Seram and Ambon Island to the small islands of the Banda Archipelago (figs. J1, J2). The Ambon Arc represents the northernmost, curved segment of the Banda Arc system. The west-facing, curvilinear Banda Arc system, which borders the Banda Sea from Wetar to Ambon, formed at the intersection of the Indo-Australian, Pacific, and Eurasian Plates. Tectonic models proposed for the Banda Sea in eastern Indonesia have interpreted the Ambon Arc as (1) a segment of the east-west-trending Sunda-Banda Arc that has been displaced to the north and rotated counter-clockwise since the Miocene as a consequence of northward and westward motion of the Australian and Pacific Plates, respectively; (2) not related to subduction; or (3) the result of active subduction along the Seram Trough (Honthaas and others, 1999). More recent seismic and stratigraphic studies suggest that the Seram Trough is a foredeep at the front of a developing fold and thrust belt on Seram that represents a post-Miocene zone of thrusting within the Australian continental margin, although subduction cannot be ruled out (Pairault and others, 2003).

Honthaas and others (1999) defined the Ambon Arc as a separate arc based on the distinctive geochemistry of Pliocene and younger volcanic rocks, the problematic interpretations of the Banda Arc as a single arc that requires a single bent subducting slab between Wetar and Ambon (fig. J2), and seismic data (McCaffrey, 1988) that support two discrete subduction zones: (1) southward subduction of Irian Jaya continental crust beneath Seram along the Seram Trough (fig. J2) and (2) northward subduction beneath Wetar.

Banda Arc rocks include geographically distinct geochemical suites in terms of K_2O contents, Sr-Nd-Pb isotopes, and oxygen-isotope signatures. These distinct suites are interpreted as indications of variable contributions of subducted continental material to depleted MORB-type mantle-derived magmas (Vroon and others, 2001) and possibly as indications of multiple subduction zones (Whitford and Jezek, 1979).

The Ambon Arc represents two suites of island-arc magmas: (1) 5–3.2 Ma, low-K calc-alkaline volcanic rocks (basalts, andesites, dacites, rhyolites) evolved from basaltic magmatism related to mantle melting above the Western Irian Jaya Plate as it subducts along the Seram Trough (north of Seram); and (2) 2.3–1 Ma, high-K calc-alkaline andesites, dacites, rhyolites, and granites, including cordierite-bearing dacites (ambonites) and granites that represent low-K magmas that assimilated continental crust. The cordierite-bearing rocks on Ambon have high K, Rb, Cs, and $^{87}Sr/^{86}Sr$ ratios (~0.715) that probably reflect a contribution from partial melting of pelitic sediments (Whitford and Jezek, 1979). Both low- and high-K rocks on Ambelau, Ambon, Kelang Haruku, Saparua, and Seram have subduction-type geochemical signatures, such as low TiO_2 and high Al_2O_3 mafic lavas, negative Nb anomalies, and high LILE/HFSE and LREE/HFSE ratios (Honthaas and others, 1999).

Ambon, Seram, and Kelang are underlain by Paleozoic metamorphic basement; Ambelau and Haraku are composed entirely of Pliocene and younger andesitic volcanic rocks.

Geologic Criteria

The tract delineates Pliocene to Pleistocene intrusive and volcanic rocks (table J2; fig. J3), as shown on a digital geologic map provided by Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP) and Geological Survey of Japan (1997) and

Table J2. Map units that define tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[Map unit, geologic-age range, and principal rock types from 1:250,000 scale geologic maps, compiled by the Geological Research and Development Centre, Badung, Indonesia, 1987–2000]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Ambon granite	Ti(d,g)	Biotite granite, biotite cordierite granite, diorite	Pliocene to Pleistocene
Volcanic rocks			
Ambelau volcanic rocks	Tpav	Andesitic lava and pyroclastics	Pliocene
Ambon volcanic rocks	Tpav	Andesite, dacite, breccias, tuff	Pliocene to Pleistocene
Kelang volcanic rocks	Tmkv	Lava, andesite, breccia, tuff, conglomerate	Pliocene to Pleistocene
Andesite (Buru)	Tpa	Biotite andesite	Pliocene

Table J3. Significant prospects and occurrences in tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[Ma, million years; t, metric ton; g/t, gram per metric ton; Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Hila	–3.612	128.092	3.6	Porphyry Cu-Au prospect on Ambon Island. Grab samples contain ≤0.014 g/t Au, 530 ppm Zn, 1,550 ppm Cu. Age of mineralization is Pliocene or younger.	Menzie and others (1997), Indo Metals, Ltd. (1997), Whyte (1998), Singer and others (2008).	2

1:250,000-scale geologic maps of the Buru, Ambon, and Masohi quadrangles (Tjokrosapoetro and others, 1993a,b,c). The cordierite-bearing rocks and granites of the high-K suite (Ambon granite) are unlikely associations for porphyry copper mineralization and probably are unrelated. However, no detailed geologic maps are available to show the distribution of the two suites, in part because of heavy vegetation, steep terrain, complex structure, and difficult access. The 1:250,000-scale geologic maps show all intrusive rocks as Ambon granite. The high-K rocks sampled by Honthaas and others (1999) were collected near-shore along the periphery of Ambon, Haraku, and Sapura. Low-K samples were collected near-shore in southern Seram and eastern Kelang. Exploration reports for Ambon Island describe intrusive rocks of intermediate composition, ranging from andesite to granodiorite, monzonite, and diorite (Quantitative Resource Assessment Team [BPPT], 1997; Menzie and others, 1997). Small areas of biotite andesite are mapped on the southern shore of Buru.

The Banda Archipelago represents emerged segments of a 5-km-high volcanic structure that includes the recently active (1988) Banda Api volcano (fig. J2) in the Ambon Arc segment. Although the lithologies (dacitic and andesitic volcanic rocks) are permissive for porphyry associations, volcanic centers were excluded from the permissive tract based on the thickness of volcanic cover (>1 km) over any possible porphyry copper deposits which may be forming at depth. Ambon and nearby islands are transpressive fault blocks that have been uplifted and eroded during the Pliocene to Pleistocene. Exposed coral reefs rimming the volcanic islands indicate rapid uplift (Menzie and others, 1997).

Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic) based on map-legend attributes. From this digital database of map units grouped by age and lithology, all Tertiary igneous rocks were selected. Using GIS tools, a 5-km buffer was applied around mapped igneous contacts of permissive lithologies to account for spatial uncertainty in digitized geology and for the possibility of greater extent of permissive rocks within a kilometer of the surface.

The buffered map units were dissolved using GIS processing tools. Finally, the resulting shapefile was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009). Permissive areas may be present offshore, in areas below ocean level in the Kepulauan Maluku and the islands around the city of Ambon; however, assessment protocols limit permissive areas to those above sea level.

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

The tract contains the Pliocene-Quaternary Hila porphyry copper-gold prospect and associated occurrences (table J3). At Hila, chalcopyrite and pyrite are present in veinlets and stockworks in Ambon andesites; quartz is the main gangue mineral (Menzie and others, 1997). Grab samples of volcanic rocks contain as much as 0.014 g/t gold, 530 ppm zinc, and 1,550 ppm copper (Menzie and others, 1997). The samples included altered (sericite, chlorite) porphyritic volcanic rock, fine-grained volcanic rock with disseminated pyrite, bleached rock with quartz stockworks, and hydrothermal breccia.

Exploration on Ambon Island by Indo Metals in the 1990s identified 42 showings classified as (1) high-grade polymetallic Cu-Pb-Zn-Ag replacements in breccias and volcanic rocks, (2) base-metal quartz veins, and (3) disseminated chalcopyrite in altered diorite intrusions. A cluster of three copper prospects identified in a 13 by 7 km area on the northwest coast of Ambon is associated with stream-sediment copper anomalies; the Buyang prospect in altered leucodiorite and volcanic rocks was considered to represent part of a porphyry system (Indo Metals, Ltd., 1997). At the southwestern tip of Ambon Island, a 6 by 4.5 km area with copper and gold showings (outcrop, float) was defined (Indo Metals, Ltd., 1997). All of the prospects identified were within 6 km of coastal areas; the interior of the island was considered equally prospective but due to the inaccessible terrain, would require exploration with helicopter support. Exploration also identified a 10-km-long belt of copper showings in northwestern Ambon; these showings include chalcopyrite stringers and disseminations in diorite and a soil copper geochemical anomaly over a 700 by 600 m area (Whyte, 1998).

Exploration suggested that felsic cores of volcanic complexes exhibit copper-dominant porphyry-style mineralization flanked by replacements and polymetallic massive sulfides; gold tends to be associated with the porphyry-style of mineralization (Whyte, 1998). The Wai Ira polymetallic prospect was drilled on Haruku during the 1997–1998 exploration period; 23 mineral occurrences including porphyry were identified in the central part of Haraku.

Exploration History

Sulfide mineral occurrences were discovered by Hila villagers in 1992. The Indonesian government and the USGS completed a reconnaissance study in 1994 (Menzie and others, 1997). Consolidated Magna Ventures, Ltd., did reconnaissance stream-sediment sampling and prospecting in 1996 to follow up copper, gold, and base-metal anomalies detected by P.T. Nusa Namorle Mining during their 1987 exploration program. Indo Metals, Ltd. (Indo Metals, Ltd., 1997; Whyte, 1998) explored Ambon and adjacent islands in 1997 as part of its Malaku Joint Venture; the contracts of work (COWs) included Haruku, Ambon, Nusa Laut, and Saparua Islands. The lack of subsequent exploration and development activity may be explained by social, political, and environmental issues that have arisen in subsequent years. In 2008, PT Oxindo Exploration and a local Indonesian company established a cooperative agreement to explore a number of porphyry copper project areas in Ambon (OZ Minerals, Ltd., 2008); however, reports on that work were not available.

Sources of Information

Principal sources of information used by the assessment team for delineation of the tract are listed in table J4.

Grade and Tonnage Model Selection

Because no well-characterized deposits are present in the tract, there is no statistical basis for testing models (table 6). In such cases, the default solution is to use a general porphyry copper model; however, Hila is described as a copper-gold porphyry prospect (Menzie and others, 1997). Chemical analyses of three grab samples reported <1 ppm molybdenum, and no molybdenite is reported in descriptions of the area. The crustal input indicated by the geochemistry of the arc rocks and the continental metamorphic basement below Seram support use of a general model that includes all porphyry copper subtypes. The magmas that produced the porphyry-related rocks have a subduction-related signature. Although contamination by crustal sediments led to the unusual ambonite compositions, the ambonite rocks probably are not associated with the copper mineralization. Copper-gold porphyry deposits, such as the giant (4.2 Mt contained copper) Batu Hijau deposit of Indonesia, are present in the Sunda Arc. The complex tectonic setting and classification of Hila as a copper-gold prospect were the basis for selecting the copper-gold subtype model for the simulation.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The assessment team considered the Hila porphyry copper prospect, the number of mineral occurrences (>30), geographically distinct areas characterized by copper and gold stream-sediments anomalies, and porphyry-style hydrothermal alteration as indications of porphyry systems on Ambon. In addition, hidden deposits may be present within 1 km of the surface under volcanic cover. The exposed intrusive rocks represent a small portion of the tract area; a cluster of occurrences near the Hila gold prospect are controlled by strike-slip and duplex faulting (Menzie and others, 1997; Tjokrosapoetro and others, 1993a). On the basis of a site visit, Menzie and others (1997) suggested that the possible presence of porphyry copper-gold deposits on Ambon merited further study. The central part of Ambon is poorly explored. Small bodies mapped as Ambon Granite on Manipa and southwestern Seram suggest that levels of exposure may be appropriate for preservation of porphyry systems.

The small area of permissive rocks is a limiting factor on the numbers of deposits that could be present. Exposed intrusions in the western part of Ambon Island indicate that uplift may have been sufficient to expose porphyry systems there. In other parts of the tract, where only volcanic rocks are shown on available maps, insufficient uplift and erosion may have occurred to bring porphyry deposits to within 1 km of the surface.

The team estimated a 50-percent chance of one or more undiscovered deposits and a 10-percent chance of two or more deposits (table J5). The 5- and 1-percent estimates are also two or more deposits, based on the team's expectations that there is insufficient room for additional deposits in the tract. The 50-percent estimate is based on the likelihood that, if fully explored, the Hila prospect area could represent a deposit like those in the grade-and-tonnage model. Based on the number of documented copper occurrences and the area under volcanic cover, the other estimates are consistent with a general guideline that between 1 and 10 percent of occurrences might be mineral deposits consistent with the grade-and-tonnage model (Singer and Menzie, 2010). The mean number of deposits for this distribution of estimates is 1.0±0.8 with a high coefficient of variation of 79 percent, indicating a high degree of uncertainty. Although the tract area is small, given the amount of cover and the distribution of permissive rocks on a number

Table J4. Principal sources of information used for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[NA, not applicable; CCOP, Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia]

Theme	Name or Title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Indonesia	1;100,000	Directorate of Mineral Resources and Inventory (2004a)
	Geologic map of the Ambon quadrangle, Maluku	1:250,000	Tjokrosapoetro and others (1993c)
	Geologic map of the Masohi quadrangle, Maluku	1:250,000	Tjokrosapoetro and others (1993a)
	Geologic map of the Buru quadrangle, Maluku	1:250,000	Tjokrosapoetro and others (1993b)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence data base	NA	Directorate of Mineral Resources and Inventory (2004b)
	The Hila prospect—a recently discovered occurrence on Ambon Island, Republic of Indonesia	NA	Menzie and others (1997)
Exploration	Indo Metals Ltd. announces 42 new base metal-silver-gold showings discovered on the Maluku Joint Venture's Ambon Island property	NA	Indo Metals, Ltd. (1997)
	Base Metals—Maluku base metal project a prospecting triumph	NA	Whyte (1998)

Table J5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). In cases where individual estimates were tallied in addition to the consensus estimate, individual estimates are listed.

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
0	1	2	2	2	1	0.79	79	0	1	1,540	65

Table J6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	660,000	6,700,000	13,000,000	3,100,000	0.21	0.3
Mo	0	0	0	32,000	73,000	18,000	0.14	0.69
Au	0	0	65	560	1,000	230	0.23	0.3
Ag	0	0	0	1,700	3,400	1,000	0.15	0.6
Rock	0	0	150	1,300	2,900	620	0.22	0.3

of islands there could be two or more deposits, albeit at a low probability of occurrence. The small size of the tract area (1,540 km^2) results in a high apparent deposit density (table J5).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold subype model of Singer and others (2008), using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table J6. Results of the Monte Carlo simulations are presented as a cumulative frequency plot (fig. J4). The cumulative frequency plot shows the estimated amounts of resource associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

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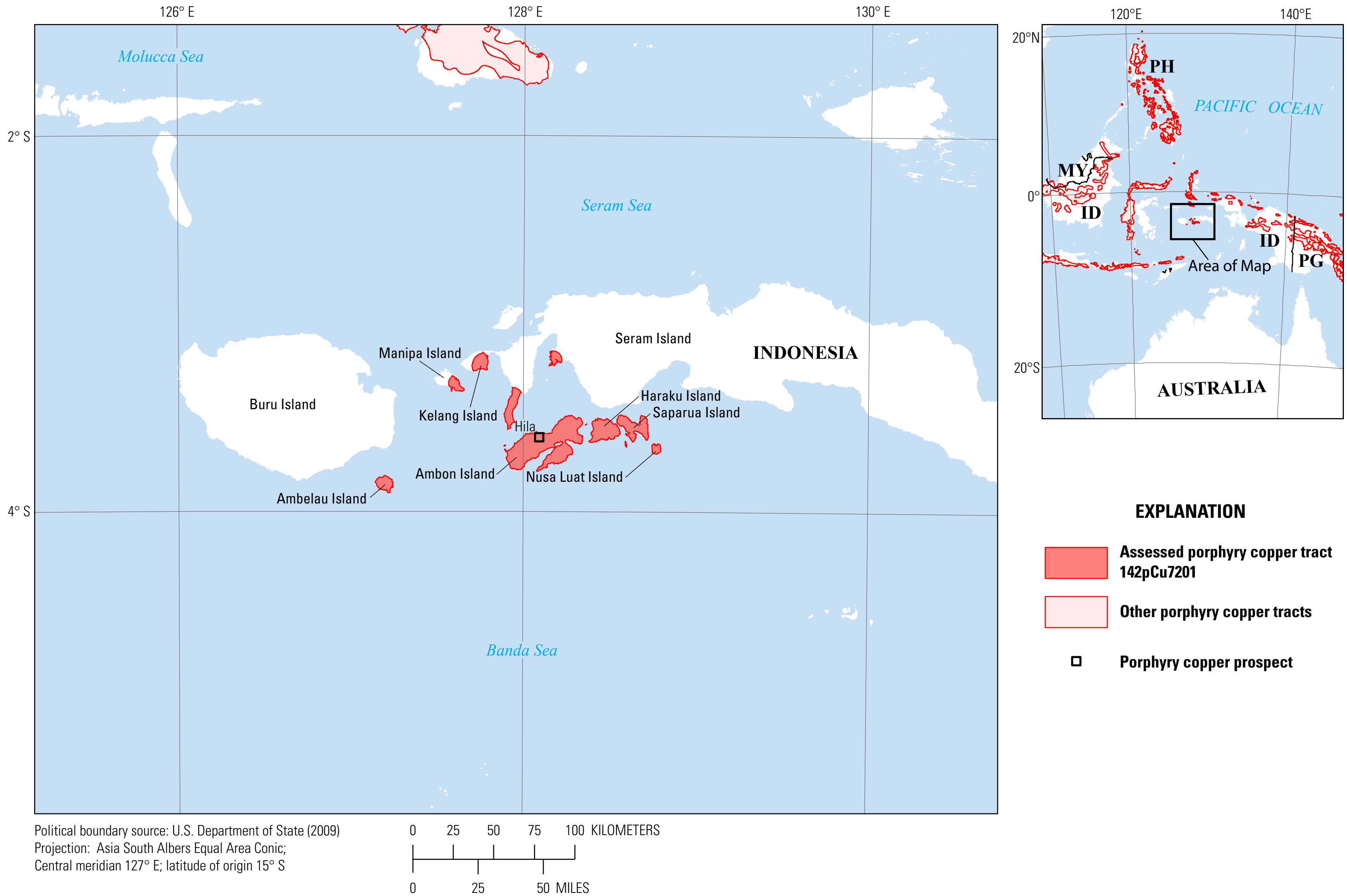
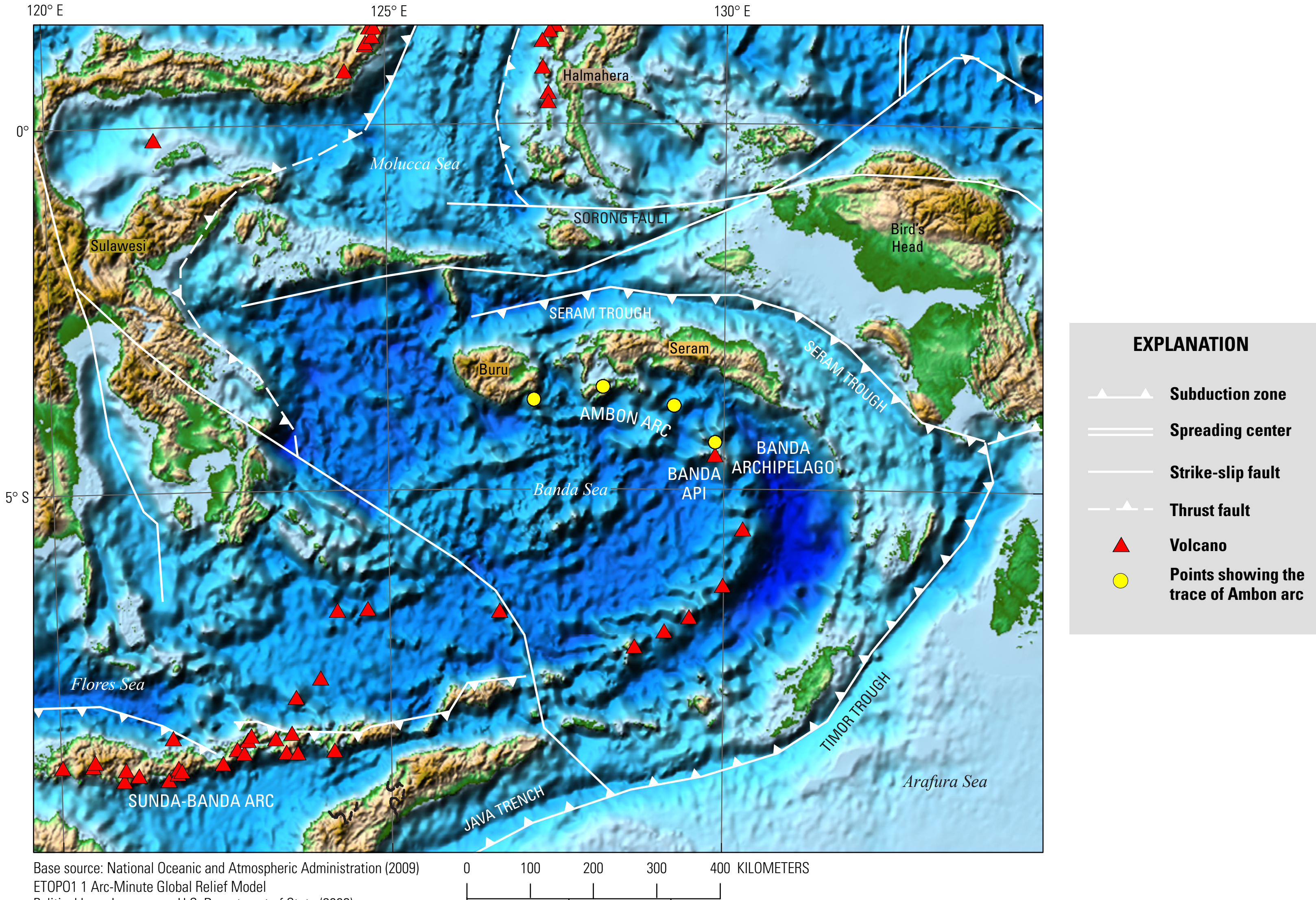


Figure J1. Map showing tract location and significant porphyry copper prospects for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia. ID, Indonesia; MY, Malaysia; PH, Philippines; PG, Papua New Guinea.



Base source: National Oceanic and Atmospheric Administration (2009)
ETOPO1 1 Arc-Minute Global Relief Model
Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 128° E; latitude of origin 15° S

Figure J2. Map showing the regional setting for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

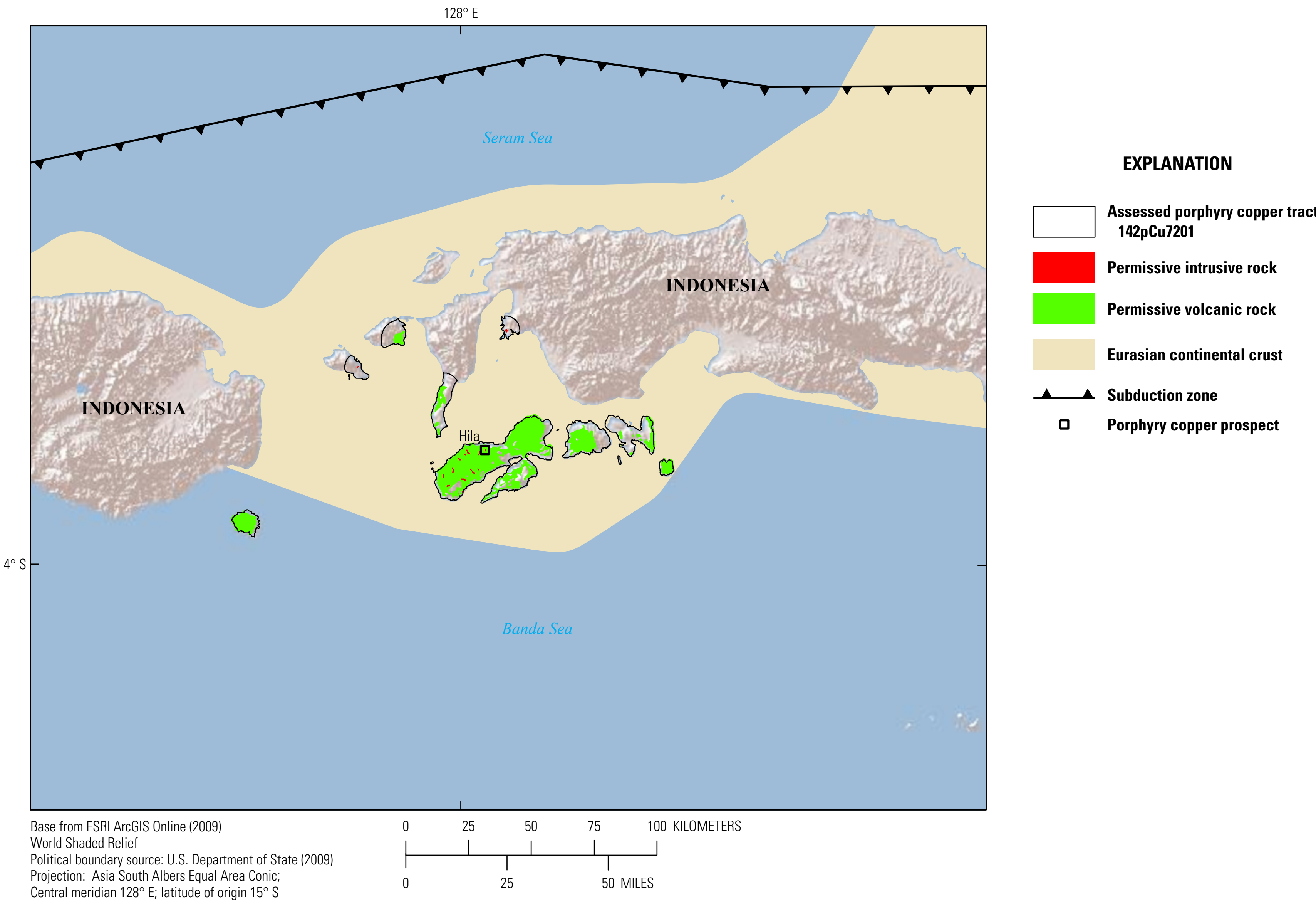


Figure J3. Map showing the distribution of permissive igneous rocks, tectonic features, and porphyry copper deposits and prospects for tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia.

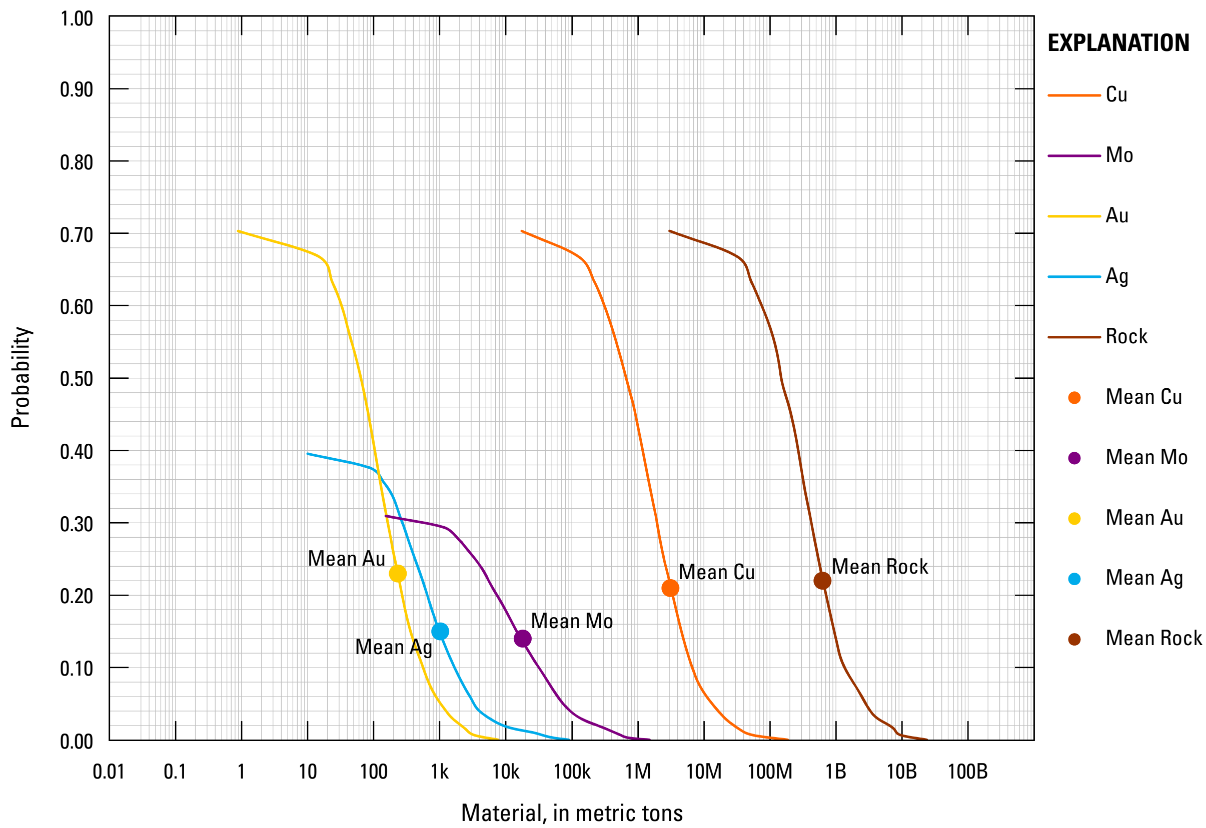


Figure J4. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7201, Ambon Arc, Central Molucca Islands—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix K. Porphyry Copper Assessment for Tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5] and Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage models: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table K1 summarizes selected assessment results.

Table K1. Summary of selected resource assessment results for tract 142pCu7202, Halmahera Arc—North Molucca Islands, Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	12,250	254,100	4,800,000	870,000

Location

The tract includes islands of North Maluku Province (Maluku Utara), Indonesia (fig. K1).

Geologic Feature Assessed

Neogene Halmahera island arc.

Delineation of the Permissive Tract

Tectonic Setting

The tract was delineated for Neogene igneous rocks of the Halmahera Arc along the western parts of Morotai and Halmahera Islands, Bacan Island, Obi Island, and several smaller islands of the North Moluccas in the Indonesian Province of North

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S Geological Survey, Spokane, Washington, United States.
[5]Mineral Resources Authority, Papua New Guinea.

Maluku (fig. K1). The 400-km-long, approximately north-south, Neogene to Holocene Halmahera magmatic arc extends from the western splay of the Sorong Fault at Obi Island in southwestern Halmahera, through Bacan Island and western Halmahera, to an area near the Philippine Trench north of the island of Morotai (fig. K2). Basement rocks for the Neogene arc in western Halmahera include Mesozoic or Tertiary volcanic rocks. The northeastern part of Halmahera Island lies on a basement of Cretaceous to Paleocene ophiolitic oceanic crust. After collision with the northern Australian margin at about 22 Ma and a period of quiescence, late Miocene to Pliocene magmatism related to east-dipping subduction of the Molucca Sea Plate migrated from south to north. The Molucca Sea Plate is almost entirely consumed by eastward subduction beneath the Halmahera Arc fragment of the Philippine Sea Plate and westward subduction beneath the Sangihe Arc of eastern Indonesia (Widiwijayanti and others, 2004). The collision zone at the convergence of the Halmahera and Sangihe Arcs marks the southern terminus of the Philippine mobile belt.

Geologic Criteria

Neogene arc rocks include diorite to granodiorite intrusions and andesites, with geochemical signatures indicating contributions of continental crust attributed to underlying Australian continental crust displaced along the Sorong Fault (Garwin and others, 2005). The northern, intraoceanic part of the arc has active volcanoes. The Neogene volcanic rocks are medium-to-high-K calc-alkaline two-pyroxene andesites and hornblende-bearing andesites with REE patterns and niobium depletion trends that are characteristic of West Pacific volcanic arcs (Hakim and Hall, 1991). The Bacan segment of the arc hosts dacites with continental trace-element signatures, as well as Quaternary basalts and andesites with oceanic affinities (Palmer, 1991). The oldest Neogene arc rocks (~11 Ma) are on Obi Island (MacPherson and others, 2003). The Neogene arc was produced by a mantle wedge that may have varied in the amount of prior melt extraction (depletion) along the length of the arc, and been metasomatized by fluids released from dehydration of subducted sediment and oceanic crust (MacPherson and others, 2003; Palmer 1991).

The tract was constructed in a GIS using 1:250,000-scale geologic maps of the Morotai, Ternate, and Bacan quadrangles, Indonesia; a 1:500,000-scale digital map of igneous rocks of Indonesia (Setiabudi, written commun., 2005); and geologic sketch maps included in Gemmell (2007). Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, Tertiary and Neogene (Oligocene-Miocene and Miocene-Pliocene) igneous rocks were selected (fig. K2). A 5-km buffer was applied around mapped intrusive-rock contacts, with a 2-km buffer around volcanic-rock contacts of these permissive lithologies; areas around Quaternary volcanoes where volcanic cover is likely to exceed 1 km were excluded.

The tract is based on map units listed in table K2. The main geologic units in the tract are andesites, breccias, and tuffs; these are interbedded with, and overlain by clastic sedimentary rocks and limestone. Small intrusive bodies of granite and granodiorite are mapped on Bacan Island (Bacan 1:250,000-scale geologic map), and small bodies of diorite and andesite are scattered through Tertiary and Quaternary andesitic volcanic units mapped in the Morotai and Ternate quadrangles. Locally, volcanic rocks are fractured and contain pyrite-bearing quartz veinlets (Apandi and Sudana, 1980). A database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group (SEARG) showed locations, ages, and lithologies for sample sites and provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). The age of the tonalite

Table K2. Map units that define tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[Map unit, age range, and principal lithologies are based 1:250,000 scale geologic maps of North Maluku, Indonesia]

Map unit	Map symbol	Lithology	Age range
		Intrusive rocks	
Intrusive rocks	gd	Granodiorite	Late Oligocene
		Volcanic rocks	
Andesite	An	Andesite	Holocene
Bacan Formation	Tomb	Andesite, volcanic breccia, lavas, tuffs, intercalations of conglomerate and sandstone	Late Oligocene
Obit Formation	Tmpo	Volcanic breccia and sandy tuff	Pliocene

associated with the Kaputusan porphyry copper deposit is unknown. Garwin and others (2005) described Kaputusan as a prospect associated with a Neogene quartz diorite intrusion in pre-Miocene volcanic host rocks. The SEARG database includes 28 isotopic age determinations on igneous rocks in the Bacan area of the Halmahera Arc; K-Ar ages (whole rock, biotite, hornblende) range from 21 to 1 Ma and include intermediate volcanic rocks (hornblende and pyroxene andesites) and intrusive rocks (quartz diorite, quartz monzodiorite). The age of the Gosowong intermediate-sulfidation epithermal system on Halmahera Island is 2.4–2.9 Ma (Olberg and others, 1999). De Waele and others (2009) suggest that the known mineral deposits in the North Moluccas, the Gosowong (Kencana mine) epithermal gold-silver deposit, and the undated Kaputusan porphyry copper-gold deposit formed in response to the end of eastward subduction and beginning of westward subduction in the Halmahera Arc. Dated rock samples include late Oligocene to early Miocene (29–23 Ma) feldspar porphyry and andesite at the northern end of the arc on Halmahera and Morotoi. Cretaceous and Neogene rocks are exposed at the southern end of the arc on Obi Island between strands of the Sorong Fault; Cretaceous rocks are excluded from the tract.

A polygon aggregation and smoothing process was applied to the revised buffered permissive geologic map units to produce a preliminary permissive tract. The processing approximates manual delineation of a tract but is rapid and reproducible. The processing steps include (1) unioning all permissive unit buffers and other polygon features that comprise the framework of the tract, (2) aggregating unioned polygons using an aggregation distance of 50 km and a minimum hole size of 2,000 km^2, (3) simplifying the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km, and (4) line-smoothing the simplified polygons using an algorithm (PAEK, polynomial approximation with exponential kernel)with a tolerance of 20 km. Necking, thinning, and contraction of the polygons resulting from processing required a subsequent manual cleaning step (for example, to remove polygon necks). Resulting tract boundaries were compared to the permissive geologic features in source materials to ensure that original permissive boundaries were honored. Regional and local mineral occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries. All operations were carried out in ArcGIS 9.3 using standard tools available in the Arc Toolbox.

These revised preliminary-tract polygons were further modified by comparison with the scanned and rectified geologic maps to exclude areas where Quaternary volcanic rocks or sedimentary deposits are greater than 1 km in thickness. The final tract boundary was clipped to the shoreline to eliminate undersea areas (U.S. Department of State, 2009).

The Halmahera tract contains a nature reserve (Gunung Sibela) and production forests, which may present a potential for land-use conflicts for exploration and development.

Known Deposits

The Kaputusan porphyry copper-gold deposit on Bacan Island contains identified resources of 77 Mt at 0.33 percent copper and 0.25 g/t gold (table K3). The deposit was discovered and drilled during a regional joint Indonesian-German exploration program done from 1977 to 1979; additional trenching and drilling occurred in 1983 and 1984 (Asia Gold, 2006, 2007). The best reported drill intercepts (<200 m depth in 10 vertical holes) are 48 m at 0.37 percent copper and 0.65 g/t gold and 153 m at 0.33 percent copper and 0.28 g/t gold. Higher copper- and gold-grade intercepts were encountered in trenches.

Table K3. Identified porphyry copper resources in tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Mo subtype, deposits that have Au/Mo ratios <3 or average Mo grades >0.03%; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent); n.d., no data]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Kaputusan	–0.517	127.583	Cu-Au	n.d.	77	0.33	n.d.	0.25	n.d.	254,100	Asia Gold (2006), Carlile and others (1998), Djaswadi (1993), Pudjowalujo and Bering (1982), van Leeuwen (1994)

In 2006, the exploration lease was converted to exploration status and split into two blocks (13,641 ha and 133,770 ha), and an additional lease area expanded the total area under exploration to 37,661 ha (South Gobi Energy Resources, 2007). Six diamond drill holes (<200 m depth) all intersected porphyry copper-gold mineralization, but technical problems thwarted completion of drilling. North Zone exploration results showed a 152 m section of 0.20 percent copper and 0.16 g/t gold; South Zone results included a 34 m section of 0.14 percent copper and 0.15 g/t gold.

Three mineralized zones (North, West, and South) are associated with altered (potassic; sericite-clay-chlorite), magnetite-bearing, tonalite porphyry stocks and tonalite porphyry dikes that intrude andesitic volcanic rocks. The stocks extend over an area of approximately 1,300 by 500 m. Exploration in 2006–2007 confirmed a 1.8 km-long-extent of mineralization along a north-south trend; the deposit is considered open along the trend (South Gobi Energy Resources, 2007).

Ore minerals include bornite, chalcopyrite, and gold. Supergene ore minerals include covellite, chrysocolla, malachite, and cuprite/tenorite (Pudjowalujo and Bering, 1982; van Leeuwen, 1994). A gold-rich (0.44 g/t gold) leached cap is present in the southern part of the deposit area. Biotite, sericite, chlorite, kaolinite, smectite, magnetite, gypsum, and hematite are present as alteration minerals. van Leeuwen (1994) reported a positive correlation between grade and intensity of quartz stockworks and noted that locally, fault-controlled quartz-sericite alteration overprints the deposit.

Prospects, Mineral Occurrences, and Related Deposit Types

Mineral occurrences west of the Kaputusan deposit include Masurung I and II, on Maluku, which are thought to be related to gold-copper porphyry systems. Five other copper occurrences also lie to the north and south of Kaputusan (Directorate of Mineral Resources and Inventory, 2004b; Garwin and others, 2005). Four low-grade porphyry copper-gold prospects are associated with the Pliocene (2.4–2.9 Ma) Gosowong quartz- adularia epithermal gold deposit in the northern part of the tract on Halmahera (Carlile and others, 1998; Gemmell, 2007). Seven partially explored prospects are included in the Indonesian database (Directorate of Mineral Resources and Inventory, 2004b); the deposit type for most of these is uncertain. Sites with reported copper are included in table K4 to illustrate the distribution of copper throughout the tract area. Note that these were considered uneconomic, reported grades are very low, and a number of prospects are closely spaced (within 2 km) which indicates that they may represent parts of the same system.

Exploration History

The Halmahera region initially was explored for porphyry copper deposits as part of an Indonesian-German program based on recognition of a possible link between the porphyry copper settings of Papua New Guinea and the Philippines (van Leeuwen, 1994). Stream-sediment and soil sampling identified the mineralization at Kaputusan. Exploration in the North Moluccas tract took place at the Kaputusan porphyry copper-gold deposit between 1981 and 1985 after the discovery of the deposit in 1979. The Indonesian Directorate of Mineral Resources did regional- and district- scale geochemical exploration for gold deposits. A project to characterize the Bora porphyry copper-gold prospect in the Gosowong district recently was announced (CODES, 2009).

Sources of Information

Principal sources of information used by the assessment team for tract 142pCu7202 are listed in table K5.

Grade and Tonnage Model Selection

The only known deposit in the tract, Kaputusan, is a porphyry copper-gold deposit (0.25 g/t gold). Molybdenum is reported (van Leeuwen, 1994), but no grade is available. Statistical tests (ANOVA) for Kaputusan against the global general and Cu-Au subtype models support use of either model (table 6). The team selected the porphyry copper-gold model, based on classification of Kaputusan and the description of low-grade copper-gold porphyries in the Gosowong district.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The assessment team considered the distribution of permissive rocks within the tract; the presence of one confirmed porphyry copper-gold deposit at Kaputusan; additional occurrences of copper and gold; and the possibility that, if fully explored, the porphyry prospects in the Gosowong district could represent one or more deposits like those included in the grade and tonnage model. Molybdenite, bornite, chalcopyrite, and pyrite are reported in the map unit descriptions for intrusive rocks in the Bacan 1:250,000-scale quadrangle, some of which intrude the extensive Bacan Formation which is propylitized in some areas (Yasin, 1980). Blocks of silicified tuff in the Ternate quadrangle contain malachite and azurite (Apandi and Sudani, 1980). These observations suggest that additional porphyry systems may be concealed beneath volcanic cover rocks. On the basis of this information, the team estimated a 50-percent chance that the tract may contain one or more undiscovered deposits, a 10-percent chance of three or more deposits, and a 5-percent chance of six or more deposits (table K6). The high standard deviation (±1.5) and coefficient of variation (110 percent) reflect the team’s uncertainty about the potential of the tract.

Table K4. Significant prospects and occurrences in tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[*,Tobobo, Matat, and Ngoali are located ~ 2, 6, and 9 kilometers (km) north of the Bora porphyry, respectively. These four areas may all represent one porphyry system. The other groups include prospects within 2 km of each other, which may represent parts of single systems. Rank 4=prospect in global database of Singer and others (2008) or <16,000 t contained copper; Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream-sediment or magnetic anomaly, or location along structural trend. n.d., no data; %, percent; t, metric tons; Mt, million metric tons]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Payahe	0.332	127.751	n.d.	Copper veinlets; 46,800 t (measurable); 0.20% Cu.	Directorate of Mineral Resources and Inventory (2004b)	1
Bora Group						
Tobobo and Bora*	1.137	127.677	n.d.	Low-grade porphyry Cu-Au center of mineralization associated with porphyritic quartz diorite 2.5 km WNW of the Gosowong epithermal deposit in the Gosowong district (reportedly subeconomic). Location for Toboba; Bora <0.5 km west of Toboba.	Carlile and others (1998), Gemmell (2007)	2
Matat and Ngoali*	1.188	127.690	n.d.	Gosowong area. Porphyry stock within argillically-altered Miocene volcanics ~2 km due north of the Gosowong vein (reportedly subeconomic). Matat porphyry is located ~6 km NE of the Bora-Tobobo area; Ngoali is ~ 3 km NW of Matat. Location plotted for Matat.	Gemmell (2007)	2
Masurung Group						
Masurung I (Kaputusan Selatan I)	–0.463	127.403	n.d.	Inactive Cu-Au porphyry prospect associated with tonalite.	Directorate of Mineral Resources and Inventory (2004b)	1
Masurung II	–0.458	127.403	n.d.	Inactive Cu-Au porphyry prospect associated with tonalite.	D.N. Sunuhadi (written commun., 2004)	1
Sugili (Kaputusan Utara)	–0.470	127.406	n.d.	Inactive Cu-Au porphyry prospect associated with tonalite. Alteration: argillic, biotite, epidote, potassic, propylitic, phyllic.	D.N. Sunuhadi (written commun., 2004)	1
Hulu Group						
Hulu S	–0.551	127.399	n.d.	Hydrothermal, 100 Mt (measurable); 0.3% Cu.	Directorate of Mineral Resources and Inventory (2004b)	4
Kapatusan P. Bacan	–0.554	127.394	n.d.	Hydrothermal, 70 Mt, 0.3% Cu.	Directorate of Mineral Resources and Inventory (2004b)	4

Table K5. Principal sources of information used for tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	Geological Survey of Japan (1997)
	Digital geologic map of Indonesia	1;100,000	Directorate of Mineral Resources and Inventory (2004a)
	Geologic map of the Ternate Quadrangle, North Maluku	1:250,000	Apandi and Sudana (1980)
	Geologic map of the Morotai Quadrangle, North Maluku	1:250,000	Supriatna (1980)
	Geologic map of the Bacan Quadrangle, North Maluku	1:250,000	Yasin (1980)
	SE Asia Radiometric Ages: GIS database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence data base	NA	Directorate of Mineral Resources and Inventory (2004b)
Exploration	25 Years of mineral exploration and discovery in Indonesia	NA	van Leeuwen (1994)
	Mining company Web sites	NA	Asia Gold (2006, 2007)

Table K6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
0	1	3	6	6	1.5	1.8	110	1	2.5	12,250	20

Table K7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	870,000	12,000,000	24,000,000	4,800,000	0.22	0.31
Mo	0	0	0	58,000	140,000	29,000	0.16	0.63
Au	0	0	80	930	1,700	340	0.25	0.31
Ag	0	0	0	3,000	7,000	1,600	0.16	0.56
Rock	0	0	210	2,600	4,800	970	0.24	0.31

Probabilistic Assessment Simulation Results

Undiscovered resources for the North Moluccas permissive tract 142pCu7202 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold grade and tonnage model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table K7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. K3). The cumulative frequency plot shows the amounts of estimated resources associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. Median (870,000 t copper) and mean (4.8 Mt copper) copper resources that could be associated with undiscovered deposits in the tract greatly exceed the identified resource at Kaputusan (254,100 t copper).

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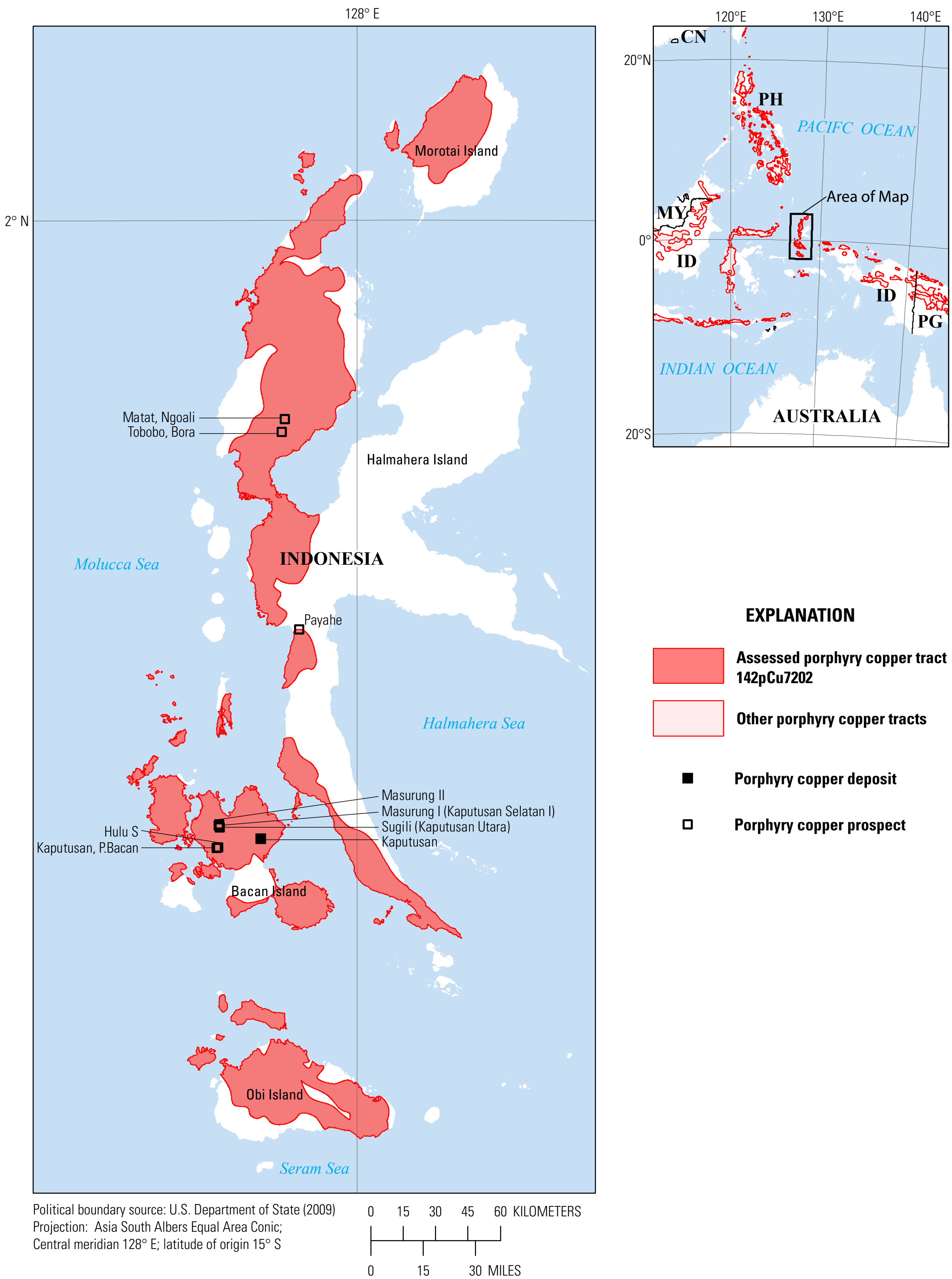

Figure K1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia. CN, China; ID, Indonesia; MY, Malaysia; PH, Philippines; PG, Papua New Guinea.

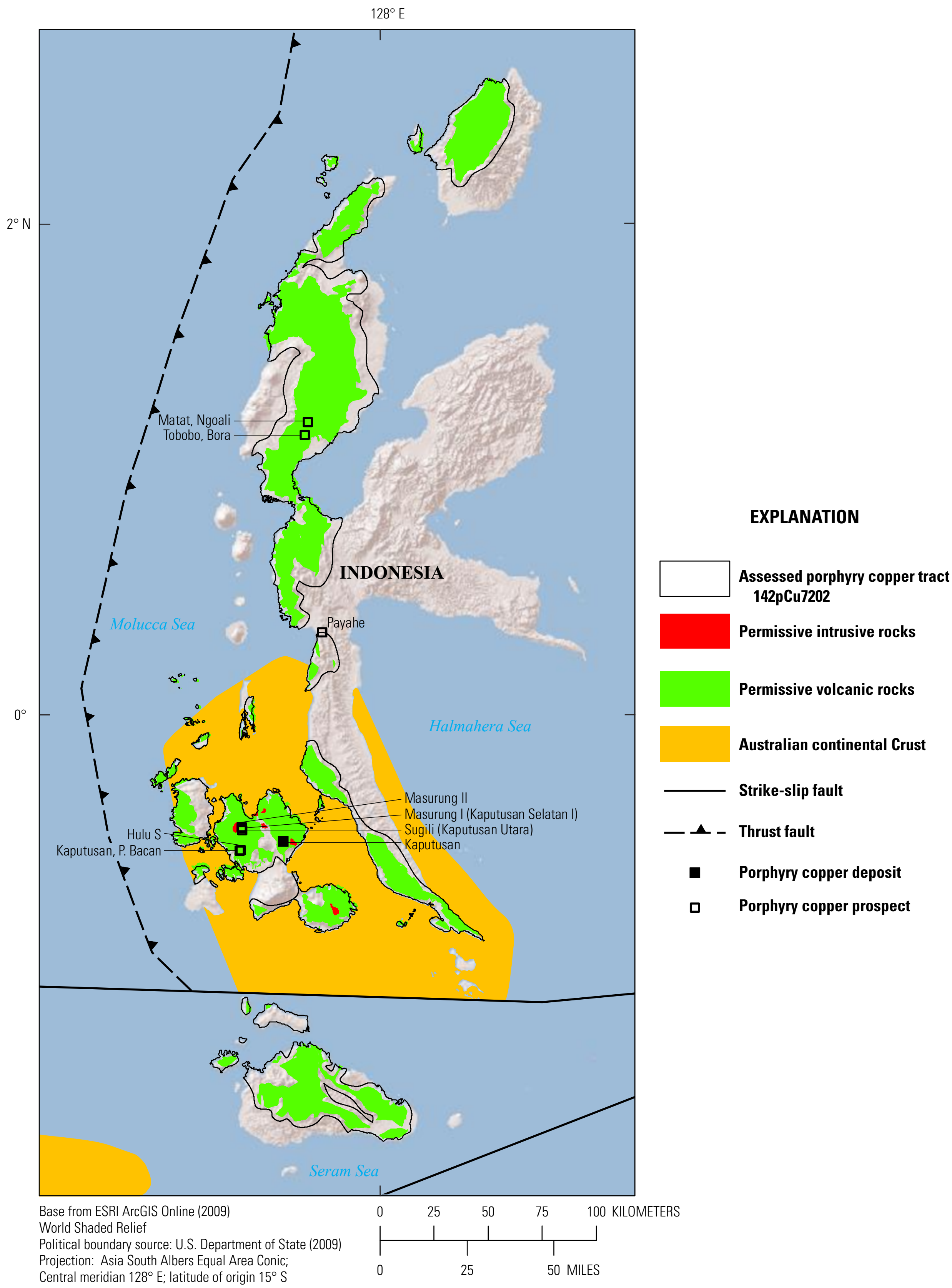

Figure K2. Map showing the distribution of permissive igneous rocks and porphyry copper deposits and prospects for tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia.

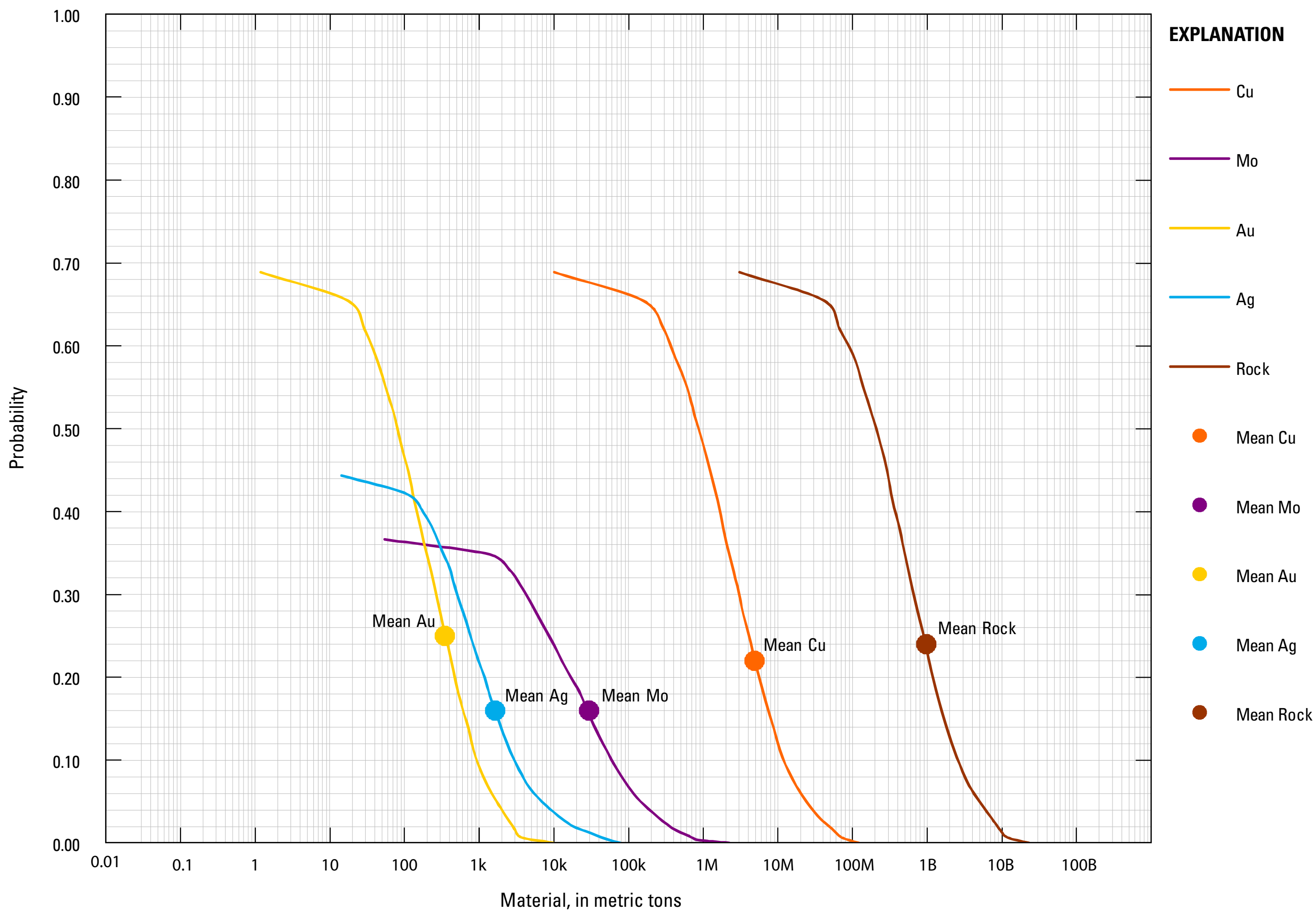

Figure K3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7202, Halmahera Arc, North Molucca Islands—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix L. Porphyry Copper Assessment for Tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5] and Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage models: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table L1 summarizes selected assessment results.

Table L1. Summary of selected resource assessment results for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	13,580	n.d.	3,200,000	660,000

Location

The tract includes the Bird's Head and Bird's Neck areas of West Papua Province, as well as the Ular Merah area of the western Central Range of Papua Province (Irian Jaya), Indonesia (fig. L1).

Geologic Feature Assessed

Miocene Moon-Utawa Arc and coeval rocks in the Ular Merah area of Papua and West Papua Provinces, Indonesia.

Delineation of the Permissive Tract

Tectonic Setting

The tract delineates middle to late Miocene igneous rocks on western New Guinea Island (fig. L2). The tract includes three areas: A, the Moon Arc area in the northern part of the Bird's Head region; B, the Utawa diorite in Bird's Neck region; and C,

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S Geological Survey, Spokane, Washington, United States.
[5]Mineral Resources Authority, Papua New Guinea.

the Ular Merah area of the western Central Range of the Bird's Body region (fig. L2). These rocks are age-equivalent to the Maramuni Arc in the Mobile Belt of Papua New Guinea (tract 009pCu7205).

The name Moon-Utawa Arc (fig. L1, areas A and B) was proposed by Carlile and Mitchell (1994) for the middle Miocene Moon Volcanics of the northern part of the Bird's Head and the mid-Miocene Utawa Diorite of the Bird's Neck. Garwin and others (2005) noted that although there is igneous activity in this region, the relation of the arc to a subduction zone is not clear. The Miocene rocks may have formed in a north-facing arc along a passive continental margin prior south-directed thrusting in the late Miocene (Melanesian orogeny) that displaced the Utawa Diorite to the south along the Weyland thrust (fig. 7) (Carlile and Mitchell, 1994; Dow and Robinson, 1985). The Moon Volcanics may be linked to the Maramuni Arc, but as noted by Malaihollo and Hall (1996), the nature and distribution of the volcanism and its relation to the Maramuni rocks remains unclear. The Miocene igneous rocks in western New Guinea lie within allochthonous arc/forearc terranes and may have originated much farther (>500 km) northeast of their present location (Cloos and others, 2005). The Bird's Head block, or microplate, represents a recent escape tectonic zone formed by convergence of the Australian Plate with volcanic arcs (Pubellier and Ego, 2002).

The Ular Merah area (fig. L1, area C) was not known to be of Miocene age prior to a recent study that established the age, chemistry, and isotopic signature (Jackson, 2010). The Ular Merah Miocene rocks may have formed due to partial remelting of mid-Cenozoic arc garnet-bearing plutons mixed with an asthenospheric mantle component (as indicated by the isotopic signature) and generated in a mid-Miocene spreading center in the Ayu Trough (see fig. 6). The Ayu Trough is an intraoceanic rift system that marked the southeastern boundary between the Philippine and Pacific Plates, prior to left-lateral fault displacement of the Ayu Trough during the last 4 million years (Jackson, 2010). The relationship to the Moon-Utawa Arc is unknown.

Geologic Criteria

The tract was constructed in a GIS using 1:250,000-scale geologic maps of Indonesia, a 1:500,000-scale digital map of igneous rocks of Indonesia (Directorate of Mineral Resources and Inventory, 2004a) and the 1:1,000,000-scale geologic map of Irian Jaya (Dow and others, 1986). Maps and figures showing the major faults, lineaments, and tectonic divisions of New Guinea by Garwin and others (2005), Hill and others (2002), and Quarles van Ufford and Cloos (2005) also were used. Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, all igneous rocks of Miocene age (>7 Ma and exclusive of rocks mapped as late Miocene or younger) were selected. Ophiolites, ultramafic rocks, and basaltic units were deemed non-permissive and are omitted from the tract. Map units included in the tract are listed in table L2.

The final tract boundaries were established by GIS processing and editing. The processing approximates manual delineation of tracts but is rapid and reproducible. The processing steps included (1) unioning of buffered permissive map units and other polygon features that comprise the framework of the tract; (2) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2 (this step was done to group closely spaced permissive areas); (3) manually aggregating and adjusting of tract areas; and (4) smoothing polygons using an algorithm (PAEK, polynomial approximation with exponential kernal) with a tolerance of 1 km. Preliminary tracts were cleaned to remove necking and thinning introduced by processing; tracts were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

The three tract areas are (fig. L1):

A. Moon Arc, Northern Bird's Head.—This area outlines the middle Miocene Lembia diorite, Moon Volcanics, Mandi Volcanics, and Dore Volcanics along the northern margins of the Bird's Head, north of the Sorong Fault. Carlile and Mitchell (1994) noted extensive hydrothermal alteration in the andesitic Moon Volcanics. An area that extends north of the Sorong Fault to the coast includes the historical Alpha prospect in the Moon Volcanics of the Bird's Head. The area is the focus of Hillgrove Resources (2009a,b,c; 2010) recent advanced exploration projects (Delta West, Delta, Golf, Bravo, Alpha, and Foxtrot prospects). Carlile and Mitchell considered the Moon-Utawa Arc to be underexplored in 1994. No deposits are known in this part of the tract.

B. Utawa Arc, Bird's Neck.—Area B outlines the Utawa Diorite in the Weyland overthrust in the Bird's Neck area. These rocks were emplaced (either intruded or by faulting) in the Melanesian Arc, translated westward as much as 500 km or more (Cloos and others, 2005), and displaced southwards from the late Miocene to the present. This part of the tract lacks known deposits and volcanic rocks; it contains more than 10 sites where anomalous gold has been detected by exploration, mainly in stream sediments. No deposits are known in this part of the tract.

C. Ular Merah, western Central Range.—The Ular Merah area is centered on a Miocene (17.4–16.6 Ma) porphyry system that intruded the allochthonous Central Ophiolite Belt in Irian Jaya, approximately 150 km northwest of the Erstberg mining district (Jackson, 2010). In the Ular Merah area, Jackson (2010) described 11 mid-Miocene intrusions as high-K calc-alkaline porphyritic diorites and monzodiorites characterized by low initial $^{87}Sr/^{86}Sr$ isotopic ratios (~0.704) and radiogenic εNd (~3.9). She demonstrated that the Ular Merah rocks are chemically distinct from coeval rocks in Papua New

Table L2. Map units that define tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[Map unit, age range, and principal lithologies are based on a digital compilation of geologic maps of Indonesia (Directorate of Mineral Resources and Inventory, 2004a) and scanned and rectified 1:250,000-scale quadrangle maps of Irian Jaya. Map symbols, lithology, and age ranges are based on 1:250,000-scale geologic maps. *, intrusions in this area recently dated as mid-Miocene (Jackson, 2010). See table L4 for references]

Map unit	Map symbol	Lithology	Age range
		Moon Arc area	
Moon Volcanics	Tmm	Andesite; comagmatic diorite intrusions	Middle Miocene
Dore Volcanics	Tmdo	Andesitic lava; include small bodies of diorite	Miocene
Mandi Volcanics	Temm	Basalt to andesite; includes small bodies of gabbro, diorite, granodiorite, porphyritic andesite	Oligocene to middle Miocene
		Utawa Arc area	
Utawa Diorite	Tmu	Diorite, quartz diorite	Middle Miocene
		Ular Merah area	
Auwewa Formation	Tema	Island-arc volcanic rocks, subvolcanic diorite and microdiorite intrusions	Eocene to early Miocene*

Guinea (Maramuni Arc), from Pliocene rocks in the Medial New Guinea magmatic belt, and from older intrusions in the Ophiolite Belt.

Area C was delineated based on mapped exposures of Auwewa Formation (Eocene to early Miocene volcanic, subvolcanic diorite and microdiorite intrusions) in the Ular Merah area and was extended to include dated samples described by Jackson (2010, table 1-1 and fig. 1-4).

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

The Moon Arc area includes more than 10 discrete historical stream-sediment anomaly localities, as well as copper and gold soil anomalies. Channel sampling at the West Delta prospect identified copper (0.6–3.1 percent), gold (<0.001–1.98 ppm) and molybdenum (1–512 ppm) in potassic and phyllic alteration zones associated with a breccia target and aeromagnetic highs (table L3) (Hillgrove Resources, 2010).

The Utawa area includes about 15 sites reported as anomalous in gold (Directorate of Mineral Resources and Inventory, 2004b), including stream-sediment sites and exploration sites.

Exploration History

The Indonesian Directorate of Mineral Resources explored throughout Papua and West Papua in 2004.

The Bird's Head area is under exploration for porphyry copper and epithermal gold deposits (Hillgrove Resources, 2009a,b,c; 2010).

The Utawa area was included in the Directorate of Mineral Resources Inventory, and parts of the area were covered by PT Nabire Bakti Mining's contract of work (COW). The team is unaware of any current exploration activity in the Utawa area.

The Ular Merah tract area covers Block 2 of Eastern Minerals COW exploration area. PT Freeport Indonesia explored the Ular Merah area in 2007; five cores drilled in areas of anomalous copper and gold in soil samples showed little evidence of copper mineralization (Jackson, 2010).

Sources of Information

Principal sources of information used by the assessment are listed in table L4.

Grade and Tonnage Model Selection

No porphyry copper deposits with identified resources are known within the tract. The team considered both the

Table L3. Significant prospects and occurrences tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[Ages all assumed to be Miocene based on associated map units or dated igneous rocks. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ppb, parts per billion]

Name	Latitude	Longitude	Comments	Reference	Rank
			Moon Arc area		
Alpha prospect (Bird's Head project)	–0.628	132.604	Alpha prospect area; discovered by stream-sediment sampling, intermediate to felsic volcanics, volcaniclastics, and hypabyssal intrusions (Moon Volcanics); epithermal Au, Pb-Zn-Ag, and Au-Cu phase. Soil sampling, trenching; recon drilling (5 holes on Au soil anomaly); drill intercepts 17.45 m at 0.29% Cu, 2.16 g/t Au, 18.36 g/t Ag, 2.08% Pb, and 5.31% Zn.	Hillgrove Resources (2009a,b,c; 2010)	2
Delta prospect (Bird's Head project)	–0.415	132.636	Low-grade copper intersected in drilling (102.4 m at 0.21% Cu) associated with a granodiorite/diorite intrusion; 6 by 1.5 km copper soil anomaly zone; possible epithermal Au-Ag. Zoned hydrothermal alteration mapped around a breccia at the West Delta prospect. Circular features and clusters of aeromagnetic highs may represent shallow buried intrusions.	Hillgrove Resources (2009a,b,c; 2010)	3
			Utawa Arc area		
Sungai Depa-Sungai Waria	–3.648	135.802	100 to 200 ppb Au associated with Utawa Diorite; chalcopyrite, pyrite, pyrrhotite.	Directorate of Mineral Resources and Inventory (2004b)	1

Table L4. Principal sources of information used for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[CCOP, Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia; NA, not applicable]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Indonesia	1;1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Geologic quadrangle maps (Enaratoli, Sorong, Kasim, West Waigeo and Misool quadrangles)	1:250,000	Harahap and others (1990); Sanyoto and others (1985)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
	Geologic map of Irian Jaya, Indonesia	1:1,000,000	Dow and others (1986)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)
Exploration	Company Web sites	NA	Hillgrove Resources (2009a,b,c; 2010), van Leeuwan (1994)

general global porphyry copper and the global copper-gold subtype models of Singer and others (2008). Based on selection of the copper-gold model for the age-equivalent Miocene Maramuni Arc of Papua New Guinea, recent exploration targets for copper-gold systems, and the likelihood that further characterization may establish that a copper-gold model is more appropriate for assessing undiscovered resources in this part of Indonesia, the copper-gold subtype model was used. The general model was tested for comparison. Note that statistical test for the Maramuni tract, based on ANOVA tests for the Frieda River deposit, also supports either model.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The three areas differ in level of exposure: Moon Arc area (A), mainly volcanic; Utawa Arc area (B), entirely intrusive; Ular Merah area (C), volcanic with very small, subvolcanic intrusions. In the age-equivalent Miocene Maramuni Arc in Papua New Guinea, the volume of intrusive rocks is greater than the volume of preserved volcanic rocks, and volcanic rocks are more abundant on the southern margin of the tract. The 12–14 Ma Frieda River deposit (1,060 Mt, 0.52 percent copper, 0.004 percent molybdenum, 0.31 g/t gold) in Papua New Guinea is within the Maramuni tract (009pCu7205). The team considered the likelihood that continued exploration in the Bird's Head area could lead to a discovery. Aeromagnetic data noted in recent exploration in the Bird's Head over an area of more than 900 km^2 along with geochemical data from exploration trenching, copper and gold soil anomalies, and mapped alteration indicate that porphyry copper deposits may be present in the subsurface (Hillgrove Resources, 2010). Further drilling is required to document the extent and quality of any potential deposits.

The Utawa area is not well-explored, but does include some indications of copper mineralization associated with the Utawa diorite. The Ular Merah area has been drilled, with no promising results reported. On the basis of this information, the team made estimates for the entire tract area: a 50-percent chance of one or more deposits and a 10-percent chance of two or more deposits (table L5), which results in a mean of 1± 0.8 deposits.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the copper-gold subtype model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). The simulation also was run using the general global porphyry copper model for comparison. Selected simulation results are reported in table L6. Results of the Monte Carlo simulations are presented as a cumulative frequency plots (fig. L3). The cumulative frequency plots show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The simulation based on the general model predicts a mean amount of 3.8 Mt copper, 110,000 t molybdenum, 93 t gold, and 1,200 t silver (table L6). Note that the probabilities of zero (none) are 0.5 or more for molybdenum, gold, and silver using the general model. Based on the simulation using the copper-gold subtype model, the mean amount of copper is 3.2 Mt and the simulation predicts a 50-percent chance of 64 or more tons of gold. For both models, the mean copper exceeds the median (0.5 probability) by an order of magnitude.

Table L5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; $C_v\%$, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and $C_v\%$ are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	$C_v\%$	N_{known}	N_{total}		
0	1	2	2	2	1	0.79	79	0	1	13,580	7

Table L6. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	*A*. Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	810,000	8,100,000	15,000,000	3,800,000	0.22	0.29
Mo	0	0	0	200,000	440,000	110,000	0.15	0.55
Au	0	0	0	230	420	93	0.20	0.51
Ag	0	0	0	2,300	5,100	1,200	0.16	0.64
Rock	0	0	190	1,700	3,000	760	0.24	0.29

Material	*B*. Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	660,000	7,200,000	15,000,000	3,200,000	0.21	0.3
Mo	0	0	0	30,000	73,000	18,000	0.14	0.68
Au	0	0	64	560	1,000	230	0.23	0.3
Ag	0	0	0	2,000	4,400	1,100	0.15	0.59
Rock	0	0	150	1,500	3,100	640	0.22	0.3

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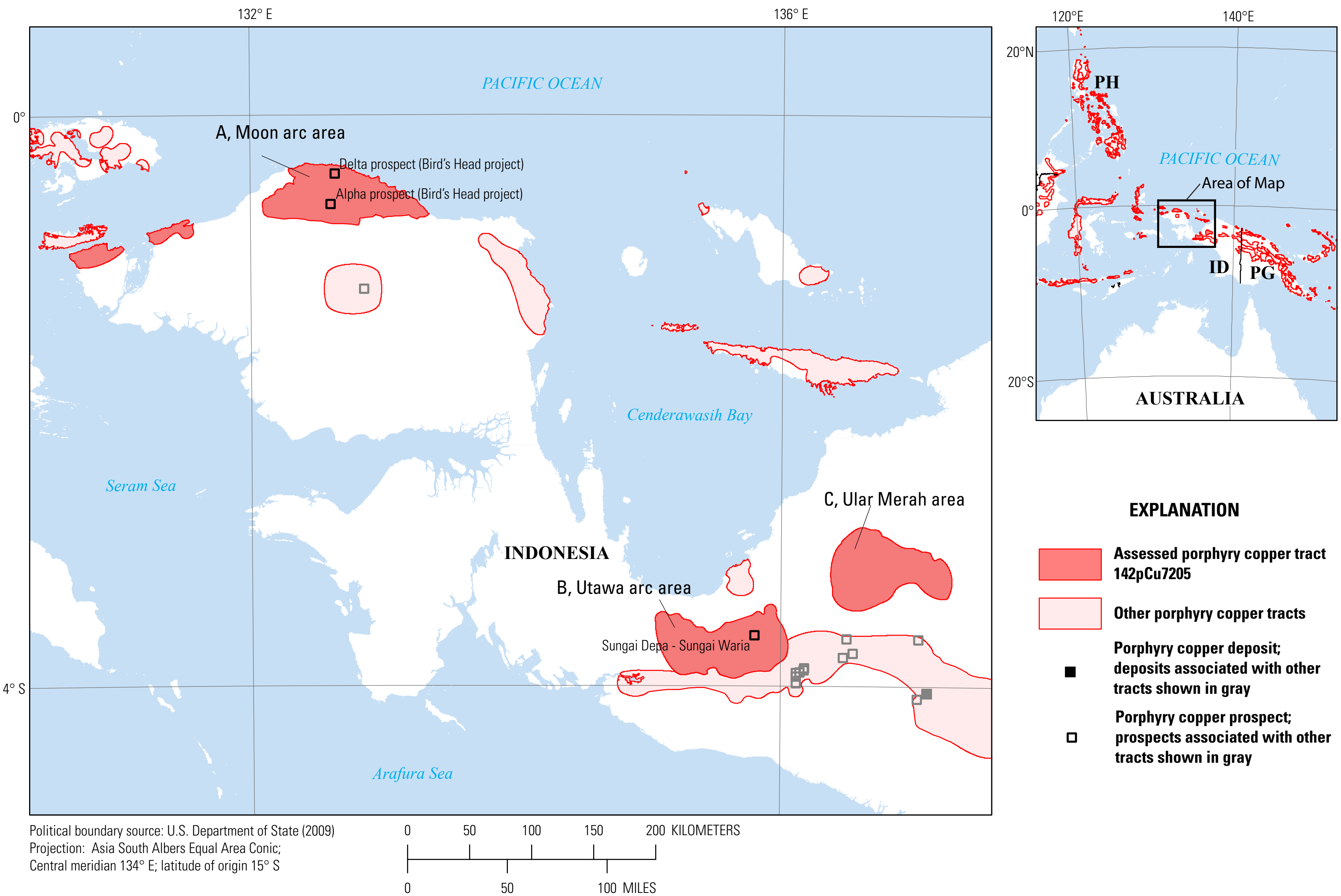


Figure L1. Map showing tract location and significant porphyry copper prospects for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia. ID, Indonesia; PH, Philippines; PG, Papua New Guinea.

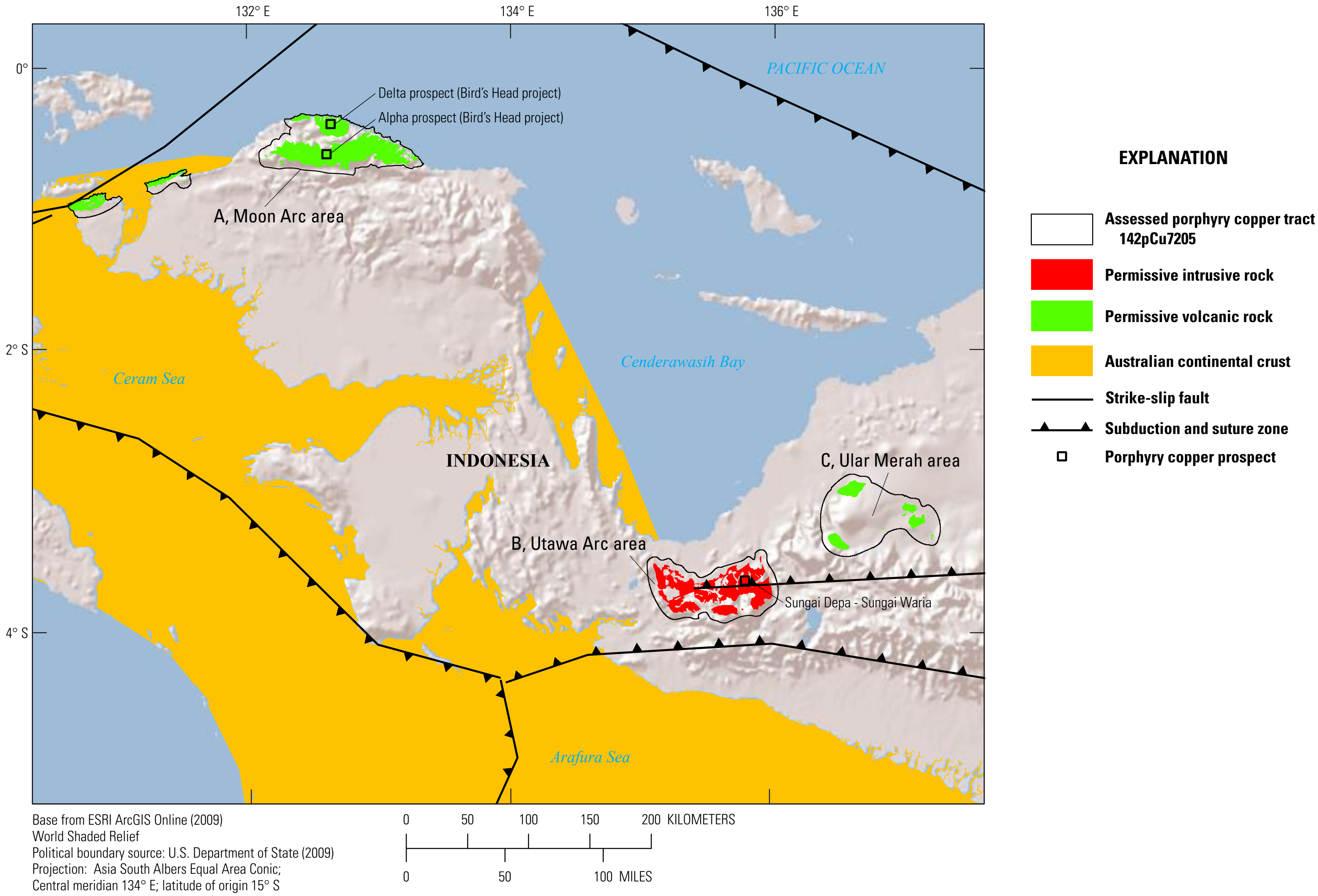
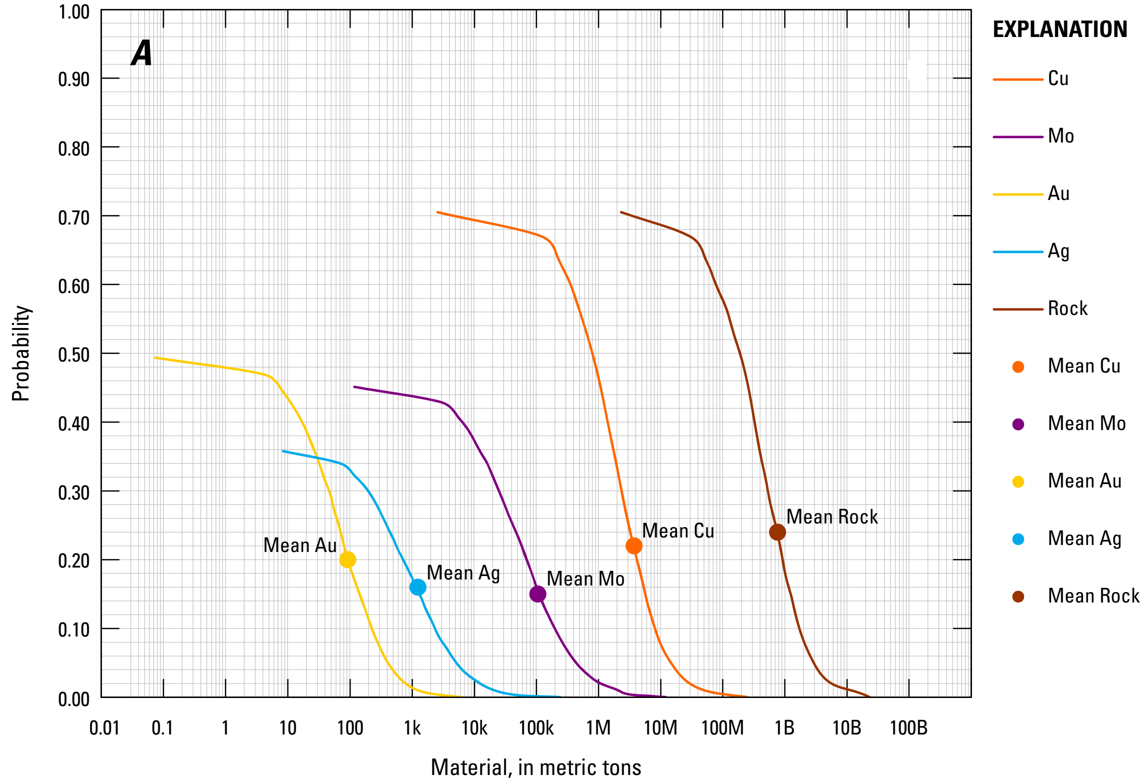


Figure L2. Map showing the distribution of permissive igneous rocks for tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia.



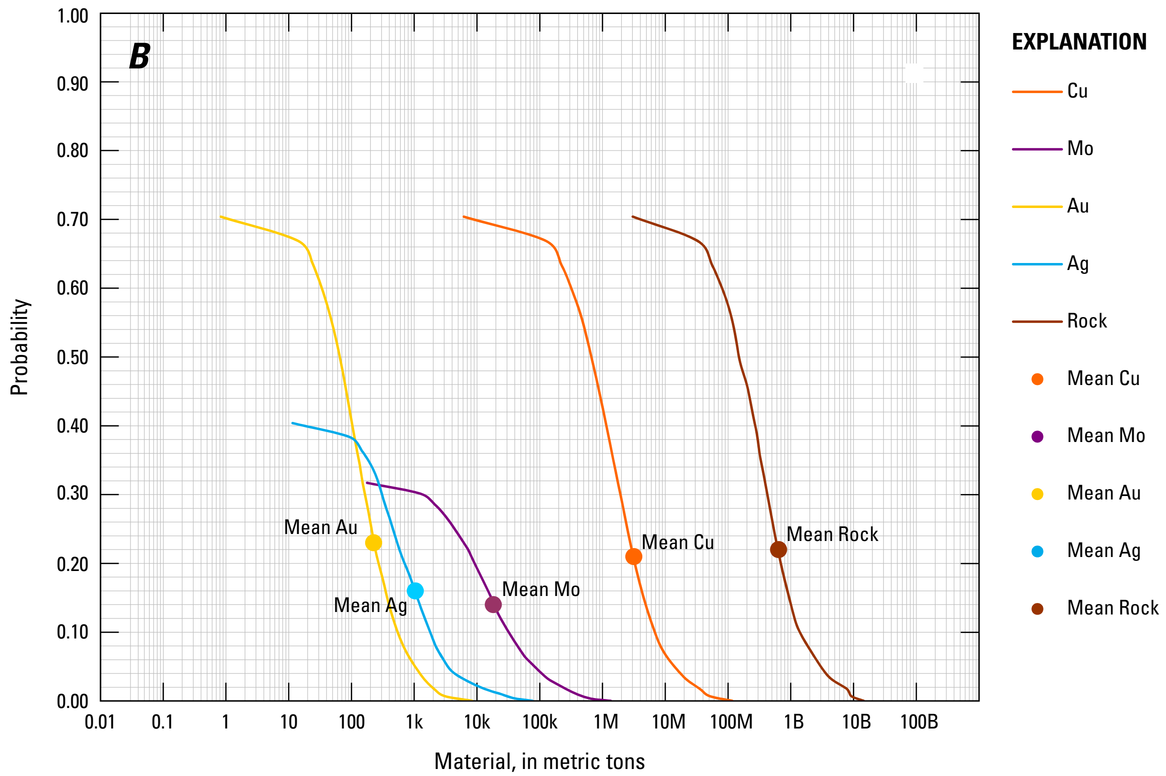


Figure L3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7205, Moon-Utawa-Ular Merah Areas—Indonesia. *A,* Based on general porphyry copper grade and tonnage model. *B,* Based on porphyry copper, copper-gold subtype grade and tonnage models. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix M. Porphyry Copper Assessment for Tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5] and Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table M1 summarizes selected assessment results.

Table M1. Summary of selected resource assessment results for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	13,270	24,000,000	14,000,000	6,500,000

Location

The tract includes the Central Highlands of New Guinea Island and the Indonesian provinces of West Papua and Papua, formerly known as Irian Jaya (fig. M1).

The tract represents the western part of the Medial New Guinea magmatic belt, an 1,800-km-long, east-west belt of discontinuous exposures of late Miocene to Pliocene igneous rocks that spans the fold belt of central New Guinea Island (fig. 3, no. 13; fig. 7). The eastern part of the belt is represented by tract 009pCu7203.

Geologic Feature Assessed

The late Miocene to Pliocene-Pleistocene Medial New Guinea magmatic belt.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S. Geological Survey, Spokane, Washington, United States.
[5]Mineral Resources Authority, Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

Tract 142pCu7203 outlines exposed segments of the late Miocene and Pliocene to Pleistocene Medial New Guinea magmatic belt in the Indonesian provinces of Papua and West Papua. The magmatic belt formed from convergence of the Indo-Australian and Pacific Plates during the Cenozoic (fig. 6). The tract lies within the western Papuan fold belt (fig. 7). No well-defined subduction zone is associated with the belt, although seismic tomography suggests the existence of old subduction slabs within the mantle under New Guinea (Hall and Sparkman, 2002; Garwin and others, 2005). South-dipping subduction following a reversal in subduction polarity, post-collision uplift, and transitions to extensional tectonism all have been postulated to explain the lower volume, more alkaline, post-Maramuni Arc (Miocene) magmatic activity (Housh and McMahon, 2000). As noted by Garwin and others (2005), the tectonic trigger for the high-K, calc-alkaline to alkaline magmatic event is not well understood, but it is likely related to the southward progressing compressional deformation that formed and uplifted the fold belt as a result of convergence of New Guinea and the Caroline Plate to the north (fig. 6). Local dilational zones formed at intersections of strike-parallel (generally east-west) frontal thrust faults and strike-perpendicular long-lived crustal transfer structures, expressed as lineaments, facilitated emplacement of magmas and associated porphyry copper-gold mineralization in central New Guinea (Hill and others, 2002). Cloos and Housh (2008) described the coincidence of magmatic-hydrothermal and structural conditions that led to the formation of the giant Grasberg orebody at about 3 Ma. Namely, the deposit was emplaced in a pull-apart zone along an active strike-slip fault. They attribute the elevated Au/Mo ratio to magma formed in a collisional delamination (rather than a subduction) tectonic setting, where the local structural environment and rate of solidification facilitated concentration of a metal-rich cupola to form the deposit. Cloos and others (2005) concluded that rocks formed from the short-lived (7–2.5 Ma) magmatic event are localized at the highest elevation in the Central Highlands because they formed above the zone of maximum asthenospheric upwelling as a result of collisional delamination. The structural style that characterized the Grasberg area has not been documented for Pliocene calc-alkaline intrusions farther to the west, such as at the Aisasjur porphyry copper prospect in the Bird’s Head (Garwin and others, 2005).

The nature of the basement in the western and eastern parts of Medial New Guinea magmatic belt differs from west to east. Tract 142pCu7203 delineates parts of the belt that lie west of the Tasman Line. The Tasman Line is interpreted as extending roughly north-south to northwest through an area approximately 100 km west of the modern Indonesian (Irian Jaya)-Papua New Guinea border (fig. 6 of main report). The Tasman Line defines two crustal provinces in northern Australia and is projected north into New Guinea Island: Paleozoic basement of the accreted terranes of the Tasman orogen lie to the east of the line; the stable craton with Precambrian basement lies to the west (Hill and Hall, 2003). These differences in basement affect the crustal response to deformation, and may influence the character of porphyry-related magmas.

Geologic Criteria

The tract was constructed in a GIS using a 1:1,000,000-scale digital map of igneous rocks of Indonesia (Directorate of Mineral Resources and Inventory, 2004a), along with the 1:1,000,000-scale geologic map of Irian Jaya (Dow and others, 1986), and 1:250,000-scale maps of Indonesia (Geological Research and Development Centre, 1987–2000). Maps and figures showing the major faults, lineaments, and tectonic divisions of New Guinea by Garwin and others (2005), Hill and others (2002), and Quarles van Ufford and Cloos (2005) also were used.

Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic) based on map legend attributes (table M2). From this digital database of map units grouped by age and lithology, all igneous rocks of late Miocene to Pliocene age were selected. Examination of cross sections on 1:250,000-scale geologic maps showed that most intrusive rocks of this age range are shown as steep-sided, cylindrical or finger-like intrusive bodies with a subsurface horizontal extent of <2–5 km; vertical extents can exceed 1 km. On Indonesian maps, predominantly volcanic units may include small intrusive bodies of diorite or microdiorite.

Using GIS tools, a 5-km buffer was applied around mapped igneous contacts of permissive lithologies to account for spatial uncertainty in digitized geology and for the possibility of greater extent of permissive rocks within a kilometer of the surface. Ophiolites and ultramafic rocks, basaltic units, and units that are predominantly ash flows, tuffs, and agglomerates were deemed nonpermissive and are omitted from the tract.

The buffered map units were aggregated using GIS processing tools with a 15 km distance to group closely spaced permissive areas, which were then edited to honor fault boundaries and include other areas of known igneous rocks of appropriate age and lithology. Databases of isotopic ages of igneous rocks for Indonesia and for Papua New Guinea compiled by the Southeast Asia Research Group provided additional information on locations, ages, and lithologies of permissive rocks (Malaihollo and others, 2002).

Late Miocene to Pliocene intrusions associated with porphyry copper mineralization crop out as hypabyssal intrusive bodies and small dikes and plugs; many are too small to show on 1:250,000-scale maps.

No regional-scale aeromagnetic data were available to the assessment team. However, the geophysical signature of the Grasberg deposit was modeled by Hoschke (2008): the deposit produces a strong discrete magnetic anomaly of less than 2,000nT (helicopter magnetic surveys), which is attributed to the high (7 percent) magnetite content of quartz stockworks

Table M2. Map units that define tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[Map unit, age range, and principal lighologies are based on a digital compilation of geologic maps of Indonesia (Directorate of Mineral Resources and Inventory, 2004a) and on scanned and rectified 1:250,000-scale quadrangle maps of Irian Jaya. Map symbols, lithology, and age ranges for Indonesia are based on 1:250,000-scale geologic maps]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Pariri Diorite	Tmpp	Diorite, quartz diorite	Miocene-Pliocene?
Timepa Monzonite	Tmpt	Quartz diorite, monzonite, andesite	Miocene-Pliocene
Ilaga intrusions	Tpi	Diorite, monzonite, quartz monzonite stock, dikes, sill	Pliocene
Volcanic rocks			
Nabire Volcanics	Tmpn	Alkali basalt, microdiorite intrusions	Miocene-Pliocene
Volcanics	Tpv	Lamprophyres	Pliocene

in the approximately 600-m-diameter orebody; the Grasberg intrusions have a vertical extent of more than 1 km.

The final tract boundaries were established by GIS processing and editing. The processing approximates manual delineation of tracts but is rapid and reproducible. The processing steps included (1) unioning of buffered permissive map units and other polygon features that comprise the framework of the tract; (2) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2; (3) manually aggregating and adjusting tract areas; and (4) smoothing polygons using an algorithm (PAEK, polynomial approximation with exponential kernel) with a tolerance of 1 km. Preliminary tracts were cleaned to remove necking and thinning introduced by processing and were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral occurrence, geochemical, and isotopic age data were plotted and used to constrain or expand tract boundaries. Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

The tract consists of three discrete areas of permissive igneous rocks of late Miocene to Pliocene age (fig. M1). Areas between the map-based parts of the tract, as indicated by the highlands areas shown in shaded relief on figure M2, may conceal unmapped permissive rocks. Access to aeromagnetic data for the entire study area would help identify potential shallow intrusions that could host porphyry copper deposits. In adjacent areas of the magmatic belt in Papua New Guinea (tract 009pCu7203), magnetic data show that the intrusions tend to be small and isolated.

A. Bird's Head.—Although no late-Miocene-Pliocene igneous rocks are shown on the 1:250,000-scale geologic maps of the Bird's Head, the team included a permissive area in the Aisasjur River region as part of the tract based on (1) locations of andesite porphyry dikes dated at 2.23 and 2.92 Ma (K-Ar on biotite) reported in Malaihollo and others (2002), based on data in Bladon (1988) and (2) the approximate extent of the Arc Exploration, Ltd., Aisasjur exploration area. The original exploration area covered about 61,000 hectares and targeted blind porphyry copper-gold deposits underlying epithermal gold occurrences, where drilling documented diorite porphyry within 1 km of the surface (Arc Exploration, Ltd., 2009). As of July 2010, an alliance between Arc Exploration, Ltd., and Anglo America held exploration tenements covering about 1,000 km^2. Epithermal gold mineralization overprints low-grade porphyry copper mineralization encountered at depth. Deeper parts of the system host bornite in porphyry-related pyrite-pyrrhotite-chalcopyrite veins (Arc Exploration, Ltd., 2010).

The permissive area lies south of the Sorong Fault and west of the Ransiki Fault, within Paleozoic sedimentary rocks, as shown on the 1:1,000,000-scale geologic map of Dow and others (1986). The permissive area may be much larger than shown, but the team had no basis for further delineation.

B. Nabire.—The Nabire area outlines the Nabire Volcanics on the southeastern edge of Cenderawasih Bay. The Nabire Volcanics are described as alkali basalt, andesite, and microdiorite intrusions. Bladon (1988) reported a K-Ar age of 5.62± 0.25 Ma on hornblende from slightly altered andesite in the tract area. A sample of Nabire Volcanics from an area 165 km northwest of the Minjauh volcanic field (area C) has an extreme isotopic Nd signature ($\varepsilon Nd=-3.4$) relative to other igneous rocks in the western part of the Central Ranges of central Irian Jaya ($\varepsilon Nd<-10$). The Nabire sample lies along the trend of lead isotopic signatures for the Minjauh volcanic field and Gunung Bijih (Grasberg area) of area C and has an intermediate isotopic initial Sr signature ($^{87}Sr/^{86}Sr_i=0.70739$) relative to those two areas (Housh and McMahon, 2000).

C. Grasberg area, southeastern West Papua and western Papua provinces, Indonesia.—The Grasberg area includes late Miocene and Pliocene intrusive rocks (<7 Ma) south of the Weyland thrust and extending eastwards across the western parts of the Central Highlands. The southern boundary of the tract area follows the approximate trace of a thrust fault along the southern margin of the Papuan Fold Belt, along the northern edge of the stable platform of southern New Guinea Island (fig. 7 of main report). The eastern boundary of the tract is placed along a buffer around the easternmost exposures of Ilaga intrusions and andesites, and is partly coincident with northeast-trending fault corridors. This area is coincident with the western limit of a 300-km-wide "gap" in Neogene intrusions that extends to the Papua New Guinea border; the gap area is lower in elevation (generally <2,000 m) than the Grasberg area (Cloos and others 2005).

The Grasberg area of the tract includes the mapped extent of the Pariri Diorite, Timepa Monzonite, diorite, and quartz diorite (Ilaga intrusions), as well as calc-alkaline, shoshonitic, and ultrapotassic lamprophyric rocks of the Minjauh volcanic field and hypabyssal intrusive bodies associated with the Gunung Bijih mining district (Grasberg, Ertsberg) based on localities reported by Housh and McMahon (2000) and McDowell and others (1996). The 5–7 Ma Minjauh volcanic field, northwest of Grasberg, includes shallow intrusive complexes. These rocks were emplaced after the collision of the older Miocene Maramuni Arc, which lies to the north. Genesis of these rocks may be related to jamming of a north-dipping subduction zone at about 7–8 Ma that resulted in partial delamination of lithospheric mantle below the continental margin of Australia, and resulted in asthenospheric upwelling (Housh and McMahon, 2000; Cloos and others, 2005). The collision-related rocks of the western Central Ranges are isotopically distinct from other Neogene igneous suites in the region (Banda Arc, New Britain, Porgera area, southeastern Papua New Guinea) by virtue of their unradiogenic Nd (ε_{Nd}=−3.4 to −22.0), radiogenic initial Sr ($^{87}Sr/^{86}Sr_i$=0.7058 to 0.71355) and variable Pb isotopic signatures, which led Housh and McMahon (2000) to propose that the source magmas represented mixtures of depleted mantle melts, ancient enriched mantle, and Proterozoic or Archean lower crust. The 3.0–2.9 Ma Komopa intrusions, west of the Minjauh volcanic field, include hypabyssal quartz monzodiorites, granodiorites, and monzogranites characterized by shoshonitic chemistry with high LILE and LREE contents, low concentrations of Nb, Ta, and Ti, $^{87}Sr/^{86}Sr_i$=0.7077, and unradiogenic Nd (ε_{Nd} ~−8.3); geochemical similarities with igneous rocks in the Minjauh and Ertsberg area suggest that all are related to collisional delamination processes at the northern edge of Australian continental lithosphere (Jackson, 2010).

Approximately 16 small (a few to several hundred m^2) hypabyssal Pliocene intrusions have been identified in the Gunung Bijih mining district; the largest intrusions (a few km^2 in outcrop area) are the Erstberg Diorite (3.00± 0.08 Ma) and the Grasberg Igneous Complex (2.6–4.4 Ma), which is located about 3 km north-northwest of Erstberg (Porter Geoconsultancy, 2001). According to Porter Geoconsultancy's 2001 report, no volcanic deposits extend beyond the mapped limits of the Grasberg Intrusive Complex. Corbett (2009) noted that quality porphyry copper deposits, including Grasberg, do not always occur in association with related volcanic rocks, and that volatiles may concentrate in apophyses localized along major structures or adjacent dilatant arc-parallel or arc-normal structures. The Erstberg mining district experienced two stages of deformation: (1) kilometer-scale folds with thrust faults and strike slip tear faults between about 12 and 4 Ma and (2) development of a left-lateral strike-slip fault system starting about 4 Ma that generated northwest-trending fault zones that facilitated emplacement of the Grasberg Igneous Complex in a 2-km-wide pull-apart zone (Sapile and Cloos, 2004).

Known Deposits

The Grasberg supergiant deposit (4,000 Mt at 0.6 percent copper, 0.64 g/t gold; table M3) is the largest copper-gold

Table M3. Identified porphyry copper resources in tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (%); n.d., no data]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Grasberg	–4.046	137.114	Cu-Au	3	4,000	0.60	n.d.	0.64	2	24,000,000	Anonymous (2004), Cloos (1997), Cloos and Housh (2008), Economou-Eliopoulos and others (2001), Freeport-McMoRanCopper and Gold, Inc. (1999, 2006, 2009, 2010), MacDonald and Arnold (1994), MacDonald and Arnold (1995), McDowell and others (1996), Meinert and others (1997), Mertig and others (1994), Paterson and Cloos (2005a,b), Pollard and Taylor, (2002), Potter (1996), Singer and others (2008)

porphyry deposit in the world and the largest porphyry deposit in southeast Asia. The Grasberg area includes the Ertsberg, Gunung Bijih, and Kusing Liar deposits and prospects. Mineralization proximal to Grasberg is copper-gold skarn. In 2009, mine operations included an open pit which is expected to be mined until 2015 or 2016; underground mining, expected to last until 2027 or later; and a mill complex. The mine is located on a 10,000 hectare block of land (Block A). Gold and copper production declined in 2008 because of lower ore grades (Kuo, 2010).

The Grasberg orebody is composed of multistage, nested orebodies: the Dalam Diatreme at 800 m depth; the Main Grasberg Stock; and the late-stage, weakly mineralized South Kali dikes. Pollard and Taylor (2005) showed that the Grasberg Igneous Complex represents several cycles of intrusion and hydrothermal alteration, based on $^{40}Ar/^{39}Ar$ studies on magmatic and hydrothermal micas that document a main stage of intrusion and alteration at 3.33± 0.12 Ma, intrusion of the Kali quartz monzonite porphyry dikes at 3.03± 0.03 and 3.01± 0.06 Ma, and post-Kali intrusions and alteration as young as 3.01± 0.06. They concluded that each cycle lasted 0.1 million years or less, and that the huge size of the deposit could not be explained by a prolonged period of mineralization. Igneous rocks associated with the Grasberg porphyry copper-gold deposit include Pliocene andesite breccia, breccia, diorite, diorite porphyry, monzodiorite porphyry, and monzonite porphyry. Country rocks are Paleozoic and Mesozoic black shale, dolomite, limestone, quartzite, sandstone, and siltstone. Porphyry copper-gold mineralization and associated skarn is Pliocene (~3 Ma) (McDowell and others 1996; Paterson and Cloos, 2005a,b). Grasberg is an unusually high-grade copper- and gold-rich porphyry copper deposit, with a consistent Cu:Au=10,000:1; gold is associated with chalcopyrite, which may replace bornite, and likely exsolved from copper sulfides (Kyle and others, 2008).

Mineralized zones extend from the surface (4,200 m elevation) to 2,700 m. Recent development activity at Grasberg is focused on transitioning from open pit to block-cave mining in 2016 (Freeport-McMoRan Copper and Gold, Inc., 2010) to exploit deeper skarn orebodies (Grasberg block cave, Big Gossan, Deep MLZ, and Kucing Liar). Reserves and resources for the deposits (porphyry and skarn) in Grasberg block A are as follows (March, 2010 data): total measured and indicated and inferred resources of 2,863,000,000 metric tons averaging 0.56 percent copper, 0.51 g/t gold, and 3.30 g/t silver; proven and probable open pit and underground reserves of 2,590,000,000 metric tons averaging 1.00 percent copper, 0.86 g/t gold, and 4.18 g/t silver (Freeport-McMoRan Copper and Gold, Inc., 2010). Most of the remaining ore is in skarn.

Prospects, Mineral Occurrences, and Related Deposit Types

Porphyry copper prospects and epithermal deposits or prospect areas that may be associated with porphyry copper deposits at depth are listed in table M4. The main prospect areas are discussed from west to east across the magmatic belt that defines the tract.

At Arc Exploration's Aisasjur project in the Bird's Head (area A), quartz-magnetite-chalcopyrite stockworks were identified in drill-hole intercepts (5 holes to approximately 700 m depth) in potassically altered diorite porphyry intrusions and intrusive breccias. Mineralized intercepts containing copper (0.17, 0.26 percent) and gold (0.4–1.25 g/t) are reported. Other copper and gold occurrences, prospects, and stream-sediment anomalies are shown on the 1:250,000-scale geologic maps of southwestern Papua province, Indonesia within the tract, including sites that were drilled with reported gold, copper, and molybdenum (Indonesian Directorate of Mineral Resources and Inventory, proprietary data, 2004b).

The Komopa-Dawagu area was drilled (301 holes) by the Nabire Bakti Joint Venture in the 1990s (Freeport McMoRan, 1999). The Komopa prospect (area C) has an in-place estimated geologic resource of approximately 363 Mt at 0.5 percent copper equivalent, with a cutoff grade of 0.3 percent copper equivalent. The Dawagu prospect estimated resource is 372 Mt at 0.5 percent copper equivalent, with a cutoff grade of 0.3 percent copper equivalent.

A number of porphyry copper-gold occurrences and associated deposits, such as the copper-gold skarns and epithermal deposits, are proximal to the main Grasberg porphyry orebody (John and others, 2010). Proximal deposits are mined from the same facilities as the main deposit and are considered part of the Grasberg ore system (Kamitani and Naito,1988).

Area C includes Nickelore Limited's (2009) Papua Gold/Copper exploration project, located 45 km northwest of Grasberg, as well as 13 prospects for gold, copper, and magnetite skarn; some of these have been partially explored by drilling (<100 m Winkie drilling; at least 1 prospect to 600 m depth). Assay results report copper, typically in the range of about 0.1–1 percent copper, ppb to ppm concentrations of gold plus molybdenum or lead.

Exploration History

The Ertsberg (Gunung Bijih) mining district was discovered by an expedition in 1936, and "rediscovered" by mineral exploration in 1960. Mining of the skarn deposits started in the 1970s, and the Ertsberg skarn body is mined out. The Erstberg skarn orebodies (Ertsberg, Ertsberg East, and Dom) formed within and at limestone contacts of the 3.2 Ma Erstberg diorite. Exploration drilling in 2000 identified porphyry copper-gold mineralization within the 3.2 Ma Ertsberg diorite, with potential resources on the order of 100 to 200 million metric tons that could be mined by open-pit or block-caving methods.

The Grasberg porphyry copper-gold deposit, located about 3 km north of Ertsberg, was discovered by exploratory drilling in 1988, and open-pit mining started in 1990. There has been extensive modern exploration since the 1960s around Grasberg-Ertsberg and, to a lesser extent, in and around the surrounding skarn and epithermal occurrences in the western parts of the tract. This exploration has included helicopter

Table M4. Significant prospects and occurrences in tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[Ages all assumed to be late Miocene to Pliocene based on associated map units. Rank 4=prospect in global database of Singer and others (2008) or >16,000 t contained copper; Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ppm, parts per million; Mt, million metric tons]

Name	Latitude	Longitude	Comments	Reference	Rank
			A, Bird's Head Area		
Aisasjur Gold/ Copper Project	–1.226	132.854	Blind porphyry copper-gold target; drilling (13 holes) intersected low-grade epithermal Au-As-Sb and at depth (from 712 m downhole), potasically altered diorite porphyry with quartz-magnetite-chalcopyrite stockwork and breccia; disseminated chalcopyrite and bornite; also magnetite-destructive argillic alteration. Drill targets based on magnetic anomalies. Drilled intercepts: 13 m at 0.21% Cu, 0.51 g/t Au from 561 m downhole; 192.8 m at 0.13% Cu, 0.19 g/t Au from 698.2 m downhole. Age based on reported ages for associated igneous rock (SEARG database). Location based on exploration maps.	Arc Exploration (2009, 2010)	3
			C, Grasberg Area		
Komopa prospect	–3.799	136.474	In place estimated geologic resource ~ 363 Mt at 0.5% copper equivalent with a cutoff grade of 0.3% copper equivalent. Komopa Porphyry is described as a subvolcanic intrusion with a well-defined,circular, hydrothermal alteration system. Explored as part of Block II of the Nabire Bakti Joint Venture west of Grasberg. Copper-gold mineralized zone 1.5 by 0.5 km in area. Partial drill results reported in 1999 included 10 holes with >10 m intercepts (12–384 m) of 0.39 to 1.16 % Cu, 0.10 to 0.718 g/t Au. Age 2.9 to 3.9 Ma.	Gold Fields Limited (2004), Directorate of Mineral Resources and Inventory (2004b)	4
Dawagu prospect	–3.771	136.551	In place estimated geologic resource ~ 372 Mt at 0.5% copper equivalent with a cutoff grade of 0.3% copper equivalent. The Dawagu prospect includes several exploration targets (Gold Fields Limited, 2004): a central porphyry stockwork, skarns (open to the east in New Guinea Limestone), and epithermal -style mineralization in overlying clastics.	Directorate of Mineral Resources and Inventory (2004b)	4
Ikerar prospect	–3.978	136.119	Winkie drilling 39–41m (Au), 35–50m (Cu, Mo); contents: 110 ppb Au max, 637.5 ppm Cu, 59.6 ppm Mo.	Directorate of Mineral Resources and Inventory (2004b)	2
Wabu skarn	–3.671	137.047	Major Au-Cu skarn prospect ~33 km N of Grasberg. Upper Miocene skarn and porphyry in the footwall of the Derewo fault. Skarn developed in New Guinea limestone along a 6-km strike length along a contact with a monzonite-diorite intrusive complex.	Allen and others (1998)	2
Papua Gold and Copper project	–3.671	136.500	Raw prospect area (91 km^2) located 45 km NW of Grasberg; target is porphyry copper-gold and skarn based on ring-structure targets on satellite imagery and photointerpretation of geology; previously unexplored area.	Nickelore Limited (2009)	1

Table M4. Significant prospects and occurrences in tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.—Continued

Name	Latitude	Longitude	Comments	Reference	Rank
			C, Grasberg Area		
Pogatadi “C” and “D” prospects	–3.932	136.121	Rock sample 0.35–1.2% Cu; stream sediments 700–959 ppm Cu.	Directorate of Mineral Resources and Inventory (2004b)	1
Pogatadi “B” prospect	–3.903	136.145	Minor prospect, soil sample: 500–1,260 ppm Cu.	Directorate of Mineral Resources and Inventory (2004b)	1
Mogo-mogo prospect	–3.873	136.183	Minor prospect; rock sample vein magnetite skarn: 0.25 ppm Au; 16.6 ppm Au; 5,500 ppm Cu.	Directorate of Mineral Resources and Inventory (2004b), Nickelore Limited (2009)	1
Obano prospect	–3.889	136.178	Minor prospect; soil 2.97 ppm Au; rock sample, 1.11% Cu, 2.33 ppm Au.	Directorate of Mineral Resources and Inventory (2004b)	1
Pogatadi “E” prospect	–3.906	136.120	Stream sediment: 0.24 ppm Au, 49 ppm Cu; rock sample: 0.07 ppm Au.	Directorate of Mineral Resources and Inventory (2004b)	1
Tango One prospect	–4.085	137.039	Stream sediment and rock sample with Au and Cu.	Directorate of Mineral Resources and Inventory (2004b)	1

and foot regional geochemical exploration including stream-sediment sampling and local airborne and ground-geophysical surveys. Some of the more prominent prospects were trenched and drilled. Freeport-McMoRan Copper and Gold, Inc., continued exploration in their original 24,700-acre concession area (Block A) and adjacent 1.6 million-acre area (Block B) in the 1990s. Security issues and regulatory issues associated with mining in forest preservation areas curtailed exploration activities outside of Block A in 2006 (Freeport-McMoRan Copper and Gold, Inc., 2006). In 2008, Rio Tinto reported that exploration was being done on about 200,000 hectares in Block B and in an additional 690,000 hectares outside of Blocks A and B in joint ventures.

Exploration drilling also occurred within a 1-million-acre concession area by P.T. Nabire Bakti Mining, which includes the Komopa porphyry copper-gold prospect located 75 km west of Grasberg (Business Wire, 1999). Nickleore Limited (2009) is exploring for large gold-copper porphyry and skarn systems based on observations of circular structures observed on satellite imagery at the Papua Project, an approximately 91 km^2 area located about 45 km northwest of Grasberg.

As of 2008, areas around Grasberg and the Aisasjur area of the Bird's Head were being explored. Exploration focus is on circular, topographic high, historically partly explored prospects that indicated copper and gold, alluvial gold, stream-sediment geochemical anomalies, geophysical anomalies, and northeast-structural trends and lineaments, especially in areas between known mineralized centers along the same structural corridors. Most areas within the tract are remote, mountainous, highly vegetated, and in places of recent political and social unrest. Therefore, all parts of the tract may not be thoroughly evaluated (see van Leeuwen, 1994; Cloos, 1997).

Sources of Information

Principal sources of information used by the assessment team for delineation of tract 142pCu7203 are listed in table M5.

Grade and Tonnage Model Selection

Grasberg, the only deposit with identified resources within the tract, is a porphyry copper-gold deposit. Preliminary data on prospects and regional characteristics indicate that a copper-gold porphyry model is appropriate for the tract. ANOVA tests comparing the grade and tonnage data for Grasberg with general porphyry copper and copper-gold subtype models support either model (table 6 of main report). In terms of tonnage and contained copper, Grasberg is the largest porphyry copper deposit in Southeast Asia. Smaller deposits occur in the eastern part of the same magmatic belt (tract 009pCu7203). Therefore, the team concluded that the global copper-gold model, with a median deposit size of 200 million metric tons of ore, was appropriate for simulation undiscovered resources associated with the tract.

Table M5. Principal sources of information used for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[CCOP, Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia; NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Indonesia	1;1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Systematic geologic map, Indonesia, map nos. 2914, 3111, 3112, 3211, 3212	1:250,000	Geological Research and Development Centre (1987–2000)
	Geologic map of Irian Jaya, Indonesia	1:1,000,000	Dow and others (1986)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)
	MRDS database	NA	U.S. Geological Survey (2005)
Exploration	USGS Minerals Yearbooks, Company Web sites	NA	Kuo (2010), Various (see references in table M3)

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

Grasberg is the only deposit in production within the tract. The tract includes five partly explored porphyry copper prospects and seven minor prospects and occurrences that may be related to porphyry copper systems (table M4). In addition, copper is noted in most of the gold occurrences (11) within the tract. The team estimated a 90-percent chance of one or more undiscovered porphyry deposits in the tract (table M6) based on the identification of porphyry-style alteration and geochemical anomalies associated with permissive, Pliocene-age igneous rocks in the underexplored Bird's Head area, partly drilled prospects with indications of porphyry characteristics near Grasberg, exploration at the Komopa prospect, and increasing recognition of geochemical similarities between the rocks at Grasberg and elsewhere within the tract. The team estimated a 50-percent chance of three or more deposits, based on the possibility that further exploration could establish resources at half of the known, or future, prospect areas. Much of the Grasberg-Ertsberg area is held by major mining companies in joint ventures who are focused on extensions of identified resources. Exploration outside of their work area has been hampered by political, social, and environmental concerns in recent years. There may be proprietary data documenting the likelihood of additional deposits, or the lack thereof, in the tract area. Based on the available data, the team estimated a 10-percent chance of 10 or more deposits in the tract. Magnetic data for adjacent areas within the same magmatic belt in Papua New Guinea show discrete, small, circular magnetic highs similar to those described for the world-class Grasberg deposit and the exploration target at the Papua project northwest of Grasberg.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table

Table M6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
1	3	10	10	10	4.4	3.4	77	1	5.4	13,270	41

Table M7. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	310,000	6,500,000	36,000,000	54,000,000	14,000,000	0.31	0.06
Mo	0	0	15,000	230,000	420,000	80,000	0.24	0.3
Au	0	32	560	2,700	3,700	1,000	0.34	0.06
Ag	0	0	1,200	11,000	21,000	4,500	0.22	0.22
Rock	0	74	1,400	7,600	11,000	2,800	0.33	0.06

M7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. M3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper contained in undiscovered porphyry copper deposits within the tract (14 Mt) is less than the identified resources at Grasberg (24 Mt). Note that in terms of contained copper, Grasberg is the largest known porphyry copper deposit in Southeast Asia. Estimated resources in undiscovered deposits are modeled using a global grade-tonnage model with the assumption that undiscovered deposits will be like those in the model (some large, some small).

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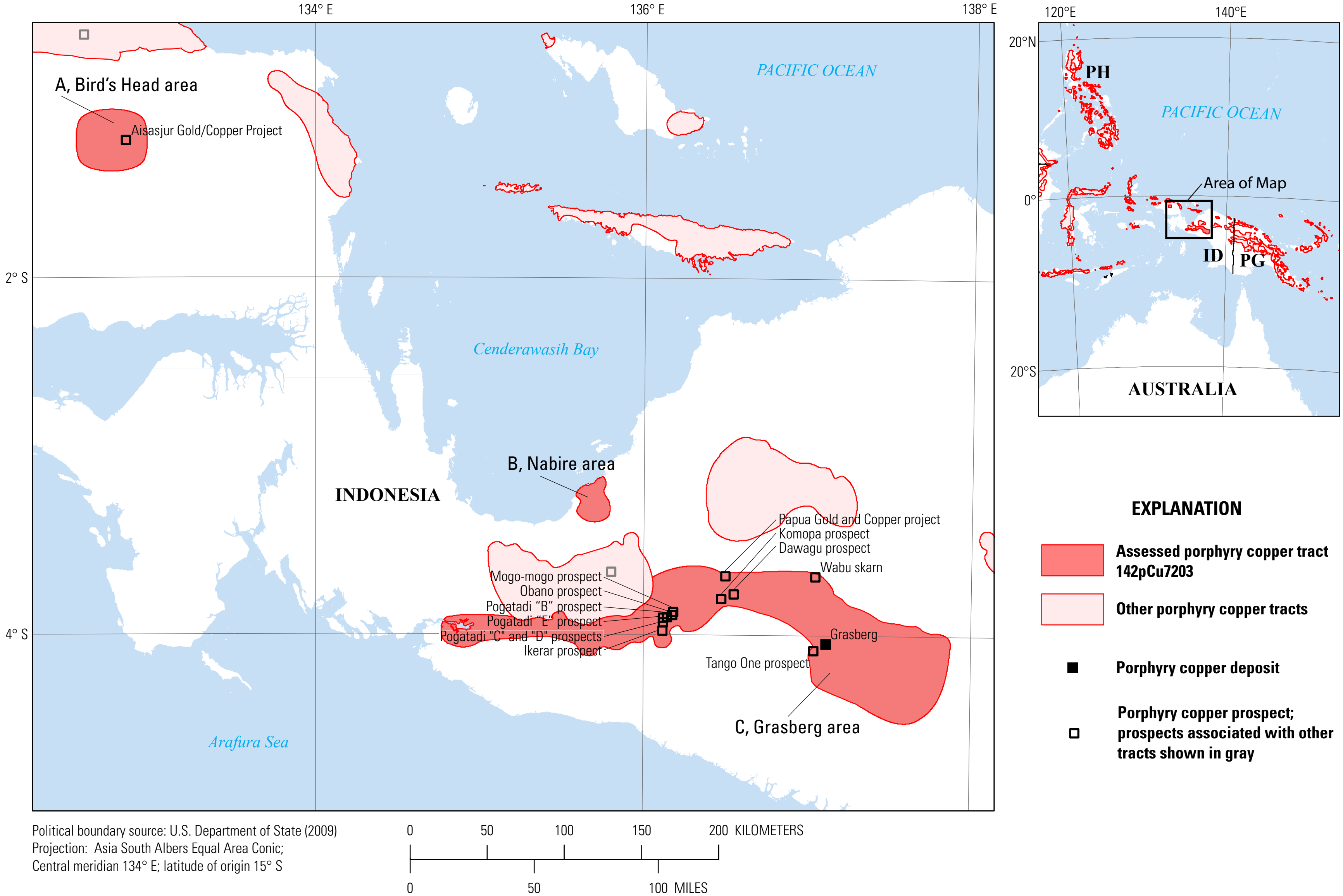
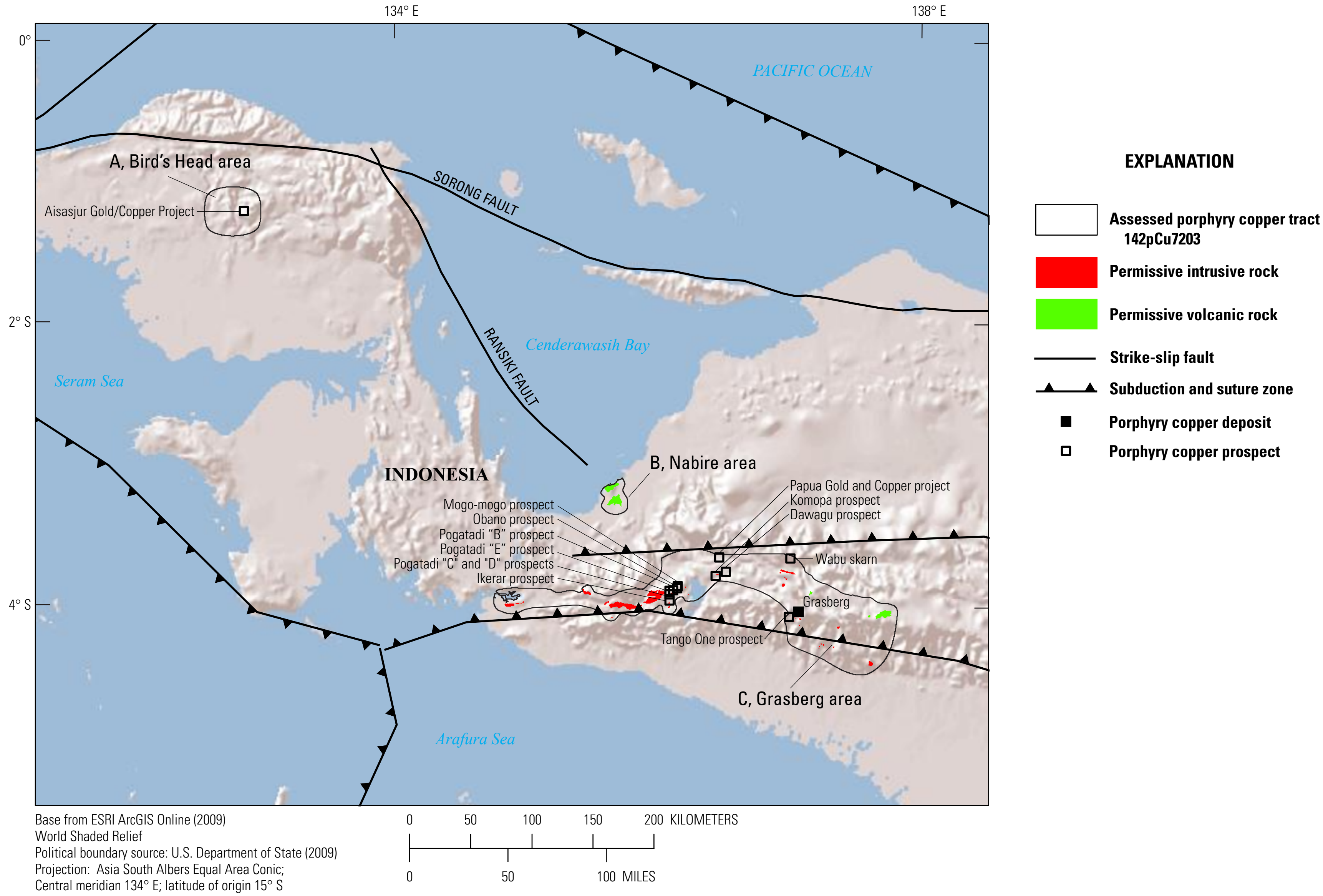


Figure M1. Map showing tract location, known deposits, and significant porphyry copper prospects for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia. ID, Indonesia; PH, Philippines; PG, Papua New Guinea.



Base from ESRI ArcGIS Online (2009)
World Shaded Relief
Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 134° E; latitude of origin 15° S

Figure M2. Map showing the distribution of permissive igneous rocks for tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia.

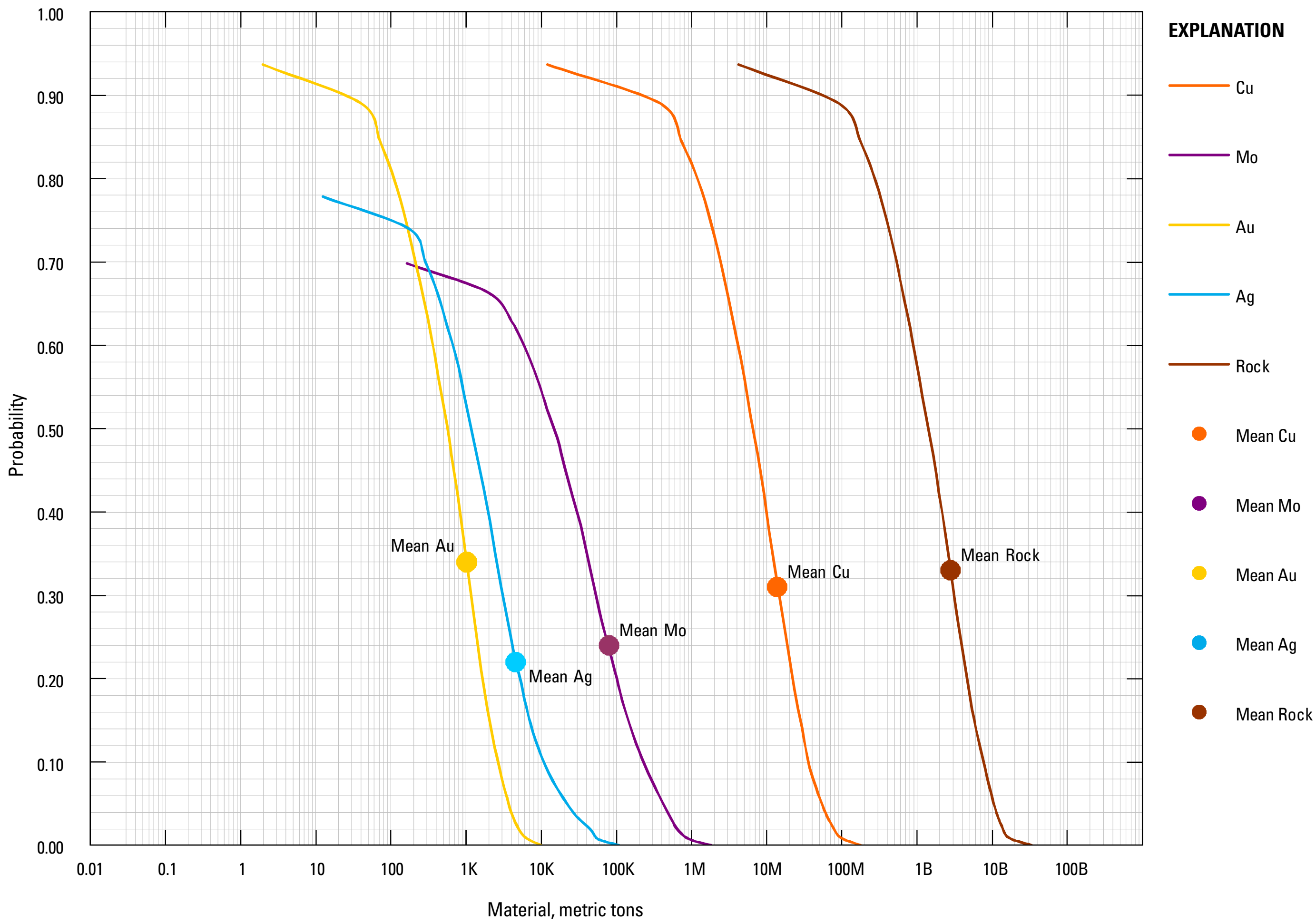


Figure M3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7203, Western Medial New Guinea Magmatic Belt—Indonesia. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix N. Porphyry Copper Assessment for Tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Gwaibo Kopi[5] and Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010)

A permissive tract is delineated based on permissive rock types depicted on 1:250,000-scale geologic maps. Insufficient information was available for a probabilistic assessment of the tract area. Summary information is listed in table N1.

Table N1. Summary of selected information for tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)
February 2010	1	9,370	n.d.

Location

The tract includes the Central Highlands of New Guinea Island and parts of the Indonesian provinces of West Papua and Papua, formerly known as Irian Jaya (fig. N1).

Geologic Feature Assessed

Late Miocene to Pliocene-Pleistocene intrusive rocks.

Delineation of the Permissive Tract

Tectonic Setting

Tract 142pCu7204 outlines exposed segments of the late Miocene and Pliocene to Pleistocene intrusive rocks in the Indonesian provinces of western New Guinea Island in an area north of the Direwo Fault, the boundary between the fold belt and

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S. Geological Survey, Spokane, Washington, United States.
[5]Mineral Resources Authority, Papua New Guinea.

Table N2. Map units that define tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia.

[Map unit, age range, and principal lithologies are based on a digital compilation of geologic maps of Indonesia (Directorate of Mineral Resources and Inventory, 2004a), and scanned and rectified 1:250,000-scale quadrangle maps of Irian Jaya. Map symbols, lithology, and age ranges are based on 1:250,000-scale geologic maps. See table N3 for references]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Timepa Intrusion rocks	Tmpt	Quartz diorite, monzonite, andesite	Miocene-Pliocene
Diorite	Tpdi	Diorite	Pliocene
Intrusive rocks	Tpd	Diorite, granodiorite	Pliocene
Volcanic rocks			
Andesite	TpAn	Andesite	Pliocene
Volcanics	Tpb	Basalt	Pliocene

the mobile belt, and east of the Central Ophiolite Belt (COB on fig. 7). The relationship of these rocks to the Medial New Guinea magmatic belt is unclear, although 1:250,000-scale geologic maps of the area ascribe them to some of the same map units that characterize tract 142pCu7203 near Grasberg, such as the Timepa diorite (table N2).

This area is questionable as a permissive area for undiscovered porphyry copper deposits. The assessment team included it because an east-west-trending belt of rocks of apparently appropriate age and lithology extends from an area about 50 km north of the Grasberg mine area to the Papua New Guinea border.

Geologic Criteria

As depicted on the 1:250,000-scale geologic maps for the Rotanburg quadrangle (Harahap and Noya, 1995), the western parts of the tract area are mapped as Timepa intrusions, whereas the eastern parts are mapped as Pliocene diorite, andesite, and granodiorite on the Taritatua (Sidarto and Hartono, 1995) and Jiyawijaya (Koswara, 1995) maps. However, no igneous rocks of this age are mapped in the immediately adjacent areas in Papua New Guinea (Bain and others, 1972). No mines, known prospects, or known copper or gold occurrences are associated with this segment of the magmatic belt; there are two small alluvial gold workings near the tract in Papua New Guinea. This area has been referred to as a 300-km-wide "gap" where no Tertiary igneous rocks have been found by exploration geologists; the area also is lower in elevation (<2,000) than areas of Tertiary igneous rocks to the west (Cloos and others, 2005). The remoteness of the area, the lack of dated igneous rocks, lack of geophysical data available to the assessment team, and some dependence on photointerpretation in assignment of geologic map units indicate that additional data are needed to assess this part of the Central Highlands. The western and eastern boundaries of this section of the tract approximately align with orogen-transverse lineaments.

The tract was constructed in a GIS using a 1:500,000-scale digital map of igneous rocks of Indonesia (Directorate of Mineral Resources, 2004a), 1:250,000-scale geologic maps of Indonesia, and the 1:1,000,000-scale geologic map of Irian Jaya (Dow and others, 1986). In addition, maps and figures showing major faults, lineaments, and tectonic divisions of New Guinea Island by Garwin and others (2005), Hill and others (2002), and Quarles van Ufford and Cloos (2005) were used.

Using GIS tools, a 5-km buffer was applied around mapped igneous contacts of permissive lithologies to account for spatial uncertainty in digitized geology and for the possibility of greater extent of permissive rocks within a kilometer of the surface. The buffered map units were aggregated using GIS processing tools with a 15 km distance to group closely spaced permissive areas, which were then edited to honor fault boundaries, merge and include other areas of known igneous rocks of appropriate age and lithology. The final tract boundaries were established by GIS processing and editing. The processing approximates manual delineation of tracts but is rapid and reproducible. The processing steps included (1) unioning of buffered permissive map units and other polygon features that comprise the framework of the tract; (2) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2; (3) manually aggregating and adjusting tract areas; and (4) smoothing polygons with a tolerance of 1 km. Preliminary tracts were cleaned to remove necking and thinning introduced by processing and were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. The western part of the geology-based tract partly overlaps Eastern Minerals contract of work (COW) Block B (Freeport McMoRan Copper and Gold, Inc., 2006). The final tract boundary was edited by hand to include the COW area.

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

No prospects or occurrences were reported within the tract area in the mineral occurrences databases examined for this study (table N3).

Exploration History

Other than anecdotal reports that exploration geologists found no evidence for porphyry copper-style mineralization, we are unaware of exploration results in the tract area. The western part of the tract overlaps parts of a COW (Block 3) that was held by Eastern Minerals Corporation (Freeport McMoRan Copper and Gold, Inc., 2006). The area is remote, and, in recent years, political and social unrest have been a detriment to exploration in the area. Given the proximity of the tract area to the Grasberg mine, it is likely that some proprietary data exist.

Sources of Information

Principal sources of information used by the assessment team for delineation of tract 142pCu7204 are listed in table N3. No mineral occurrence, geochemical, geophysical, isotopic-age data, or exploration results were available to the assessment team for this area.

Table N3. Principal sources of information used for tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia.

[CCOP, Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia; NA, not applicable]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Indonesia	1;1,000,000	Directorate of Mineral Resources and Inventory (2004a)
	Geologic quadrangle maps (Rotanburg, Taritatua, Jayawijaya)	1:250,000	Harahap and Noya (1995), Sidarto and Hartono (1995), Koswara (1995)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
	Geologic map of Irian Jaya, Indonesia	1:1,000,000	Dow and others (1986)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Mineral Resources Data System (MRDS)	NA	U.S. Geological Survey (2005)
	World distribution of porphyry, porphyry-related skarn, and bulk-mineable epithermal deposits	NA	Dunne and Kirkham (2003)
	Selected world mineral deposits database	NA	Kirkham and Rafer (2003)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)

Qualitative Assessment

Notes on the 1:250,000-scale geologic maps that cover the tract area (table N3) infer that the igneous rocks may be related to those in the Grasberg-Ertsberg area. However, the age of the igneous rocks is unknown and no deposits or prospects are recorded in available databases. The mapped extent of intrusions is greater than that of coeval volcanic rocks, and compared to the small, circular intrusions that characterize the New Guinea magmatic belt, the intrusions are larger and more similar to the Miocene and older igneous rocks. The tract area may be too deeply eroded to preserve porphyry copper deposits.

On the basis of a lack of additional information and anecdotal reports of lack of mineralization reported by explorationists, the team included the area as permissive, but made no estimate of numbers of undiscovered deposits. Further work in the tract area may change the outlook for undiscovered deposits in the tract area.

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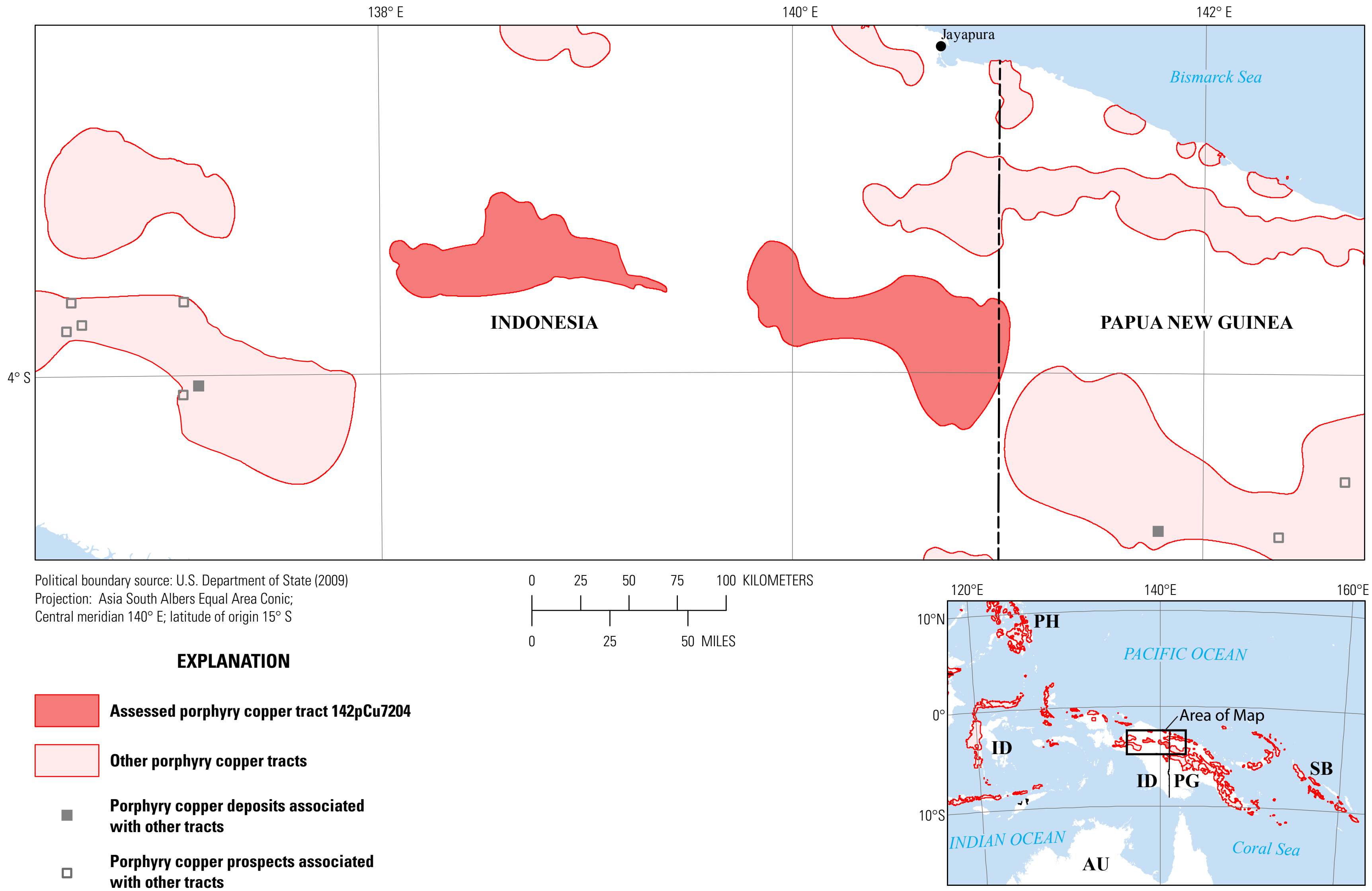

Figure N1. Map showing tract location for tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia. AU, Australia; ID, Indonesia; PH, Philippines; PG, Papua New Guinea; SB, Solomon Islands.

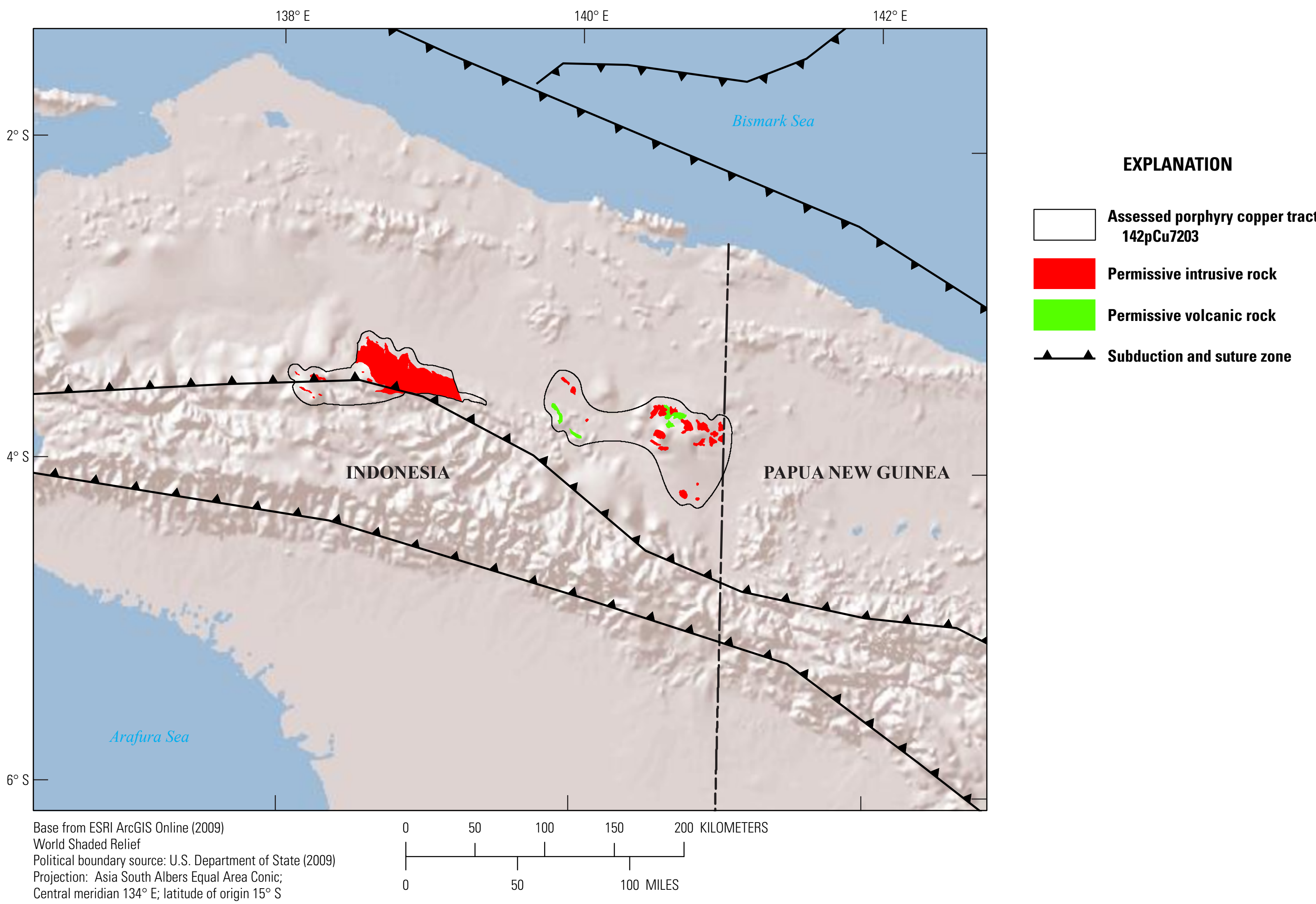

Figure N2. Map showing the distribution of permissive igneous rocks for tract 142pCu7204, Rotanburg-Taritatua Area—Indonesia.

Appendix O. Porphyry Copper Assessment for Tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Benjamin J. Drenth[4], Steve Ludington[5], Arthur A. Bookstrom[6], and Michael L. Zientek[6], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[5]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table O1 summarizes selected assessment results.

Table O1. Summary of selected resource assessment results for tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[km, kilometers; km^2, square kilometers; t, metric tons; preliminary assessment in 2005, revised in 2010]

Date of assessment	Assessment depth (km)	Sub-tract	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	009pCu7203a	14,230	6,116,600	5,100,000	1,200,000
		009pCu7203b	53,220	11,368,926	20,000,000	10,000,000

Location

The tract includes the Central Highlands of Papua New Guinea and easternmost Papua province, Indonesia (fig. O1).

Geologic Feature Assessed

Eastern part of the late Miocene to Pliocene-Pleistocene Medial New Guinea magmatic belt.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Denver, Colorado, United States.
[5]U.S. Geological Survey, Menlo Park, California, United States.
[6]U.S. Geological Survey, Spokane, Washington, United States.

Delineation of the Permissive Tract

Tectonic Setting

Tract 009pCu7203 outlines exposed segments of the late Miocene and Pliocene to Pleistocene Medial New Guinea magmatic belt (fig. 3, no. 13). The tract represents the eastern part of the 1,800-km-long Medial New Guinea magmatic belt that formed from convergence of the Indo-Australian and Pacific Plates during the Cenozoic. The western part of the Belt is delineated as tract 142pCu7203 in Indonesia. These two coeval tracts span two United Nations (UN) regions and are separated by a gap in mapped igneous rocks of late Miocene to Pliocene age. Region codes are used to designate tracts in the global assessment. UN region 142 represents Asia, including Indonesia; region 009 represents Oceania, including Papua New Guinea. In order to preserve this distinction, we used tract identifier 7203 for both regions, preceded by the appropriate UN region code.

Most of the tract is within the Fly-Highlands province along the eastern part of the Central Range (FHP on fig. 7). The western part of the magmatic belt (tract 142pCu7203) is late Miocene to Pliocene, whereas the eastern part of the belt (tract 009pCu7203) predominantly is Pliocene to Pleistocene in age (Cloos and others, 2005). A well-defined subduction zone is not associated with the belt, although seismic tomography suggests the existence of old subduction slabs within the mantle under New Guinea (Hall and Sparkman, 2002; Garwin and others, 2005). A number of explanations for the lower volume, more alkaline, post-Maramuni Arc (Miocene) magmatic activity have been suggested, including south-dipping subduction following a reversal in subduction polarity, post-collision uplift, and transitions to extensional tectonism (Housh and McMahon, 2000). As noted by Garwin and others (2005), the tectonic trigger for the high-K, calc-alkaline to alkaline magmatic event is not well understood, but it is likely related to the southward progressing compressional deformation that formed and uplifted the fold belt as a result of convergence of New Guinea and the Pacific-Caroline Plate to the north (fig. 6). Local dilational zones formed at intersections of strike-parallel (generally east-west) frontal thrust faults and strike-perpendicular long-lived crustal transfer structures, which are expressed as lineaments. These dilational zones facilitated emplacement of magmas and porphyry copper-gold mineralization in central New Guinea (Hill and others, 2002). Cloos and others (2005) suggested that the late Neogene volcanism in the eastern parts of the Medial New Guinea Belt appears more widespread than in the western parts of the Central Range and represents a younger, less eroded part of the belt; at 3 Ma, the western part of the belt may have looked like the present-day eastern part of the belt. Based on differences in the relative amounts of intrusive and volcanic rocks and, therefore, differences in the depth of exposure and likelihood of undiscovered porphyry copper deposits within the eastern part of the belt, the tract was subdivided into two sub-tracts (009pCu7203a and 009pCu7203b) for assessment.

The nature of the basement of the Medial New Guinea magmatic belt differs from west (tract 142pCu7203) to east (tract 009pCu7203). The Tasman Line is interpreted as extending roughly north-south to northwest through an area approximately 100 km west of the modern Indonesian (Irian Jaya)-Papua New Guinea border (fig. 6). The Tasman Line defines two crustal provinces in northern Australia: Paleozoic basement of the accreted terranes of the Tasman orogen lie to the east of the line; the stable craton with Precambrian basement lies to the west (Hill and Hall, 2003). These differences in basement affect the crustal response to deformation, and may influence the character of porphyry-related magmas.

Geologic Criteria

The tract was constructed in a GIS using a digital compilation of 1:250,000-scale geologic maps of Papua New Guinea and a 1:1,000,000-scale geologic map of Papua New Guinea (Bain and others, 1972). In addition, maps and figures showing the major faults, lineaments, and tectonic divisions of New Guinea by Garwin and others (2005), Hill and others (2002), Cloos and others (2005), and Quarles van Ufford and Cloos (2005) were used.

Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic) based on map-legend attributes. From this digital database of map units grouped by age and lithology, all igneous rocks of late Miocene to Pliocene-Pleistocene age were selected. Examination of cross sections on 1:250,000-scale geologic maps showed that most intrusive rocks of this age range are shown as steep-sided, cylindrical or finger-like intrusive bodies with a subsurface horizontal extent of less than 2–5 km; vertical extents can exceed 1 km.

Using GIS tools, a 5-km buffer was applied around mapped igneous contacts of permissive lithologies to account for spatial uncertainty in digitized geology and for the possibility of greater extent of permissive rocks within a kilometer of the surface. Ophiolites and ultramafic rocks, basaltic units, and units that are predominantly ash flows, tuffs, and agglomerates were deemed nonpermissive and are omitted from the tract. Pliocene to Pleistocene andesitic volcanic centers (for example, Kerewa Volcanics, Crater Mountain Volcanics) are included; these may cover buried intrusions that host porphyry copper deposits, although the volcanic cover may be >1 km thick in some places. Diatremes around the periphery of these centers are current exploration targets. The occurrence of the diatreme at Grasberg in the western part of the magmatic belt, small cylindrical steep-sided stocks associated with known porphyry copper deposits, and the recognition of telescoped epithermal systems overlying young porphyry systems in this tectonically active region (such as at Lihir Island) suggest that the volcanic centers should be included within the tract.

The buffered map units were aggregated using GIS processing tools with a 15 km distance to group closely spaced permissive areas, which were then edited to honor fault boundaries and include other areas of known igneous rocks of appropriate age and lithology. Databases of isotopic ages of igneous rocks for Papua New Guinea compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002) by providing locations and lithologic descriptions of dated samples.

Late Miocene to Pliocene intrusions associated with porphyry copper mineralization crop out as hypabyssal intrusive bodies and small dikes and plugs; many are too small to show on 1:250,000-scale maps. Aeromagnetic data for the Central Highlands area of Papua New Guinea (109.5 to 145.5°W) from the Mineral Resources Authority of Papua New Guinea were processed by Benjamin J. Drenth (USGS, Denver, Colorado). The data were transformed by a reduction to pole and compared with mapped geology to identify areas of possible shallow buried intrusions for inclusion in tracts, and areas of magnetic quiescence that correlate with thick sedimentary basins for exclusion from tracts.

The initial tract boundaries were established by GIS processing. Final editing was accomplished by hand. The processing steps included (1) unioning buffered permissive map units and other polygon features that comprise the framework of the tract; (2) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2; (3) manually aggregating and adjusting tract areas; and (4) smoothing polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing and were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; magnetic data also were used where available (Central Highlands of Papua New Guinea). Tract boundaries were clipped at shorelines using a Global GIS dataset (U.S. Department of State, 2009).

The southern boundary of the tract area follows the approximate trace of a thrust fault between the southern margin of the Papuan Fold Belt and the northern edge of the stable platform of southern New Guinea Island (fig. 6). The team delineated the tract as a series of geologic map-based, GIS-derived polygons, as described above. However, areas between the map-based parts of the tract, as indicated by the highlands areas shown in shaded relief on figure O2, may conceal unmapped permissive rocks. Access to aeromagnetic data for the entire study area would help identify potential shallow intrusions that could host porphyry copper deposits. In areas where such data are available, the magnetic data suggest that the intrusions tend to be small and isolated, and therefore, the team chose to portray the tract in map-based segments. Sub-tract a represents the border area; sub-tract b represents all areas east of the diagonal line shown in figure O1. The dividing line approximately corresponds to the Porgera lineament (Garwin and others, 2005) and separates an area of dominantly intrusive rocks (A) from an area of mainly volcanic rocks (B). The dividing line also correlates with a change in texture of aeromagnetic data.

Sub-tract 009pCu7203a

Sub-tract a includes a small area in Indonesia just west of the Papua New Guinea border (fig. O1).

Border area (Fold Belt area, South of the Direwo Fault, at the Indonesia-Papua New Guinea border).—Diorite and granodiorite intrusions mapped in Indonesia are contiguous with rocks mapped as late Miocene to Pliocene Antares Complex in Papua New Guinea (quartz monzodiorite, quartz monzonite, diorite and microdiorite, granodiorite, granite, some porphyry, some volcanic rocks) and porphyritic rocks of the Star Mountain Intrusives associated with the Ok Tedi, Star Mount Futik, and Star Mount Nong River porphyry copper-gold deposits. Page (1975) reported biotite, hornblende, plagioclase, and whole-rock K-Ar ages on mineralized porphyries in the Star Mountains Intrusives (3.4–4.6 Ma and Antares Monzonite (2.4–3.1 Ma). The eastern boundary of sub-tract 009pCu7203a marks a transition from areas where intrusive rocks are more abundant than volcanic rocks to areas to the east where volcanic rocks are more abundant than intrusive rocks (fig. O2).

Sub-tract 009pCu7203b

Sub-tract b, entirely within the country of Papua New Guinea (fig. O1), includes several areas of late Miocene and younger permissive igneous rocks. In sub-tract b, permissive rocks tend to be younger than in sub-tract a, the extent of mapped volcanic rocks tends to be much greater than the extent of mapped intrusive rocks, and the large amount of volcanic cover may conceal buried deposits. The tract is based on the intrusive and volcanic rocks shown in figure O2 and listed in table O2. Extensive Quaternary volcanic cover is present in the western parts of sub-tract 009pCu7203b.

Central Highlands of Papua New Guinea.—This area outlines small micromonzonite and microdiorite intrusions in the Fold Belt of western Papua New Guinea. The tract includes late Miocene intrusions associated with the Porgera mine, late Miocene intrusive rocks at the Yandera porphyry copper deposit, the late Miocene Michael Diorite, and areas that may represent shallowly buried intrusions and volcanic centers based on aeromagnetic data. Exposed volcanic centers (Sisa Volcanics, Kerewa Volcanics, and Crater Mountain Volcanics) lie along northeast-trending orogen-transverse structural corridors. Magnetic data suggest that an unexposed intrusion is located along a northeast-trending corridor and about 80 km from exposed volcanic centers that lie to the west and east. The magnetic data also were used to delineate permissive areas around isolated, shallow magnetic anomalies that may represent shallow buried intrusions or diatremes. The Nevera Intrusive Complex, the locus of the Crater Mountain Project (New Guinea Gold Corp., 2009; Gold Anomaly, Ltd., 2011) is in a diatreme along the northern edge of the Crater Mountain Volcanic field (fig. O3). Volcanic cover may be more than 1 km thick in some areas; however, the Crater Mountain volcano is deeply eroded (Global Volcanism Program, 2010).

Table O2. Map units that define tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[Map unit, age range, and principal lithologies are based on a digital compilation of 1:250,000 scale geologic maps of Papua New Guinea (Papua New Guinea Geological Survey, 2002), a digital compilation of igeous rocks of Southeast Asia (Directorate of Mineral Resources and Inventory, 2004a), and scanned and rectified 1:250,000-scale quadrangle maps of Irian Jaya. Map symbols, lithology, and age ranges for Indonesia are based on 1:250,000-scale geologic maps; Papua New Guinea 1:250,000 map numbers and publication dates are listed. *, Indonesia. Major volcanic units and representative map sources are listed; variants of these units occur within the tract area on other maps. - -, no map unit]

Map unit	Map symbol	Lithology	Age range	Map number	Map year
		009pCu7203a, Intrusive rocks			
Antares Monzonite	Tpa	Monzonite, granodiorite, adamellite, fine-grained equivalents; minor tuff, agglomerate, lava, skarn	Late Miocene to Pleistocene	B5407	1972
Antares Complex (Ban Quartz Monzodiorite)	Tpb	Quartz monzodiorite, granodiorite, quartz monzonite	Late Miocene to Pliocene	B5403	1979
Fubilan Stock	Tpf	Quartz monzonite porphyry, quartz monzonite: mineralized	Late Miocene to Pleistocene	B5407	1972
Mount Ian gabbro	Tpg	Gabbro	Late Miocene to Pleistocene	B5407	1972
- -	Tpi	Diorite and microdiorite porphyry, some biotite, much altered (Porgera); altered microdiorite porphyry (Baia); coarse hornblende granite and diorite (Lai-Tsak)	Pliocene?	B5408	1980
Nong River Diorite	Tpn	Diorite, quartz diorite, monzodiorite, quartz monzodiorite	Late Miocene to Pliocene	B5403	1979
Stolka Quartz Diorite	Tpo	Quartz diorite, quartz monzodiorite, minor porphyry	Late Miocene to Pliocene	B5403	1979
Star Mountains Intrusives	Tps	Porphyritic micromonzonite, microdiorite, microgranodiorite; minor medium-grained equivalents; Sulphide, magnetite and epidote-garnet skarn	Late Miocene to Pleistocene	B5407	1972
Tumfakama Microdiorite	Tpt	Microdiorite, diorite, microgranodiorite	Late Miocene to Pliocene	B5403	1979
Antares Complex	Tpv	Andesitic and dacitic volcanic agglomerate, volcaniclastic sandstone and mudstone, crystal tuff	Late Miocene to Pliocene	B5403	1979
Intrusive rocks*	Tpt	Diorite, granodiorite; intrudes Miocene rocks; may be skarns where intrude carbonates	Pliocene	Jiyawijaya 250K	
		009pCu7203a, Volcanic rocks			
Kendupwa Volcanics	Tpk	Andesitic agglomerate, tuff, and volcanic sandstone, minor marl	Pliocene	B5408	1980
Antares Complex	Tpp	Andesitic and dacitic porphyry; phenocrysts are hornblende, plagioclase, minor pyroxene, rare biotite	Late Miocene to Pliocene	B5403	1979
		009pCu7203b, Intrusive rocks			
Elandora Porphyry	Tme	Hornblende andesite porphyry, microdiorite	Late Miocene	B5510	1972
- -	Tmi	Diorite, monzonite, minor granodiorite, gabbro; dykes, small plutons and stocks	Miocene to Pliocene	C5502	1973

Table O2. Map units that define tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.—Continued

Map unit	Map symbol	Lithology	Age range	Map number	Map year
		009pCu7203b, Intrusive rocks			
Suckling Granite	Tmk	Medium and coarse granite	Late Miocene	C5508	1972
Oveia Diorite	Tmo	Diorite, monzonite	Early Miocene?	C5507	1978
Benembi Diorite	Tmub	Porphyritic microdiorite	Late Miocene?	B5505	1971
Michael Diorite	Tmum	Porphyritic hornblende microdiorite	Late Miocene	B5509	1971
- -	Tmuy	Monzonite, porphyritic microdiorite, porphyry	Late Miocene	B5505	1971
Mai'iu Monzonite	Tpx	Xenolithic granodiorite, biotite monzonite, biotite hornblendite	Late Miocene to early Pliocene	C5508	1972
Bonua Porphyry	Tpb	Microdiorite and micromonzonite porphyry stocks, lamprophyric dykes	Pliocene	C5508	1972
Edie Porphyry	Tpe, Tpp	Biotite and hornblende dacite and andesite porphyry stocks and dykes	Pliocene	B5510, B5514	1972
- -	Tpg	Granodiorite, minor tonalite, adamellite, and granite	Pliocene	C5605	1969
Gidogidora Granodiorite	Tpgg	Granodiorite	Pliocene	C5605	1969
Observation Island Granodiorite	Tpgb	Granodiorite	Pliocene	C5605	1969
Luboda Granodiorite	Tpgl	Granodiorite stock with marginal xenoliths of altered gabbro	Pliocene	C5605	1969
Omara Granodiorite	Tpgo	Granodiorite, some granite, some amphibolite xenoliths	Pliocene	C5605	1969
- -	Tpi	Dolerite, microdiorite, microtonalite, diorite, granodiorite, tonalite	Late Pliocene	B5501	1974
		009pCu7203b, Volcanic rocks			
Aifunka Volcanics	Tmf	Andesitic lava, tuff, agglomerate	Middle Miocene	B5510	1972
Astrolabe Agglomerate	Tpa	Basalt and minor andesite agglomerate and tuff, partly reworked	Pliocene	C5507	1978
Amphlett Volcanics	Tpm	Trachyte, andesite and basaltic andesite lava and agglomerate	Pliocene	C5605	1969
Cloudy Bay Volcanics	Tpc, Tpt	Basaltic and andesitic agglomerate and lava: shoshonitic affinities; volcanic plugs; tuff	Pliocene	C5512, C5507	1970, 1978

Table O2. Map units that define tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.—Continued

Map unit	Map symbol	Lithology	Age range	Map number	Map year
		009pCu7203b, Volcanic rocks			
Crater Mountain Volcanics	TQvc	Andesitic and basaltic lava; minor tuff, agglomerate, derived sediments	Pliocene to Holocene	B5509	1971
Kerewa Volcanics	TQk	Fine grained trachyandesite lava and lava breccia, some andesitic agglomerate and tuff	Pliocene to early Pleistocene	B5408	1980
Kukuia Volcanics	TpQk	Rhyolite, rhyolitic obsidian, andesite ashflow tuff, and some basalt	Pliocene to Pleistocene	C5605	1969
Mount Cameron Volcanic Complex	Tpia	Basalt and andesitic agglomerate, minor tuff; tuffaceous sandstone and volcanic conglomerate at base (Kwikila Agglomerate)	Pliocene	C5507	1978
Mount Davidson Volcanics	Tpd	Basaltic and minor andesitic agglomerate, tuff, lava, lava breccia; massive to vesicular olivine and augite-phyric basalt	Latest Miocene to early Pliocene	C5503	1998
Bulolo Agglomerate	Tpg	Dacite and andesite agglomerate; minor crystal tuff	Pliocene	B5514	1972
Musa Volcanic Member	Tpz	Basaltic agglomerate: shoshonitic affinities	Pliocene	C5508	1972
Namie Breccia	Tpv	Volcanic breccia	Pliocene	B5514	1972
Ne Volcanics	TQn	Andesite lava	Pliocene to early Pleistocene	B5408	1980
Normanby Volcanics	Tpn	Andesite lava with some rhyolite, dacite, trachyte, trachyandesite and olivine basalt; basaltic agglomerate	Pliocene	C5609	1972
Sesara Volcanics	Tps	Basalt agglomerate, lava, tuff, minor volcanic sandstone; shoshonitic affinities; minor sediments; volcanic plugs	Late Miocene to early Pliocene	C5508	1972
Sisa Volcanics	TQs	Andesitic and basaltic agglomerate, tuff, lava: old cone	Pliocene to early Pleistocene	B5408	1980
Talama Volcanics	Tmt	Andesitic to basaltic agglomerate, tuff, lava breccia, lava; intercalated volcanically derived conglomerate, sandstone, minor mudstone	Middle to late Miocene	C5502	1973
Uvo Volcanics	Tpu	Andesite agglomerate, lapilli tuff, tuff including ash-flow tuff	Late Pliocene	B5501	1974
- -	TQp	Probably pyroclastics, jointed and faulted (airphoto interpretation)	Pliocene to early Pleistocene	B5408	1980
- -	Tp	Basic volcanics; mainly horizontal basalt flows	Pliocene	B5511	1972

Parts of the tract overlap with the older Maramuni Arc; margins of older rocks localize some younger intrusions.

Peninsular Papua New Guinea.—Small stocks of diorite, porphyritic microdiorite, monzonite, and granodiorite associated with coeval volcanic rocks (Mount Davidson Volcanics, Cloudy Bay Volcanics) delineate the tract on the main island of New Guinea. On offshore islands, the tract is delineated based on outcrops of Pliocene andesitic Normanby Volcanics, Gigogidorra Granodiorite, Omara Granodiorite, and other late Miocene-Pliocene rocks. The Kodu (Mount Bini) porphyry copper deposit and a number of prospects occur within this segment of the tract. The tract also includes Pliocene granodiorites and andesites in the D'Entrecasteaux Islands of Milne Bay Province.

Finisterre Range-northeastern Papua New Guinea coastal area.—Small stocks of Pliocene gabbro, diorite, clinopyroxene diorite, hypersthene gabbro, dolerite, microdiorite, quartz gabbro, tonalite, microtonalite, granophyric differentiates, diorite, and late Pliocene volcanic rocks (partly andesitic), crop out within 20–50 km of the coast in northeastern Papua New Guinea. This area is considered to be underexplored and currently is under exploration for porphyry copper-gold and skarn targets (Chrome Corp., 2009; Pacific Niugini, 2010).

Known Deposits

Porphyry copper deposits within the tract are listed in table O3 and plotted on figure O1. Only deposits with reliable identified resources and reserves are included. Partially explored deposits that lack reliable resource estimates are discussed below as prospects and are included in table O4.

Sub-tract 009pCu7203a

Ok Tedi (also known as Mount Fuliban), with 5.5 Mt contained copper, is the largest of three porphyry copper deposits in the Star Mountains of Papua New Guinea and the only copper-producing mine in the country in 2007 (Wacaster, 2010). Ok Tedi is an open-pit mine (~22,000-hectare lease area) that was discovered in 1968 by reconnaissance exploration by Kennecott; production started in 1985 with mining of the gold-rich supergene oxide cap. Copper production started in 1987 (Hendry and others, 2005). Ok Tedi produced 159,650 t of copper and 16,032 kg of gold in 2008 (Wacaster, 2010). As of December 31, 2009, proven and probable reserves were reported as 113 Mt of 0.80 percent copper and 1.10 g/t gold (Inmet Mining Corp., 2009). Expected mine life is projected to 2013, although the managers are exploring options for extending mine life to 2022.

At Ok Tedi, chalcopyrite, chalcocite, and minor bornite are present in quartz veins and stockworks in a porphyritic monzonite intrusion; copper and gold occur in magnetite and sulfide skarns in country rocks (van Dongen and others, 2007). Intrusive rocks are alkaline in character. Sulfur isotopic values ($\delta^{34}S = -0.8$ to 5.1) are slightly elevated relative to typical porphyry copper sulfide isotopic signatures ($\delta^{34}S = -5$ to 1). Low rare-earth element concentrations may reflect destruction of monazite, xenotime, and apatite during hydrothermal alteration (van Dongen and others, 2007).

Two smaller porphyry copper deposits, Star Mount Nong River and Star Mount Futik (300,000 and 350,000 Mt contained copper, respectively), lie about 25 km to the north of Ok Tedi along a northeast-trending structural corridor.

Sub-tract 009pCu7203b

Central Highlands of Papua New Guinea.—Geochemical exploration in the 1970s led to identification of the Yandera porphyry copper deposit. Anomalous copper concentrations in stream sediments sampled at a density of one sample per 1 to 2 km^2 delineated the porphyry copper system (Fleming and Neale, 1979). In 2009, Marengo Mining, Ltd., was developing an open-pit mine at the Yandera porphyry copper deposit to produce copper and molybdenum, with byproduct gold, iron ore, silver, and rhenium starting in 2010 (Wacaster, 2010). Indicated and inferred resources announced in 2011 (Marengo Mining, Ltd., 2011b), listed in table O2, include estimates of byproduct rhenium that could be recovered from molybdenum. Note that the JORC-compliant data (Marengo Mining, Ltd., 2011a,b) reported in table O2 are for the lowest reported cut-off graded (0.2 percent CuEq, where CuEq is calculated as Cu+(10 × Mo). At this cut-off grade, the Yandera deposit contains 5.7 million metric tons of copper. At the more commonly cited higher cut-off grade of 0.3 percent CuEq, the deposit contains 2.9 million metric tons of copper. The 7 by 2 km mineralized system extends beyond the area included in resource estimates.

Peninsular Papua New Guinea.—The Golpu porphyry copper-gold deposit is part of the Wafi-Golpu mineralized intrusive system, which includes a high-grade core of stockwork veining in altered diorite porphyry (174 Mt at 1.57 percent copper and 0.88 g/t gold), a halo of stockwork in metasedimentary host rocks (314 Mt at 0.59 percent copper and 0.6 g/t gold), and the Wafi high-sulfidation epithermal gold deposit (Harmony Gold Mining Co., 2011). The porphyry deposit is centered on a diatreme associated with the Miocene Golpu diorite to dacite porphyry plug and late-stage breccias (Porter Geoconsultancy, 2004). Harmony expanded the footprint of their Wafi-Golpu project area to include the Nambonga porphyry copper-gold prospect, located 2 km northwest of Golpu (Harmony Gold Mining Co., 2009). The project is part of the 50:50 Morobe Mining Joint Venture between Harmony Gold Mining Company and Newcrest Mining Limited. Total resources for the Golpu and Nambonga porphyry deposits are listed in table O3 (Harmony Gold Mining Co., 2010; Newcrest Mining Limited, 2010). Both deposits are open and continue to be explored; prefeasibility studies were underway in 2011 to confirm resource classifications and acquire geotechnical and metallurgical data (Hannah, 2011).

The Kodu deposit (formerly called Mount Bini) was located by stream-sediment and rock-float sampling (Dugmore and others, 1996, 1998). The deposit, situated along a NNE-trending lineament defining a 15–20 km wide structural zone, is hosted in the

Table O3. Porphyry copper deposits in tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (%); NA, not applicable; n.d., no data; *, data for Yandera reported at cutoff grade of 0.2% CuEq, average rhenium grade 0.05 ppm; **, data for Wafi-Golpu based on 2010 data for Golpu and Nambonga porphyry deposits, excludes the Wafi epithermal gold deposit]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Sub-tract 009pCu7203a											
Ok Tedi	–5.200	141.133	Cu-Au	1	854	0.64	0.011	0.78	n.d.	5,465,600	Andrew (1995), Bamford (1972), Davies and others (1978), Page (1975), Rush and Seegers (1990), Sillitoe (1995), Stapleton (1993), Tarkian and Stribrny (1999), van Dongen and others (2007)
Star Mount Nong River	–5.017	141.217	NA	4	60	0.50	n.d.	n.d.	n.d.	300,000	Arnold and Griffin (1978), Page (1975)
Star Mount Futik	–5.067	141.333	NA	4	65	0.54	n.d.	0.10	n.d.	351,000	Arnold and Griffin (1978), Page (1975)
Sub-tract 009pCu7203b											
Yandera*	–5.750	145.167	NA	7	1,639	0.35	0.010	0.07	1.5	5,749,926	Lole (2005), Marengo Mining Limited (2009, 2011a,b), Titley and others (1978), Watmuff (1978)
Wafi-Golpu**	–6.883	146.450	Cu-Au	9	540	0.90	0.01	0.56	n.d.	4,860,000	Andrew (1995), Corbett and Leach (1998), Freebrey (1998), Funnel (1990), Gillman (2004), Harmony Gold Mining Co. (2010), Newcrest Mining Limited (2010), Leach (1999), Lole (2005), Ryan and Vigar (1999), Tau-Loi and Andrew (1998)
Kodu (Ofi Creek, Mount Bini)	–9.300	147.583	Cu-Au	4	276	0.28	0.008	0.30	1.75	759,000	Anonymous (1996), Dugmore and others (1998), Dugmore and others (1996), Leaman (1996) , Frontier Resources, Ltd. (2007a), Keele and Lindley (2004)

Table O4. Significant prospects and occurrences in tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[Ages all assumed to be Late Miocene to Pliocene based on associated map units. Rank 4=Prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1= copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ppm, parts per million; Mt, million metric tons]

Name	Latitude	Longitude	Comments	Reference	Rank
			Sub-tract 009pCu7203a		
Porgera	–5.468	143.086	Epithermal gold deposit with some porphyry characteristics; potential for deep porphyry? Deep exploration (1,000 m below epithermal gold deposit workings identified hydrothermal magnetite, secondary biotite, chalcopyrite, and pyrrhotite. No economic copper mineralization.	Richards and Kerrich (1993), Richards (1997)	2
			Sub-tract 009pCu7203b		
Wamum (Wau-Morobe)	–6.750	146.283	Average for 5 drill holes: 0.37% Cu, 0.24 g/t Au and 1.1 g/t Ag. Drill-defined resource for Mount Wamum of 45 Mt at 0.30 % Cu and 0.12 g/t Au.	Shedden (1990); Singer and others (2008); Triple Plate Junction PLC (2010)	4
Tifalmin	–5.046	141.208	Grass roots exploration project for copper-gold targets on old prospects in the Tifalmin-Nong River area; aeromagnetic surveys and and drilling underway in 2010. Exploration areas may include Star Mount Futik and Star Nong River deposits. Drilling (2010) at Olgal prospect intercepted 474 m at 0.42% Cu and 0.24 g/t Au.	Highlands Pacific (2009a, 2011)	3
Ipi River	–8.250	146.713	Petromin (2008) high priority exploration area for shallow epithermal Au to porphyry Cu-Au deposits based on 2007 rock sample assays.	Petromin PNG Holdings Limited (2008)	1
Oram	–9.869	148.291	Exploration license area (1,286 km^2) in Central and Oro Provinces, SE of Port Moresby. Explored for copper in the 1970s (BHP) and 1980s (CRA); old targets warrant further exploration.	Triple Plate Junction PLC (2004)	2
Elo	–9.374	147.518	Elo porphyry copper-gold-molybdenum system ~ 18 km NW of the Kodu Deposit. Elo exploration target based on 2 km by 3 km elliptical topographic high, soil anomalies (max, 0.12% Cu, 90 ppm Mo, 0.54 g/t Au), and trench results (212 m of 0.08% Cu, 0.10 g.t Au). One drill hole intercepted 46 m of 0.18% Cu, 0.17 g/t Au, 133 ppm Mo, and 0.6 g/t Ag.	Frontier Resources, Ltd. (2007b, 2008b)	2
Gusap	–5.796	146.230	Finisterre Range: chalcopyrite float and gossan outcrop associated with Pliocene diorite; magnetic anomalies.	Pacific Niugini (2010)	2
Zenag gold-copper project	–6.990	146.527	Porphyry copper-gold exploration target area mapped as Morobe Granodiorite; magnetic anomaly; surface Au and Cu	Harmony Gold Mining Co. (2009), Pacific Niugini (2010)	1
Crater Mountain project	–6.356	145.086	Exploration license area for Porgera-type epithermal gold deposit; widespread argillic alteration at surface. Andesites, dacite, diorite with porphyry-style alteration; gold and elevated copper hosted in quartz-pyrite veins associated with diatreme-dome complex. Several undrilled prospects; reccent drilling focus on gold system.	Christopher and Smith (2002); Gold Anomaly, Ltd. (2011)	2
Mount Hagen	–5.670	144.162	Exploration license area along Bismarck fault zone; Au,Cu, Mo associated with diorite and dacite along fault zone (NW-trending). Disseminated supergene chalcocite and covellite; hypogene chalcopyrite, bornite in quartz stockwork veinlets. Not drilled.	Harmony Gold Mining Co. (2009), Pacific Niugini (2010)	2

Bini porphyry, a dike-like K-rich calc-alkaline composite stock that has a circular topographic expression (Dugmore and others, 1996), on the southeast side of the 10 by 4 km Pliocene Bavu Igneous Complex. Historical inferred resources of 85 Mt of 0.40 percent copper and 0.60 g/t gold were reported on the basis of 7 shallow diamond drill holes, open at depth and along strike. Revised resources (0.2 percent copper equivalent cut-off) based on additional drilling are reported as: indicated resources of 105 Mt grading 0.30 percent copper, 0.35 g/t gold, 68 ppm molybdenum, and 2.0 g/t silver; inferred resources of 171 Mt grading 0.26 percent copper, 0.27 g/t gold, 82 ppm molybdenum, and 1.6 g/t silver (Frontier Resources, Ltd., 2007a). A conceptual mining study suggested that a 10-year, 200 million-metric ton operation could potentially be economic. In 2008, a decision on land use (ecotourism and environmental concerns) led to cessation of further exploration and development at the Kodu deposit.

Prospects, Mineral Occurrences, and Related Deposit Types

Porphyry copper prospects and epithermal deposits or prospect areas that may be associated with porphyry copper deposits at depth are listed in table O4. The main prospect areas are discussed from west to east across the magmatic belt that defines the tract.

Sub-tract 009pCu7203a

Arnold and Griffin (1978) described characteristics of Mount Fubilan (Ok Tedi) and ten other prospects in the Tifalmin and Nong River areas of the Star Mountains (table O3, fig. O1). Resource estimates were deemed not practical or negligible for most of the prospects at the time; citing McGee (1976), Arnold and Griffin (1978) reported order-of-magnitude estimates for some of the prospects in the Star Mountains. Some of the prospects in the Star Mountains north of the Ok Tedi deposits are undergoing exploration (drilling, high-resolution airborne geophysical surveys) by Highlands Pacific, Ltd. (Highlands Pacific, Ltd., 2011). Drilling on the Olgal prospect in the Tifalmin area, which may be part of the undeveloped and perhaps incompletely delineated Star Mount Futik deposit of Singer and others (2008), intercepted 210 m of 0.50 percent copper and 0.37 g/t gold (Highlands Pacific, Ltd., 2011).

Sub-tract 009pCu7203b

Crater Mountain is a stratovolcano with a Pliocene-early Pleistocene andesitic phase and a Holocene basaltic phase. Mineralization at several prospects within the Crater Mountain exploration-project license areas is associated with the older phase andesite, dacite, and diorite plugs, and localized along north to north-northeast structures. Hydrothermally altered felsic to intermediate intrusive rocks with copper minerals are present; porphyry copper deposits may be associated with the epithermal gold systems at depth, but have not been drilled (Gold Anomaly, Ltd., 2011).

The Wamum prospect (Shedden, 1990) in the Edie porphyry has a reported noncompliant resource estimate of 45 Mt of 0.3 percent copper, 0.12 g/t gold (Triple Plate Junction PLC, 2006).

Exploration in the Mount Bini area of the Central Province of Papua New Guinea identified several areas of porphyry Cu-Au-Mo mineralization in addition to the Kodu (Ofi Creek, Mount Bini) deposit. These include prospects and occurrences at Kodu Northwest (separated from Kodu by a ridge), Elo, and Oomargi (7 km northwest of Kodu), Tamala, and Ua-Ule. The Elo prospect, 18 km northwest of Kodu (Mount Bini), is an exploration target based on a 2 by 3 km elliptical topographic high along a northeast-trending lineament; drilling in 2007 indicated that Elo is molybdenum-rich compared with average grades observed at Kodu (Frontier Resources, Ltd., 2007b).

Gusap (table O4) is the only porphyry copper prospect that the team was aware of in the Finisterre Range-northeastern Papua New Guinea coastal area. However, much of the area is under exploration license.

Related Deposit Types

The Medial New Guinea magmatic belt includes at least nine significant intermediate-sulfidation, Pliocene to Pleistocene epithermal gold deposits (Garwin and others, 2005). The Porgera epithermal gold deposit is associated with a 6 Ma, epizonal, mafic, alkaline intrusive complex, coincident with a roughly circular aeromagnetic anomaly (Richards and Kerrich, 1993). Early stage (I) mineralization at Porgera is similar to porphyry, but higher in Au/Cu ratio and lacking in a potassic alteration zone (Richards and Kerrich, 1993). Porgera represents a gold-rich type of porphyry/epithermal gold deposit associated with mafic, alkaline magmatism; precursor magmatic-hydrothermal stages activity at such deposits rarely is economic (Richards, 1997). Similar alkaline rocks are present at the Mount Kare epithermal gold prospect, 18 km southwest of Porgera (Richards and Kerrick, 1993).

The tract also includes exploration projects targeting epithermal gold (Kamitani and Naito, 1998; Porter Geoconsultancy, 2003; Papua New Guinea Mineral Resources Authority, 2008). Artisanal alluvial gold workings are present in many parts of the tract.

Exploration History

Exploration in the Star Mountains in the 1960s led to the discovery of Ok Tedi and other porphyry and skarn prospects. The Tifalmin prospects were drilled in the 1970s; the Geological Survey of Papua New Guinea continued geochemical and geophysical exploration in the area, which led to the discovery of the Nong River deposit (Arnold and Griffin, 1978). Abandoned prospects from 1970s-era exploration are currently being re-evaluated with aeromagnetic surveys and drilling (Highlands Pacific, 2009a).

Since the 1970s, there has been a long history of exploration using geochemistry, mapping, and geophysics (airborne and ground), mostly around or near known occurrences. The Wamum deposit was found by CRA Exploration in 1977 by using geochemical prospecting. The Wamum Idzan Creek gold-copper porphyry prospect in the Edie porphyry was abandoned in the late 1990s; drilling returned 43.3 m grading 2.09 g/t gold and 0.68 percent copper and 36 m grading 1.79 g/t gold and 0.45 percent copper at Idzan Creek. Recent exploration on a 2,500 km^2 license area held by Triple Plate Junction PLC focuses on circular features, stream-sediment gold anomalies, and geophysical targets. Previous drill-defined resources for one of the prospect areas, Mt. Wamum, are 45 Mt at 0.30 percent copper and 0.12 g/t gold.

Exploration at Crater Mountain in the 1970s focused on porphyry copper targets (Christopher and Smith, 2002). The focus then shifted to delineation of a Porgera-type epithermal gold deposit.

Many areas within the tract are remote, highly vegetated, and may not have been thoroughly explored. As of 2008, however, almost all of the areas covered by the permissive tracts in Papua New Guinea were under exploration license. The Yandera district, last explored in the 1960s, currently is being explored by Marengo Mining Limited (2009). The exploration focus is on circular, topographic highs, and historically partly explored prospects that have indications of copper and gold, alluvial gold, stream-sediment geochemical anomalies, geophysical anomalies, and northeasterly structural trends and lineaments, especially in areas between known mineralized centers along the same structural corridors.

Sources of Information

Principal sources of information used by the assessment team for delineation of tract 009pCu7203 are listed in table O5.

Grade and Tonnage Model Selection

Three of the six known deposits in the tract are classified as porphyry copper-gold deposits based on gold grades >0.2 g/t. Statistical tests (*t*-tests) comparing the deposits within each sub-tract with the global general and porphyry copper-gold subtype models indicate that either model is appropriate for the assessment (table 6). Because half of the known deposits are copper-gold subtype, and that deposit type is representative of the New Guinea magmatic belt and other post-collisional porphyry systems, the assessment team selected the copper-gold subtype grade-tonnage model for the simulation of undiscovered resources.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The tract contains six porphyry copper deposits that have identified resources; only Ok Tedi (sub-tract a) is in production. At least nine porphyry copper prospects are under evaluation (table O4); many of the historical prospects and abandoned mine areas were under exploration license in 2008 (Papua New Guinea Mineral Resources Authority, 2008). The tract includes 46 copper occurrences (27 abandoned prospects and mines; 19 minor mineral occurrences) and 51 gold occurrences (nine abandoned or unworked mines or prospects, the rest are minor or alluvial gold workings).

Sub-tract a is partly well explored due to the presence of an active mine. The team concluded that there is a 50-percent chance that at least one additional deposit may be present in sub-tract a. Magnetic data suggest that additional shallow intrusions may be present between the cluster of known deposits and Porgera (fig. O1), which led to the estimate of a 10-percent chance of four or more undiscovered deposits.

Sub-tract b has more volcanic cover than sub-tract a, is less thoroughly explored, and has a number of widespread exploration targets. The team considered that further exploration could reveal porphyry systems below, or proximal to, known epithermal gold deposits, such as Porgera. Sub-tract b contains three known deposits and 9 significant prospect areas. The 90-percent estimate of at least one deposit is based on the likelihood that the partially-drilled Wamum (Wau-Morobe) prospect or one of the other recent exploration projects could represent a deposit once fully delineated (rank 4, table O4). The team reasoned that about half (4) of the prospects could represent undiscovered deposits as the basis for the 50-percent estimate. Exploration in areas that have not previously received much exploration for porphyry copper deposits, such as the Finisterre Range, could yield new discoveries. Sub-tract b is three times the size of sub-tract a (table O6); prospects are widely dispersed. Given that some areas are poorly explored, and that modern geophysical exploration and drilling are increasingly targeting historical prospects and mineral occurrences, the team estimated a 10-percent chance of 16 or more deposits, which is about twice the number of known prospects in the tract.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table O7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. O3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper contained in undiscovered porphyry copper deposits within sub-tract a, 5.1 Mt of copper, is slightly less than the amount of identified copper resources (6.1 Mt). For sub-tract b, the mean amount of copper, 20 Mt, is almost double the 11.4 Mt of identified copper resources.

Table O5. Principal sources of information used for tract 009pCu7203—Eastern Medial New Guinea Magmatic Belt, Papua New Guinea and Indonesia.

[CCOP, Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia; NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Geology of Papua New Guinea	1;1,000,000	Bain (1972)
	Digital geological map of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital geological map of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Digital mineral occurrence database	NA	Directorate of Mineral Resources and Inventory (2004b)
	MRDS database	NA	U.S. Geological Survey (2008)
Exploration	USGS Minerals Yearbooks	NA	Wacaster (2010), Various (see references in table O4)
	Company Web sites	NA	
Geophysics	Central Highlands of Papua New Guinea magnetic data	NA	Mineral Resources Authority

Table O6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract Area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
					Sub-tract 009pCu7203a						
0	1	4	4	4	1.60	1.54	97	3	4.6	14,230	32
					Sub-tract 009pCu7203b						
1	4	16	16	16	6.6	5.58	84	3	9.6	53,220	18

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Table O7. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7203, Eastern Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
				Sub-tract 009pCu7203a				
Cu	0	0	1,200,000	12,000,000	24,000,000	5,100,000	0.23	0.29
Mo	0	0	0	63,000	150,000	29,000	0.17	0.59
Au	0	0	110	930	1,600	360	0.27	0.29
Ag	0	0	0	3,200	6,900	1,700	0.17	0.51
Rock	0	0	300	2,600	4,900	1,000	0.25	0.29
				Sub-tract 009pCu7203b				
Cu	0	390,000	10,000,000	55,000,000	76,000,000	20,000,000	0.34	0.07
Mo	0	0	28,000	360,000	580,000	120,000	0.26	0.25
Au	0	39	830	3,900	5,100	1,500	0.36	0.07
Ag	0	0	1,900	18,000	34,000	6,700	0.25	0.19
Rock	0	99	2,200	11,000	14,000	4,100	0.36	0.07

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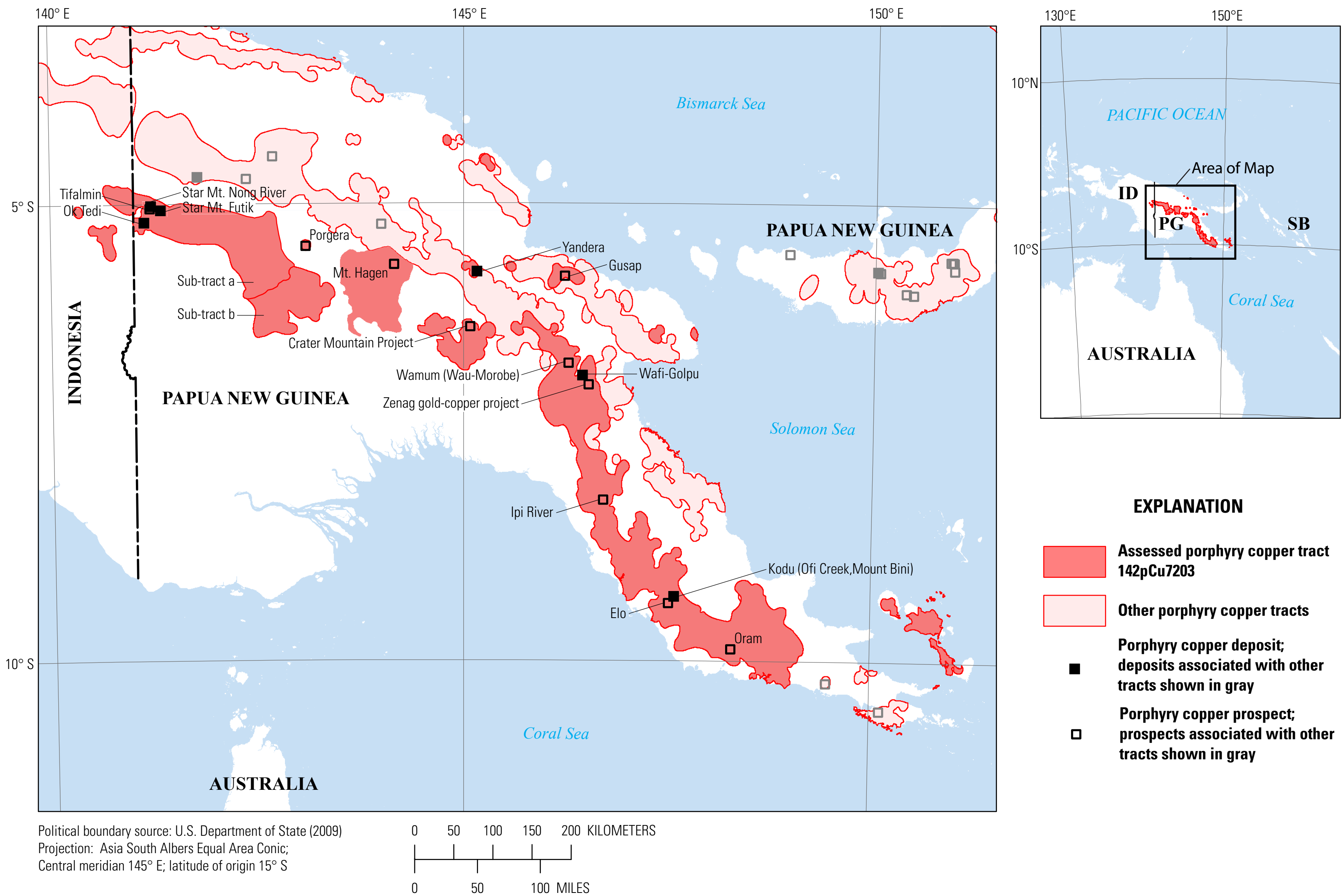


Figure 01. Map showing the location, known deposits, and significant prospects and occurrences for permissive tract 009pCu7203, Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia. ID, Indonesia; PG, Papua New Guinea; SB, Solomon Islands.

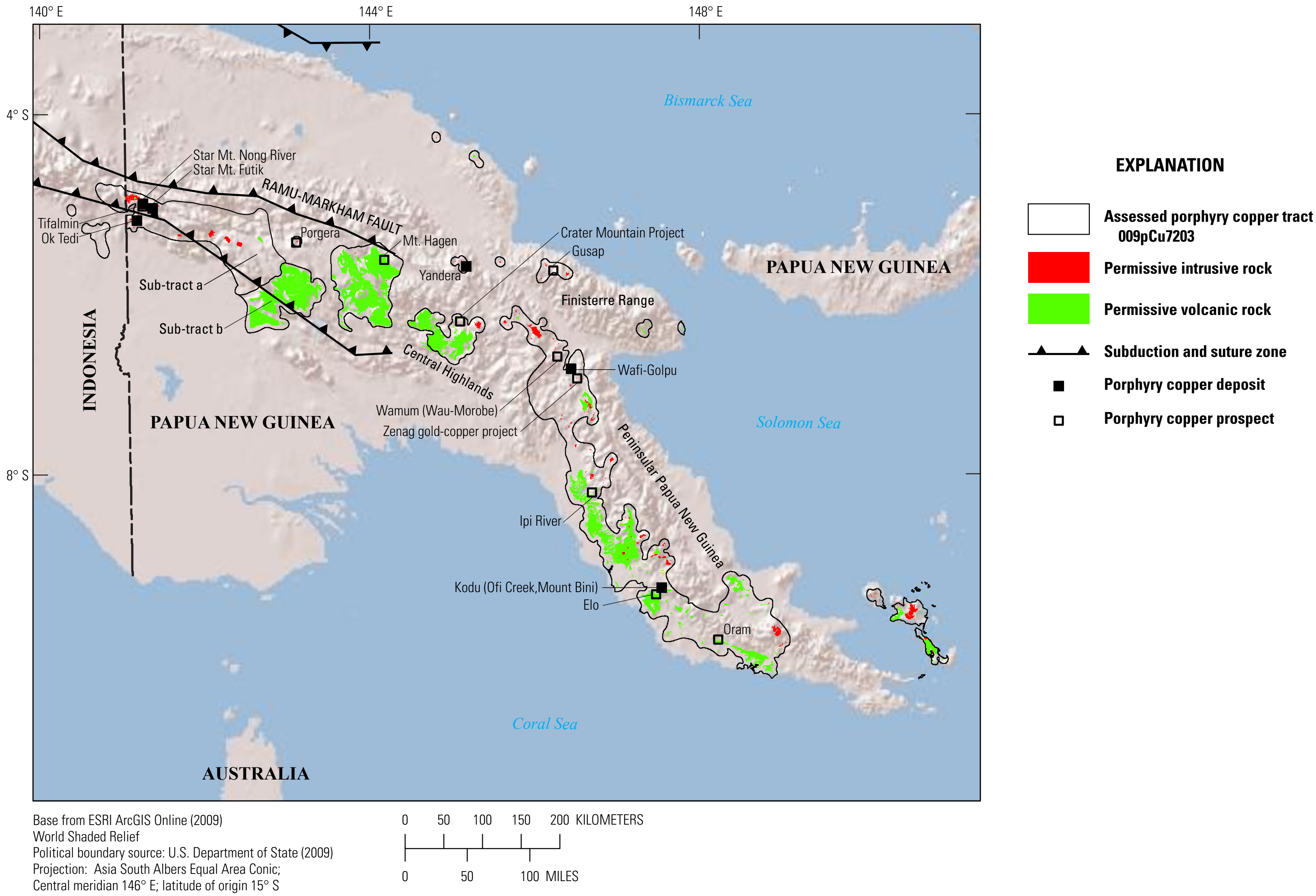
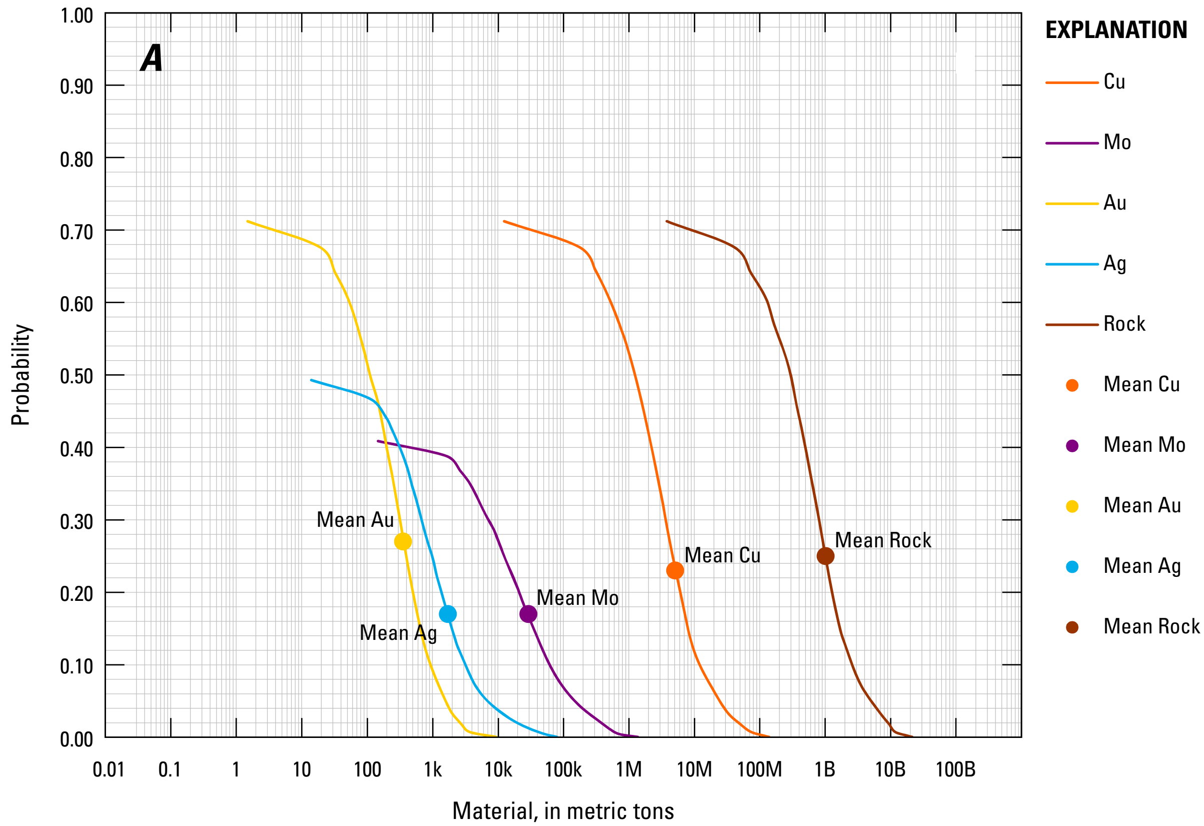


Figure O2. Sub-tracts of 009pCu7203, Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia, shown on a shaded relief map of New Guinea Island to illustrate the extent of the highlands areas, with mapped areas of surface exposures of late Miocene-Pliocene igneous rocks permissive for the occurrence of porphyry copper deposits. Sub-tract a is the Indonesia-Papua New Guinea border area. Sub-tract b includes permissive rocks in the Central Highlands of Papua New Guinea, the Finisterre Range, the Peninsular area of southeastern Papua New Guinea, and the D'Entrecasteaux Islands.



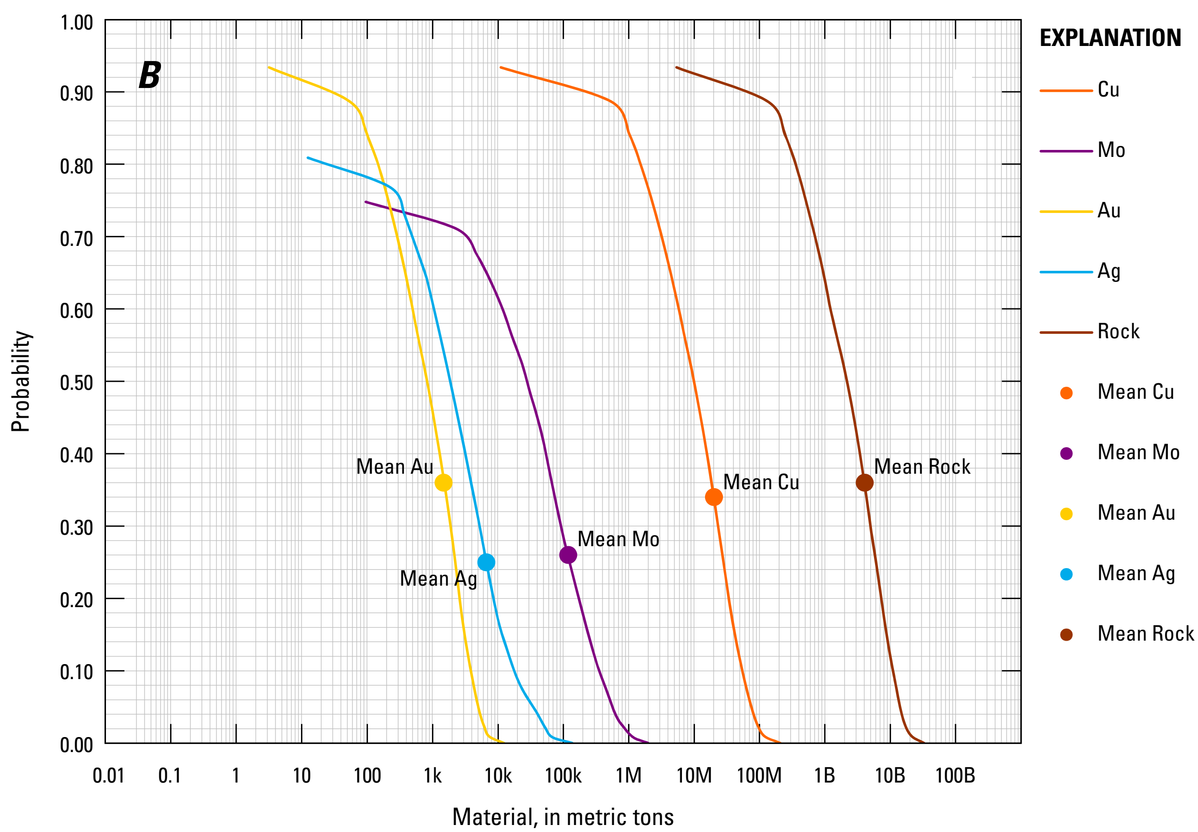


Figure O3. Cumulative frequency plots showing the results of Monte Carlo computer simulation of undiscovered resources in 009pCu7203, Medial New Guinea Magmatic Belt—Papua New Guinea and Indonesia. *A*, Sub-tract 009pCu7203a. *B*, Sub-tract 009pCu7203b. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix P. Porphyry Copper Assessment for Tract 009pCu7205, Maramuni Arc—Papua New Guinea

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[4], Arthur A. Bookstrom[5], and Michael L. Zientek[5], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[4]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive models: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others,1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table P1 summarizes selected assessment results.

Table P1. Summary of selected resource assessment results for tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	38,970	8,550,000	9,900,000	3,300,000

Location

The tract is in the central part of New Guinea Island, Papua New Guinea (fig. P1).

Geologic Feature Assessed

Miocene Maramuni magmatic arc.

Delineation of the Permissive Tract

Tectonic Setting

The tract delineates igneous rocks associated with the Miocene Maramuni Arc in Papua New Guinea. The Maramuni Arc probably formed in middle Miocene time as a result of southwest-dipping subduction of the Solomon Sea Plate beneath eastern

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Menlo Park, California, United States.
[5]U.S. Geological Survey, Spokane, Washington, United States.

New Guinea. Most authors contend that the Maramuni Arc does not extend west of the Papua New Guinea-Irian Jaya border (as shown on figures by Garwin and others, 2005). The Maramuni Arc lies south of the Melanesian Arc terrane and north of the Medial New Guinea magmatic belt, although there are some areas of overlap (fig. 7). The northern border of the tract lies south of the Ramu-Markham Fault Zone in eastern Papua New Guinea. Margins of Maramuni Arc intrusions are the locus of many of the late Miocene to Pliocene intrusions of the Central Highlands Belt. The assessment team followed the general arc classification of Garwin and others (2005). Maramuni magmatism was volumetrically more extensive, formed large plutons and batholithic complexes, and the rocks are more deeply eroded than the hypabyssal diatremes, dikes, and small stocks that characterized the late Miocene to Pliocene magmatic event. Findley (2003) noted that the concept of a Maramuni Arc was postulated in the 1970s to explain 18–12 Ma middle Miocene calc-alkaline magmatism in Papua New Guinea; he attributed the younger late Miocene-Pliocene magmatism in the area (tract 009pCu7203) to the same process and, therefore, questioned separating the two events.

Equivalent-age igneous rocks in the Moon-Utawa Arc of Indonesia are delineated as tract 142pCu7205. The Moon Volcanics may be linked to the Maramuni Arc, but as noted by Malaihollo and Hall (1996), the nature and distribution of the volcanism and its relation to the Maramuni rocks remains unclear.

Geologic Criteria

The tract was constructed in a GIS using a digital compilation of 1:250,000-scale geologic maps of Papua New Guinea. Maps and figures showing the major faults, lineaments, and tectonic divisions of New Guinea by Garwin and others (2005), Hill and others (2002), Quarles van Ufford and Cloos (2005), and Cloos and others (2005) also were used. Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, all igneous rocks of Miocene age (>7 Ma and exclusive of rocks mapped as late Miocene or younger) were selected. Using GIS tools, a 5-km buffer was applied around mapped igneous contacts of permissive lithologies to account for spatial uncertainty in digitized geology and for the possibility of greater extent of permissive rocks within a kilometer of the surface. Ophiolites, ultramafic rocks, and basaltic units were deemed nonpermissive and are omitted from the tract.

The final tract boundaries were established by GIS processing and editing. The processing approximates manual delineation of tracts but is rapid and reproducible. The processing steps included (1) unioning all buffered permissive map units and other polygon features that comprise the framework of the tract; (2) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 m^2, a step done to group closely spaced permissive areas; (3) manually aggregation and adjustment of tract areas; and (4) smoothing of polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing and compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Papua New Guinea compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks by providing locations of dated samples and lithologic information (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

The resulting tract outlines early to middle Miocene and middle to late Miocene intrusive and volcanic rocks of the 1,000-km-long Maramuni Arc. Igneous rocks designated as late Miocene to Pliocene are excluded (see tract 009pCu7203). Miocene rocks crop out within the mobile belt along the northern margin of the Central Highlands of Papua New Guinea (fig. P2). The tract primarily is based on the mapped extent of the rocks listed in table P2. Intrusive rocks are exposed along the northern part of the east-west-trending arc; volcanic rocks are confined to the southern part of the arc (fig. P2). Late Miocene to Pliocene rocks generally are present to the south of the Maramuni Arc; however, some of the younger rocks intrude along the margins of the intrusive rocks of the Maramuni Arc, and along arc-transverse northeast-trending structures. Part of the tract was extended north and west of the Salumei prospect (fig. P2) based on aeromagnetic data and topography.

Known Deposits

The Frieda River, Yandera, and Wafi-Golpu porphyry copper deposits lie within the Maramuni Arc according to Garwin and others (2005). Both Wafi-Golpu and Yandera are proximal to younger (<7 Ma) late Miocene-Pliocene intrusions that were emplaced into, or along the margins of older Maramuni-age rocks. The team arbitrarily assigned Wafi (possibly as young as 9 Ma) and Yandera (7 Ma) to the late Miocene-Pliocene Eastern Medial New Guinea magmatic belt (tract 009pCu7203B). Therefore, the 12 Ma Frieda River project is the only deposit with identified resources that we included as belonging to the Maramuni tract (table 3).

The Frieda River Intrusive Complex initially was explored in the 1960s. Continued exploration led to discovery of the Nena copper-gold high-sulfidation deposit in 1977 by regional reconnaissance (Bainbridge and others, 1998); the discovery was made by following the source of copper float. At Nena, weathering has leached copper from an oxidized, gold-rich supergene cap; chalcocite and covellite form a supergene blanket below the gold zone (Lole, 2005). Drilling to 780 m below the covellite zone at Nena intercepted weakly-altered porphyry-copper style mineralization characterized as biotite-quartz alteration of porphyry containing chalcopyrite and bornite (Bainbridge and others, 1998; Onglo and others, 2008). Horse/Ivaal and Koki are porphyry copper deposits

Table P2. Map units that define tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[Map unit, age range, and principal lithologies are based on a attributes in a digital compilation of geologic maps of Papua New Guinea Indonesia (Papua New Guinea Geological Survey, 2002). Numbers and publication dates of 1:250,000-scale maps avaiable from the Papua New Guinea Geological Survey are listed for reference – –, no map unit]

Map unit	Map symbol	Lithology	Age range	Map number	Map date
		Intrusive rocks			
– –	Ti	Diorite, porphyritic microdiorite	Part Eocene, Oligocene to middle Miocene	B5403	1979
Ananadi Diorite	Tma	Hornblende and quartz monzonite; gabbro, granophyre	Early Miocene	B5403	1979
Akuna Intrusive Complex	Tmak	Gabbro, porphyritic dolerite, diorite; minor granodiorite	Early Miocene	B5510	1972
Bismarck Intrusive Complex	Tmb	Gabbro, diorite; minor tonalite, granodiorite, mangerite, granite, aplite, pegmatite, hornblendite, dunite, peridotite, anorthosite	Middle Miocene	B5505	1971
Frieda Complex (Older intrusives)	Tmf	Biotite-hornblende-quartz microdiorite and porphyry, hornblende-quartz diorite and andesitic porphyry; propylitic, silicic and potassic alteration; disseminated Cu, Au mineralization	Middle Miocene	B5403	1979
Hunstein and Chambri stocks	Tmh	Monzonite, granodiorite, diorite: Hunstein and Chambri stocks	Early Miocene	B5404	1979
Nekiei batholith	Tmi	Granodiorite, diorite, some porphyry	Miocene	B5404	1979
Oipo Intrusives	Tmi?	Gabbro, granodiorite, tonalite, diorite, pyroxenite, lamprophyre	Middle Miocene	B5505	1971
Tarua stock	Tmit	Granodiorite, diorite	Middle Miocene	B5408	1980
Wale batholith	Tmiw	Grandodiorite, diorite; plagioclase-pyroxene porphyry with much opaques (Timun area)	Middle Miocene	B5408	1980
Kimil Diorite	Tmk	Diorite, gabbro, tonalite, granodiorite; andesite porphyry, dolerite and basalt dykes; minor trachyandesite	Middle Miocene	B5505	1971
Frieda Complex (Younger intrusives)	Tmk	(Biotite-) hornblende-quartz diorite, diorite and andesitic porphyry, unaltered, acicular hornblende typical	Middle Miocene	B5403	1979
Kenangi Gabbro	Tmke	Gabbro, mangerite, granodiorite	Middle Miocene	B5509	1971

Table P2. Map units that define tract 009pCu7205, Maramuni Arc—Papua New Guinea.—Continued

Map unit	Map symbol	Lithology	Age range	Map number	Map date
Intrusive rocks					
Morobe Granodiorite	Tmm	Granodiorite, adamellite; minor monzonite, diorite, pegmatite	Middle Miocene	B5510	1972
Maramuni Diorite	Tmm	Diorite, microdiorite, granodiorite; minor gabbro, rhyodacite, porphyry, monzonite; andesite and dolerite dykes	Middle Miocene	B5505	1971
Nena Diorite	Tmn	Medium to fine quartz diorite	Middle Miocene	B5403	1979
Yuat North batholith and stocks	Tmny	Diorite, granodiorite, some porphyry	Early to middle Miocene	B5404	1979
Karawari batholith	Tmr	Diorite, granodiorite, some porphyry: Karawari batholith	Middle to late Miocene	B5404	1979
Yuat South batholith	Tmsy	Granodiorite, minor diorite, some gabbro	Middle to late Miocene	B5408	1980
Manawai Diorite	Tom	Diorite, some gabbro, inliers of hornfels and chert	Middle Oligocene	B5403	1979
Paupe Granodiorite	Top	Hornblende granodiorite, slightly altered	Late Oligocene	B5403	1979
– –	Ts	Gabbro, andesitic porphyry, diorite	Early Miocene?	B5510	1972
Maumiavi Diorite	Tv	Diorite, some tonalite, monzonite, adamellite, rare porphyry	Part Eocene, early Miocene	B5403	1979
Yaveufa Formation	Tma, Tmay1	Volcanolithic conglomerate, greywacke, tuff	Middle Miocene	B5510	1972
Volcanic rocks					
Frieda Complex - Debom Volcanics	Tmd	Porphyritic hornblende andesite lava, pyroclastics, sediments	Middle Miocene	B5403	1979
Tarua Volcanics	Tmt	Andesitic and basaltic lava, agglomerate, tuff, minor pillow lava	Middle Miocene	B5408	1980

Table P3. Identified porphyry copper resources in tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Mo subtype, deposits that have Au/Mo ratios <3 or average Mo grades >0.03%; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (%). *, includes Horse-Ivaal-Trukai total resources at 0.2% copper cutoff grade from Xstrata Copper (2011); (Mo) from Singer and others (2008)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage	Grade				Contained Cu (t)	Reference
						Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)		
Frieda River*	–4.7	141.783	Cu-Au	12	1,900	0.45	(0.004)	0.22	0.7	8,550,000	Andrew (1995), Highlands Pacific (2009a,b), Singer and others (2008), Xstrata Copper (2011)

Table P4. Significant prospects and occurrences tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Comments	Reference	Rank
Salumei	–4.477	142.692	Grass roots exploration project. Exploration focus (Sierra Mining): gold target and secondary copper enrichment over copper prospects	Sierra Mining, Limited (2008)	1
Bismarck	–5.225	144.008	Exploration project areas focused on gold; includes some prospect areas with features compatible with porphyry copper mineralization: Cu and Au anomalies in stream sediments, soils and bedrock associated with potassically-altered granodiorite, disseminated pyrite and minor chalcopyrite, bornite, chalcocite, molybdenite. Associated with mid-Miocene Yuat South batholith.	Stagg and Swriridiuk (2007)	1
Wasi	–4.724	142.371	Porphyry Cu-Au-Mo prospect; limited previous drilling. Mapping and soil sampling in 2010; Au,Cu, Mo soil anomalies (peak values 0.11% Cu, 3.2 g/t Au). Outcrop assayed 0.21% Cu, 872 ppm Mo. Location based on company map; appears to be on W flank of a small stock mapped as Oligocene to middle Miocene diorite, porphyritic microdiorite.	Frontier Resources (2010)	2

within a 3 km^2 zone in the southeastern part of the intrusive complex. The deposits are associated with multiphase intrusions. Chalcopyrite and bornite are the main ore minerals, with some development of supergene chalcocite (Lole, 2005).

The Frieda River Intrusive Complex contains at least seven centers of porphyry copper mineralization, including the Horse-Ivaal-Trukai deposit, and is considered one of the world's largest undeveloped porphyry copper and gold deposits with estimated resources of more than 7 Mt of copper and 14.3 million ounces of gold (D. Saroa, written commun., 2010). Recent updates put the estimated copper resource at 8.5 Mt (Xstrata Copper, 2011).

Prospects, Mineral Occurrences, and Related Deposit Types

The tract includes three porphyry copper prospects (table P4), none of which are proven by drilling to date. In addition, the tract includes 59 copper occurrences where copper is reported as the primary commodity (15 prospects and unworked or abandoned mines and prospects; the remainder are reported as minor mineral occurrences). Gold is reported as the main commodity at 64 sites, including 18 minor mineral occurrences, 7 unworked or abandoned mines and prospects, and 39 alluvial gold workings (Papua New Guinea Mineral Resource Authority, 2002).

Exploration History

The entire tract area was under exploration lease, or application for exploration lease, in 2008 (Papua New Guinea Mineral Resources Authority, 2008).

Sources of Information

Principal sources of information used by the assessment team are listed in table P5.

Grade and Tonnage Model Selection

Frieda River is classified as a porphyry copper-gold deposit based on reported gold grades and Au/Mo ratio >30. The grade and tonnage data fit either the global general or copper-gold subtype models based on analysis of variance (ANOVA) (see table 6 of main report). The copper-gold subtype model was selected based on the classification of the deposit and the likelihood that other deposits in the tract will be gold-rich.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

Based on geologic maps, the apparent volume of exposed intrusive rocks exceeds the volume of preserved volcanic rocks; volcanic rocks are more abundant in the southern part of the tract. The tract contains one known deposit, and three exploration projects targeting porphyry copper deposits, as well as numerous copper and gold occurrences. Based on

Table P5. Principal sources of information used for tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[NA, not applicable; CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Map or title	Scale	Citation
Geology	Geology of Papua New Guinea	1;1,000,000	Bain and others (1972)
	Digital geology of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Page size maps in published papers	NA	Garwin and others (2005), Hill and others (2002), Quarles van Ufford and Cloos (2005), and Cloos and others (2005)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital geology of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
Exploration	Company Web sites	NA	Sierra Mining Limited (2008), Xstrata Copper (2010, 2011)
	Quarterly report		Papua New Guinea Mineral Resources Authority (2008a)
	Papua New Guinea Mineral Resources Authority tenement maps		Papua New Guinea Mineral Resources Authority (2008b)
	CCOP country report		Dulcie Saroa (oral commun., 2010)

Table P6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km², area of permissive tract in square kilometers; N_{total}/100k km², deposit density reported as the total number of deposits per 100,000 km². N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km²)	Deposit density (N_{total}/100k km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
0	2	8	8	8	3.2	3	93	1	4.2	38,970	11

Table P7. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7205, Maramuni Arc—Papua New Guinea.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount based on the Cu-Au subtype model						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	3,300,000	27,000,000	44,000,000	9,900,000	0.28	0.20
Mo	0	0	4,300	140,000	320,000	56,000	0.21	0.43
Au	0	0	290	2,000	2,900	710	0.32	0.20
Ag	0	0	530	7,400	15,000	3,200	0.21	0.37
Rock	0	0	720	5,700	8,900	2,000	0.30	0.20

this information, the team reasoned that at least two of the three known prospect areas might, if fully explored, represent deposits like those in the grade and tonnage model. The recent (2007 to present) upswing in exploration activity prompted by high gold prices and the large number of exploration concessions that cover the area suggest that modern exploration drilling and use of geophysics, especially along prospective structural corridors may lead to additional deposit discoveries. This consideration led the team to consider the possibility that more deposits might be found within the tract area. The team estimated a 50-percent chance of two or more deposits and a 10-percent chance of eight or more deposits (P6), which results in a mean of 3.2± 3.0 deposits (table P6).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table P7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. P3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper (9.9 Mt) represents 1.8 times the identified resources (5.5 Mt). The median expected value (3.3 Mt) is less than the identified resources at the Frieda River deposit. The simulation predicts a mean of 710 t, or about twice as much gold as identified at Frieda River (418 t), and a median of 290 t of gold for the tract. See table 7 in the main report for comparisons with identified resources and with other tracts.

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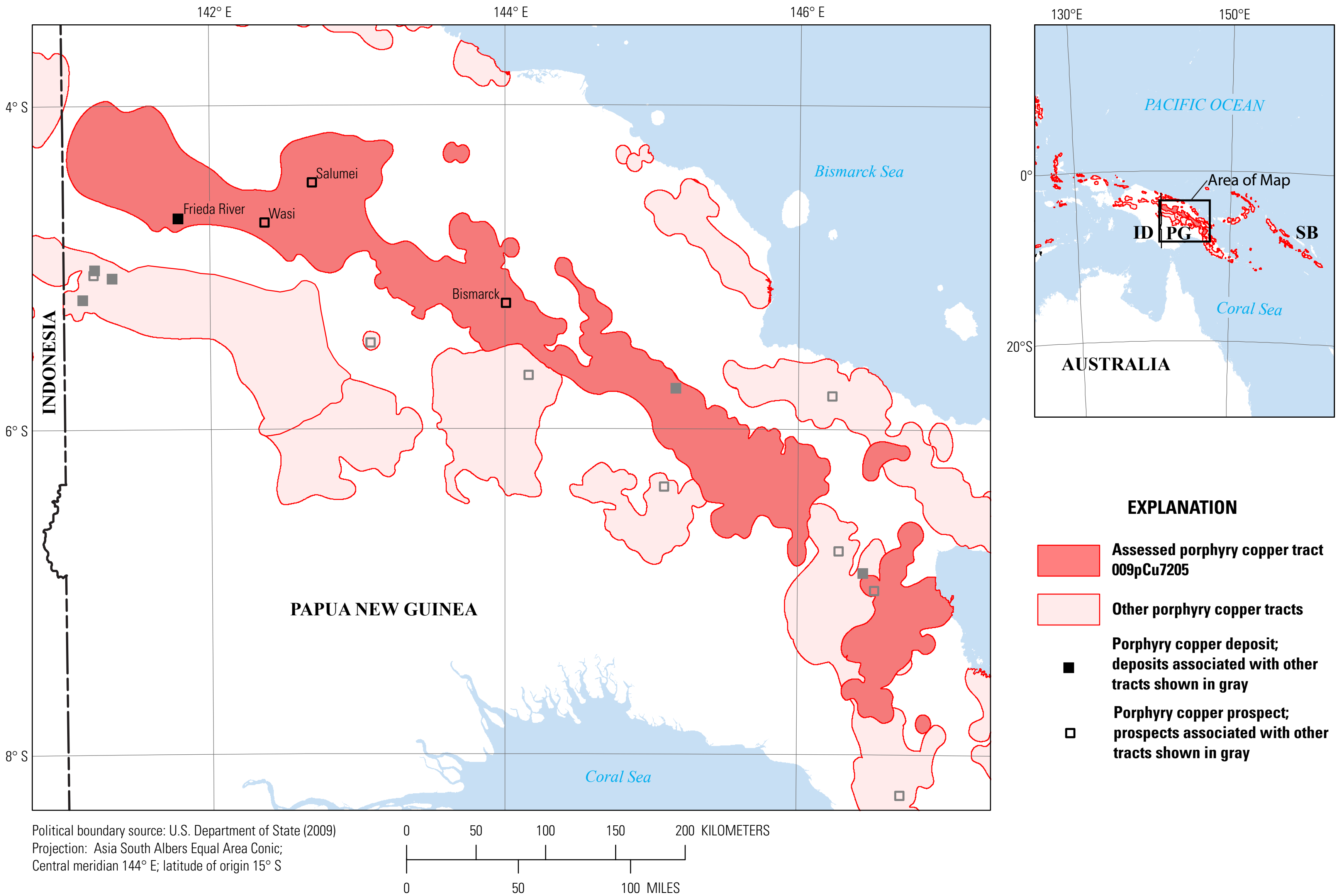

Figure P1. Map showing the location, known deposits, and significant prospects and occurrences for permissive tract 009pCu7205, Maramuni Arc—Papua New Guinea. ID, Indonesia; PG, Papua New Guinea; SB, Solomon Islands.

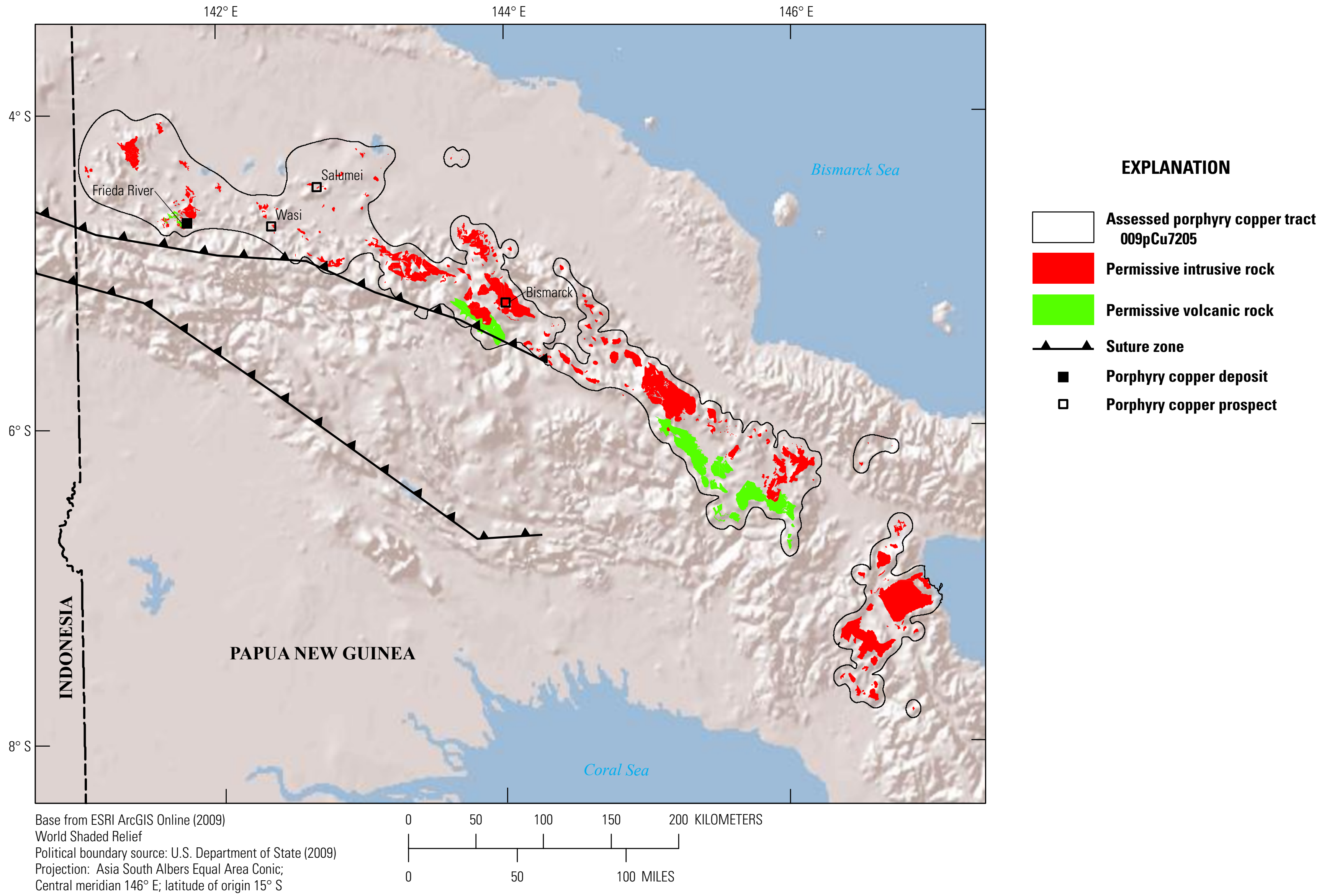

Figure P2. Map showing igneous rocks used to delineate 009pCu7205, Maramuni Arc—Papua New Guinea.

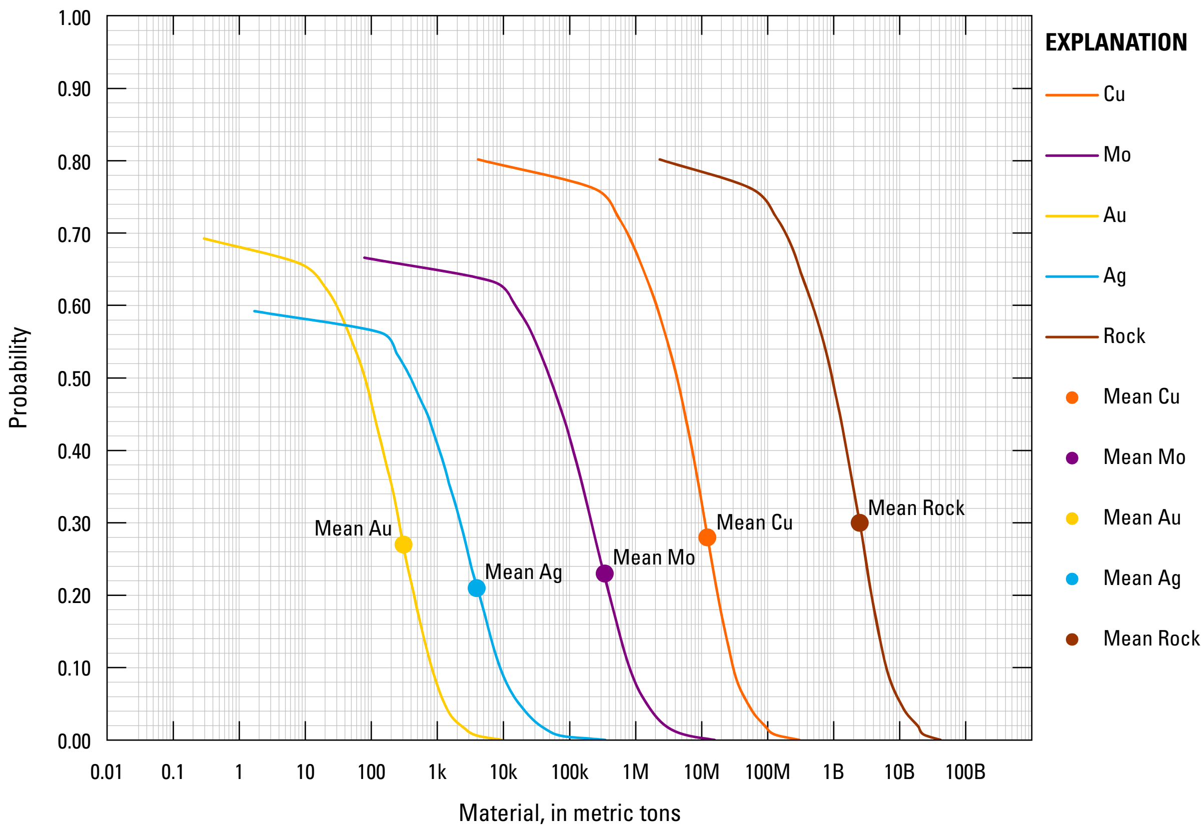

Figure P3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 009pCu7205, Maramuni Arc—Papua New Guinea. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix Q. Porphyry Copper Assessment for Tract 009pCu7206, Miocene Alkaline Rocks—Southeastern Papua New Guinea

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Benjamin J. Drenth[4], Steve Ludington[5], Arthur A. Bookstrom[6], and Michael L. Zientek[6], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[5]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table Q1 summarizes selected assessment results.

Table Q1. Summary of selected resource assessment results for tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	1,640	n.d.	1,200,000	0

Location

The tract includes the Central and Milne Bay provinces of southeastern Papua New Guinea (fig. Q1).

Geologic Feature Assessed

Miocene alkaline island arc intrusive rocks.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Denver, Colorado, United States.
[5]U.S. Geological Survey, Menlo Park, California, United States.
[6]U.S. Geological Survey, Spokane, Washington, United States.

Delineation of the Permissive Tract

Tectonic Setting

The tract outlines four areas of middle Miocene alkaline intrusions of probable island-arc affinity in southeastern Papua New Guinea. These rocks were described by Smith (1972) as a suite of high-potassium (shoshonitic) intrusions that may represent small magma chambers intruded into a subvolcanic environment at the beginning of a period of Late Cenozoic uplift. Smith and Milsom (1984) described two phases of extension in eastern Papua: (1) a middle to late Miocene subduction-related phase and (2) a middle Pliocene to Holocene phase of calc-alkaline and shoshonitic rocks interpreted as reactivation of subduction-modified mantle under the sea-floor spreading occurring in the Woodlark Basin (fig. 6).

Geologic Criteria

The tract was created by selecting late Oligocene to middle Miocene alkaline intrusive rocks described by Smith (1972) from the 1:250,000-scale digital geologic map of Papua New Guinea (table Q2, fig. Q2). These rocks intrude Eocene basalt (Kutu Volcanics). Basalt and andesite lavas, agglomerate and tuff, pillow lava, minor tuffaceous sedimentary rocks, and dikes of the Fyfe Bay Volcanics are present in the area of the Magavara prospect (fig. Q1). These volcanic rocks are mapped as Pliocene. However, Smith and Milsom (1984) noted that Fyfe Bay Volcanics are dated at 12.6 Ma south of Mullins Harbor and included them in the discussion of Miocene high-K, shoshonitic rocks of the Papuan Peninsula. The late Oligocene to middle Miocene Watuti Gabbro is adjacent to the tract but is excluded because of its composition (gabbro, pyroxenite). All of the pre-

Table Q2. Map units that define tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[Map unit, age range, and principal lithologies are based on a attributes in a digital compilation of geologic maps of Papua New Guinea Indonesia (Papua New Guinea Geological Survey, 2002). Numbers and publication dates of 1:250,000-scale maps available from the Papua New Guinea Geological Survey are listed for reference. *, within tract area and part of alkaline complex, but likley too mafic for porphyry association]

Map unit	Map symbol	Lithology	Age range	Map number	Map date
		Intrusive rocks			
Sige Lele Gabbro	Tmb	Gabbro	Late Oligocene? to middle Miocene	C5609	1972
Gabahusuhusu Syenite	Tmg, Tmgd	Syenite, monzonite, diorite, minor gabbro, dunite	Late Oligocene? to middle Miocene	C5609	1972
Imudat Monzonite	Tmi	Monzonite, minor trachyandesite	Late Oligocene? to middle Miocene	C5512	1970
Magavara Syenite	Tmm	Syenite, monzonite, minor gabbro; trachybasalt, latite, sanidine melanite porphyry dykes	Late Oligocene? to middle Miocene	C5512	1970
Ulo Ulo Gabbro	Tmo	Gabbro, monzonite	Late Oligocene? to middle Miocene	C5609	1972
Watuti Gabbro*	Tmw	Gabbro	Late Oligocene? to middle Miocene	C5609	1972
		Volcanic rocks			
Fyfe Bay Volcanics	Tpf	Basaltic and andesitic lava, agglomerate and tuff, some pillow lava, minor tuffaceous sedimentary rocks, many dykes	Pliocene	C5609	1972
Fyfe Bay Volcanics, Mount Suat member	Tpfs	Welded basaltic agglomerate	Pliocene	C5609	1972

late Miocene igneous rocks shown on the 1:250,000-scale maps in this part of Papua New Guinea are alkaline, associated with monzonite, syenite, and gabbro. Smith (1972) reported K-Ar ages for some of the rocks in the area as follows:

- Imudat River area monzonite 12.5± 2 Ma (biotite)
- Gabahusuhusu River area diorite 11.1± 0.3Ma (biotite)
- Gabahusuhusu River area syenite 16.0±0.8 Ma (hornblende)
- Magavara River area latite 16.5± 0.2 Ma (hornblende)
- Magavara River area porphyry 27.5±3.5 Ma (hornblende)

These ages are all Miocene, except for the porphyry age, which is Oligocene. The alkaline rocks are separated geographically from the calc-alkaline Miocene Maramuni Arc (tract 009pCu7205) rocks southeast of Port Moresby by a distance of 150 km and are older than the late Miocene to Pliocene rocks of the Medial New Guinea magmatic belt (tract 009pCu7203). The alkaline rocks (gabbro, monzonite, diorite, syenite) form small stocks with outcrop areas ranging from less than 4 to 36 km^2. The tract was constructed in a GIS using a digital compilation of 1:250,000-scale geologic maps of Papua New Guinea. Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, Miocene alkaline map units in southeasternmost Papua New Guinea were selected. Ophiolites, ultramafic rocks, and basaltic units were deemed nonpermissive and are omitted from the tract. Using GIS tools, tract boundaries were extended out from mapped contacts using a 5-km buffer to include possible extensions under shallow cover. The final tract boundaries were established by GIS processing and editing. The processing approximates manual delineation of tracts but is rapid and reproducible. Regional and local mineral occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries. Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

The tract covers the areas of the Poi and Magavara prospects (table Q3). These prospects are associated with the Imudat and Magavara intrusive rocks, respectively. Alluvial gold occurrences are associated with all parts of the tracts. The Ulo Ulo abandoned gold mine in the Ulo Ulo Gabbro is under exploration (drilling) along northwest-trending, high-grade, quartz-limonite gold veins (Vangold Resources, Ltd., 2009). The Milne Bay Goldfield in the southeasternmost part of the tract produced less than 10,000 ounces of alluvial gold between 1899 and 1926 (Swiridiuk and Lindley, 2004).

Exploration History

The recent boom in gold prices renewed exploration interest in areas that were identified previously as anomalous in gold based on stream-sediment surveys done in the 1980s and on historical alluvial-gold mining. Several current exploration projects focus on such areas associated with the alkaline rocks that delineate the permissive tract. Regional geochemical sampling identified a 16 km^2 area of anomalous gold in stream sediments (0.12–3.30 g/t gold) at the Poi porphyry copper-gold prospect. The area was explored in reconnaissance fashion in 1971, 1984, 1994, and 2007. Ongoing (2009) exploration is following up on a geophysical anomaly that coincides with a ridge of syenite (Imudat intrusive complex) and areas of anomalous gold in stream sediments. Activities include mapping, trenching, rock-chip and sediment sampling and geophysical modeling to define drill targets at the Poi (Kebei Ridge) prospects (MIL Resources, 2009a,b). The Magavara area, which was explored in the 1970s, and again starting in 2008, is targeted for high-grade epithermal gold and copper-gold porphyry (Sierra Mining Limited, 2008). The UloUlo prospect area was explored as part of the 243 km^2 Allemata property for mesothermal gold in intrusion-related quartz veins and gold-copper skarn in limestone at gabbro contacts (Swiridiuk and Lindley, 2004). Surface exploration of the Ulo Ulo area for porphyry gold-copper in the 1960s and early 1970s included mapping, stream-sediment sampling, and detailed grid sampling but proved unsuccessful. Recent (2009) trenching and drilling at Allemata identified an east-west trend of high-grade gold lodes with up to 1-percent copper (Vangold Resources, Ltd., 2009). No porphyry-style mineralization has been substantiated to date.

Sources of Information

Principal sources of information used by the assessment team are listed in table Q4.

Grade and Tonnage Model Selection

The grade and tonnage model used in this assessment was the porphyry copper-gold subtype described by Singer and others (2008). The use of this subtype is not based on the nature of known deposits within the tract as there are none (table 6). The rationale is based on the observation that porphyry copper deposits associated with alkaline source rocks tend to be enriched in gold (Mutschler and others, 1985, 1991; Sillitoe, 2004; Solomon, 1990). Singer and others (2008) do

Table Q3. Significant prospects and occurrences for tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend.; %, percent; g/t, grams per metric ton; km, kilometers, m, meters. Ages based on ages for associated igneous rocks. Ma, million years]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Poi	–10.236	149.466	Miocene	Undrilled porphyry copper-gold target based on a 1-km strike length radiometric and magnetic anomaly associated with the Imudat alkaline intrusive complex. Regional rock-chip and stream-sediment sampling in 1982; trenching on Aladdin skarn prospect (20 m at 0.50% Cu, 7.17 g/t Au, 9.6 g/t Ag); drilling planned for 2011.	MIL Resources (2009a,b; 2010)	1
Maga-vara	–10.537	150.124	Oligocene-Miocene	Copper and gold identified in 1970s; artisanal gold mining. Reconnaissance exploration 2008 on 627 km^2 area covering the Magavara syenite complex identified chalcopyrite and pyrite+arsenopyrite and copper oxide minerals in 50-m-wide zone in propylitically altered, sheared, and brecciated syenite and monzonite porphyries; Cu, Au, Ag in grab samples and anomalous Au in stream sediments. Likely abandoned by past exploration due to lack of inferred tonnage.	Sierra Mining Limited (2008)	1

Table Q4. Principal sources of information used for tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[NA, not applicable]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Geology of Papua New Guinea	1;1,000,000	Bain and others (1972)
	Digital geology of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Page size maps in published papers.	NA	Garwin and others (2005), Hill and others (2002), Quarles van Ufford and Cloos (2005), Cloos and others (2005)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Mineral deposits of Papua New Guinea	1:250, 000	Granger (1973)
			Mineral Resources Authority of Papua New Guinea (2002)
Exploration	Company Web sites	NA	MIL Resources (2009ba,b; 2010), Sierra Mining Limited (2008), Vangold Resources Ltd. (2009)
	Papua New Guinea Mineral Resources Authority tenement maps		Mineral Resources Authority of Papua New Guinea (2008)

not specifically classify deposits as alkaline or not, but the inclusion of associated rock types within their compilation allows the examination of the data for those deposits with alkaline rock names. Those data, along with the grade and tonnage information from Schroeter and others (1989), seem to confirm that whereas not all gold-rich porphyry copper deposits are alkaline, nearly all alkaline porphyry copper deposits are gold-rich. The association of the prospects in the area with alluvial gold, and the gold-rich character of porphyry copper mineralization in the region suggest that any porphyry copper deposits in the permissive tract will be enriched in gold.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The tract delineates four areas of exposed Miocene alkaline rocks. Three of the four areas are targets of recent, as well as historical exploration, and one area hosts an abandoned gold mine. Three areas are spatially associated with artisanal alluvial gold mining. None of the areas have been thoroughly explored by drilling. Magnetic and radiometric data, as well as anomalous gold, copper, and base-metal concentrations in stream-sediment and rock-chip geochemical surveys are the basis for the current round of exploration activities. At least some of the intrusions display alteration characteristics compatible with porphyry copper-style mineralization. Lack of coeval volcanic rocks in some parts of the tract area suggests that these rocks may be deeply eroded and, therefore, would not preserve porphyry copper deposits. However, coeval high-K Fyfe Bay volcanic rocks are present in the Magavara prospect area.

The assessment team estimates that there is a 10-percent chance for at least one undiscovered porphyry deposit compatible in grade-tonnage characteristics with the porphyry Cu-Au model, and a 1-percent chance of three or more deposits. The estimate was carried out to five levels to provide three nonzero numbers to constrain the estimate. The high coefficient of variation (207 percent) reflects a high degree of uncertainty about the tract. Another consideration is that the small area of the tract (1,640 km^2) limits the number of discrete deposits that could be present. The mean number of deposits is less than one (table Q5).

Probabilistic Assessment Simulation Results

Undiscovered resources were estimated by combining consensus estimates for numbers of undiscovered porphyry copper-gold deposits with the porphyry copper-gold model using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in

Table Q5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
0	0	1	1	3	0.36	0.75	210	0	0.36	1,640	22

Table Q6. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	0	2,000,000	4,700,000	1,200,000	0.14	0.71
Mo	0	0	0	1,500	17,000	7,000	0.07	0.89
Au	0	0	0	170	380	82	0.16	0.71
Ag	0	0	0	330	990	340	0.10	0.86
Rock	0	0	0	430	930	230	0.15	0.71

table Q6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. Q3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper is 1.2 Mt; median expected value is none.

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Vangold Resources, Ltd., 2009, New release November 19, 2009: accessed February 10, 2010, at http://www.theaureport.com/cs/user/download/co_file/1490/Vangold_11-4_C6FC80DEd01-1.pdf.

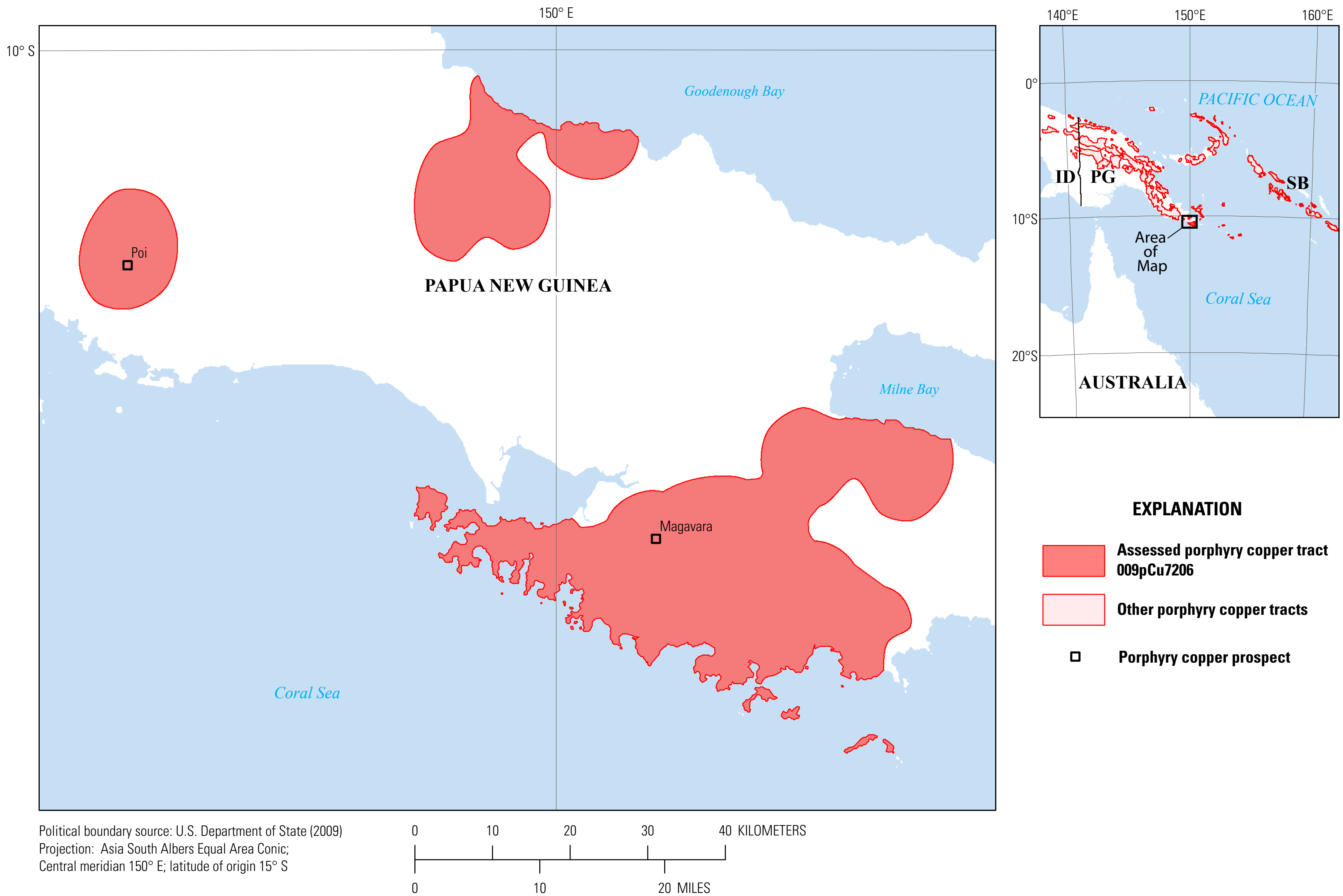

Figure Q1. Map showing the location, known deposits, and significant prospects and occurrences for permissive tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea. ID, Indonesia; PG, Papua New Guinea; SB, Solomon Islands.

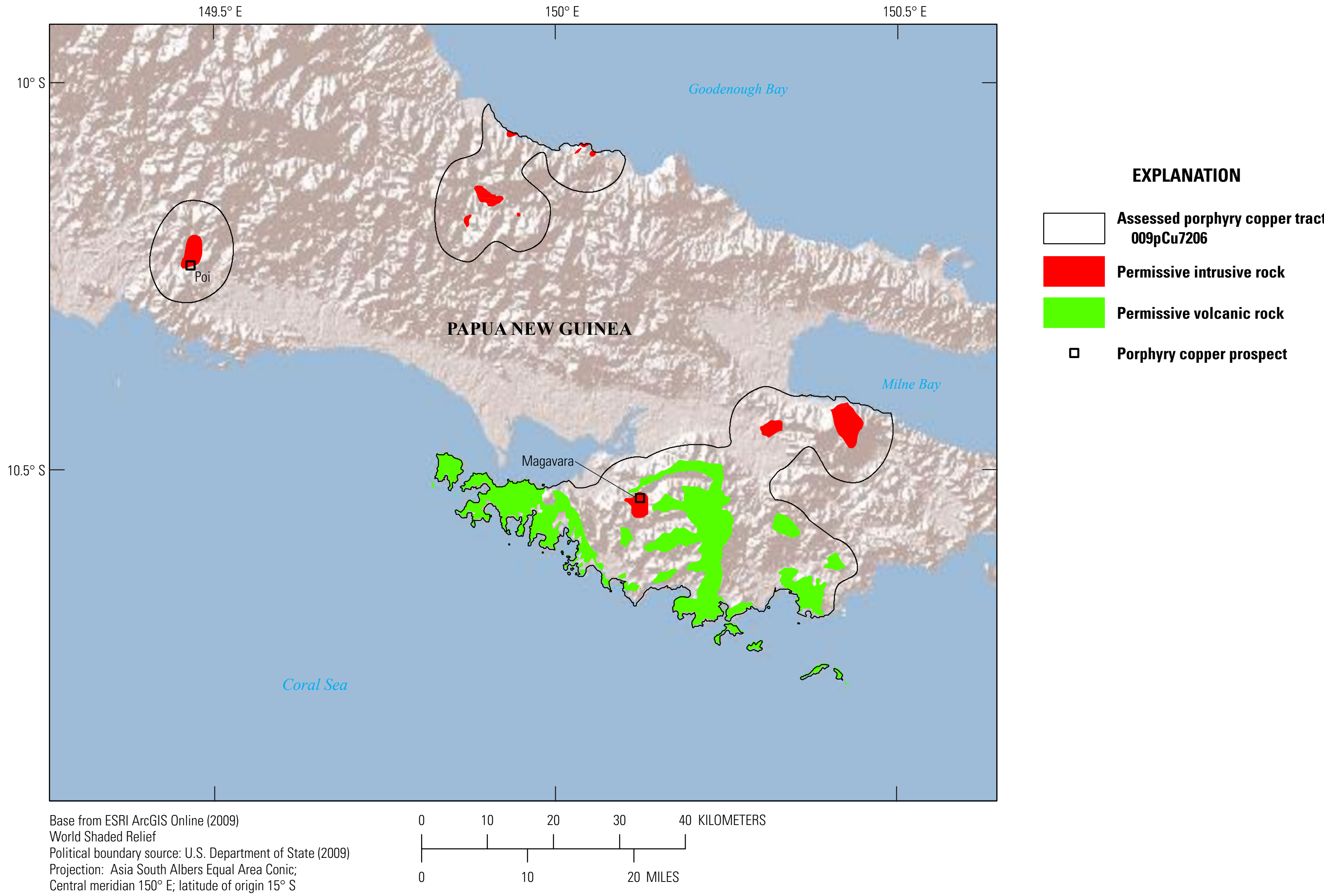

Figure Q2. Map showing igneous rocks used to delineate tract 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea.

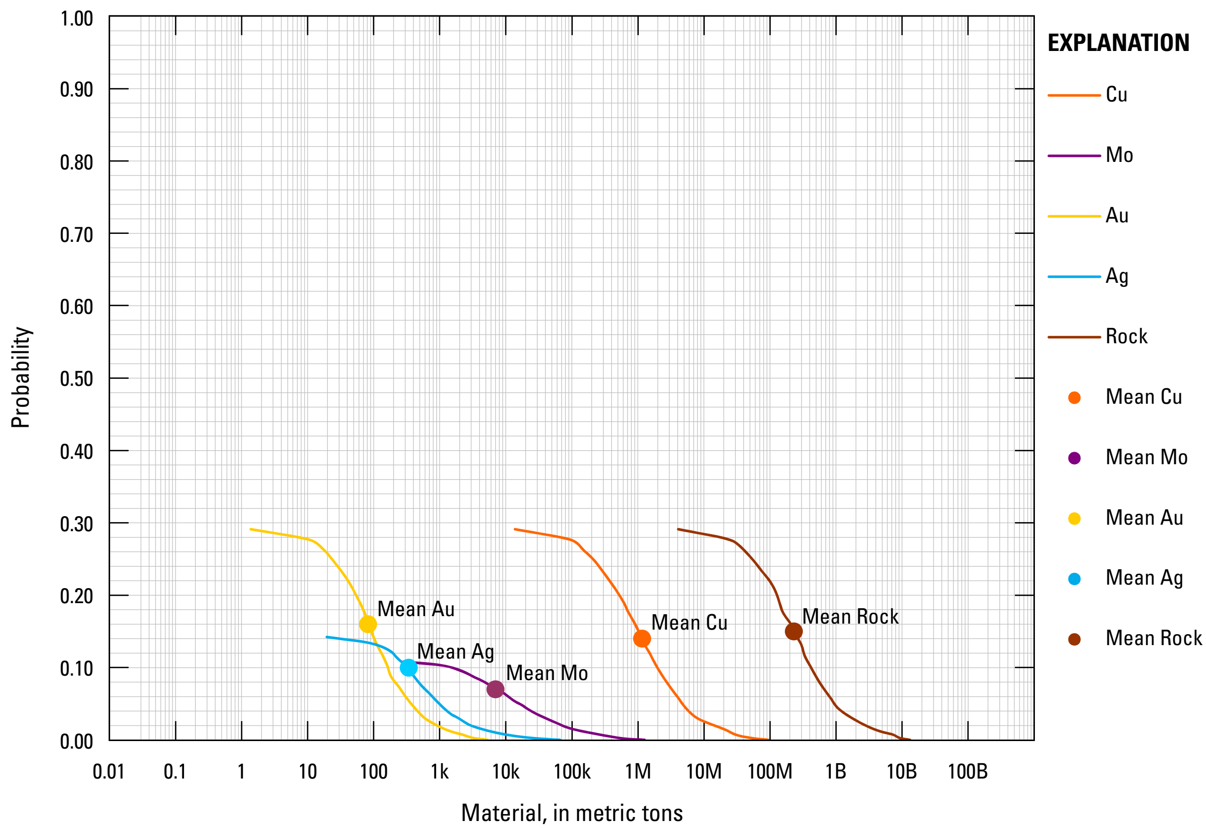

Figure Q3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 009pCu7206, Miocene Alkaline Rocks of Southeastern New Guinea Island—Papua New Guinea. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix R. Porphyry Copper Assessment for Tract 142pCu7208, Inner Melanesian Arc Terranes I—Indonesia

By Jane M. Hammarstrom[1], Bambang Tjahjono Setiabudi[2], Dwi Nugrono Sunuhadi[2], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[3], Arthur A. Bookstrom[4], and Michael L. Zientek[4], with contributions from Dennis P. Cox[3]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010)

A permissive tract is delineated based on permissive rock types depicted on 1:250,000-scale geologic maps. Insufficient information was available to the assessment team members for them to complete a probabilistic assessment of the tract area. Summary information is listed in table R1.

Table R1. Summary information for tract 142pCu7208, Inner Melanesian Arc Terranes I—Papua and West Papua, Indonesia (fig. R1).

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)
February 2010	1	10,130	n.d.

Location

The tract includes the northern margin of the island of New Guinea in Papua and West Papua provinces, Indonesia.

Geologic Feature Assessed

Eocene-Oligocene to early Miocene accreted Inner Melanesian magmatic arc terranes of western New Guinea Island.

Delineation of the Permissive Tract

Tectonic Setting

The Inner Melanesian tract outlines parts of the Inner Melanesian Arc, a 1,000–km-long calc-alkaline arc that developed in the Eocene to early Oligocene from southwestward subduction of the Pacific Plate. The tract is delineated on the extent of permissive Paleo-

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[3]U.S. Geological Survey, Menlo Park, California, United States.
[4]U.S. Geological Survey, Spokane, Washington, United States.

gene to early Miocene igneous rocks shown on 1:250,000-scale geologic maps along the northern margins of the island of New Guinea in the Indonesian provinces of Papua and West Papua. The tract segments represent arcs of uncertain origin accreted to the northern edge of Australian continental crust (fig. 4). The accreted terranes are not well-understood; however, they all include Paleogene volcanic rocks and may represent remnants of the Philippine Sea Plate that were fragmented by strike-slip faulting since 25 Ma (Ali and Hall, 1995; Hall, 2001). Accreted terranes in Papua New Guinea are described as tract 009pCu7208.

The tract corresponds with the Melanesian Arc terrane as defined by Cloos and others (2005). The tract area in Indonesia correlates with the region along the coast of the Bird's Head referred to as the Coastal Irian Jaya Arc (age unknown, inferred Neogene) by Carlile and Mitchell (1994).

These rocks are age-equivalent to accreted terranes in the Adelbert-Finisterre area of Papua New Guinea (tract 009pCu7208) and to rocks that host porphyry copper deposits on New Britain Island (tract 009pCu7205) but are more poorly characterized and less explored, and therefore, they were delineated as a separate tract.

Geologic Criteria

The tract was constructed in a GIS using 1:250,000-scale geologic maps of Indonesia, a 1:500,000-scale digital map of igneous rocks of Indonesia (Directorate of Mineral Resources and Inventory, 2004a), and a 1:1,000,000-scale geologic map of Irian Jaya (Dow and others, 1986). Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, all igneous rocks of Miocene age (>7 Ma) and rocks mapped as Eocene to early Miocene were selected (fig. R2). Ophiolites, ultramafic rocks, and basaltic units were deemed nonpermissive and are omitted from the tract. Map units included in the tract are listed in table R2.

The final tract boundaries were established by GIS processing and editing. The processing steps included (1) buffering permissive map units with a 5-km concentric buffer; (2) unioning buffered permissive map units and other polygon features that comprise the framework of the tract; (3) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2, a step done to group closely spaced permissive areas; (4) manually aggregating and adjusting tract areas; and (5) smoothing polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing; tracts were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral-occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

None.

Exploration History

No information.

Sources of Information

Principal sources of information used by the assessment team are listed in table R3.

Table R2. Map units that define tract 142pCu7208, Inner Melanesian Arc Terranes I—Papua and West Papua, Indonesia.

[Map unit, age range, and principal lithologies are based on a attributes in a digital compilation of igneous rocks of Southeast Asia (Directorate of Mineral Resources and Inventory, 2004a) and 1:250,000-scale geologic quadrangle maps for Indonesia (Geological Research and Development Centre, 1987–2000). Ma, million years]

Map unit	Map symbol	Lithology	Age range
Lembia Diorite	Tmle	Diorite	Miocene (15.8 Ma hornblende age)
Auwewa Formation	Tema, Teoa	Island arc volcanics, subvolcanic diorite and microdiorite intrusions	Eocene to early Miocene (radiometric ages 10.6
Batanta Volcanics	Temb	Basaltic to andesitic lavas; small diorite bodies, gabbro	Eocene to early Miocene
Volcanic Rock member of Rumai Fm	Temv	Basalt to andesite	Eocene to early Miocene
Yapen Volcanics	Temya	Breccia, tuff, basalt-andesite, comagmatic microdiorite and andesite porphyry dikes	Eocene to early Miocene

Table R3. Principal sources of information used for tract 142pCu7208, Inner Melanesian Arc Terranes I—Papua and West Papua, Indonesia.

[NA, not applicable]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Geologic map of Irian Jaya	1:1,000,000	Dow and others (1986)
	Geologic quadrangle maps	1:250,000	Directorate of Mineral Resources and Inventory (2004a)
	Page size maps in published papers.	NA	Garwin and others (2005), Hill and others (2002), Quarles van Ufford and Cloos (2005), and Cloos and others (2005)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database for Indonesia	NA	Directorate of Mineral Resources and Inventory (2004b)

Qualitative Assessment

Permissive tract 142pCu7208 was delineated to recognize that Eocene-Oligocene to Miocene permissive igneous rocks for porphyry copper deposits are present in the accreted terranes along northern New Guinea Island and offshore islands. The presence of coeval volcanic and plutonic rocks suggest that at least in some areas, the erosion levels may be appropriate for preservation of deposits. However, the team members had too little information available to them to make resource estimates. More information about the exploration history, ages, and lithologies of permissive igneous rocks would be helpful to assess the porphyry potential of the tract area.

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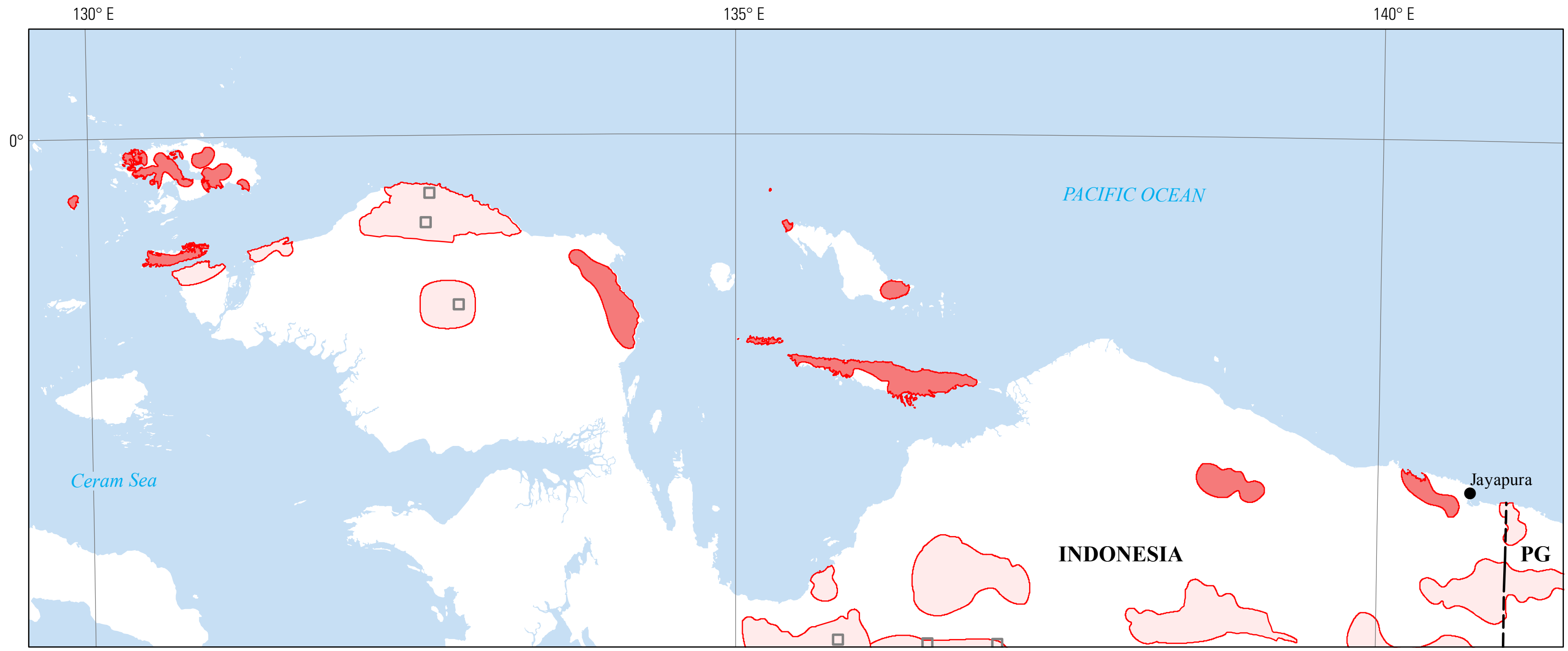


Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 135° E; latitude of origin 15° S

0 50 100 150 200 KILOMETERS
0 50 100 MILES

EXPLANATION

- Assessed porphyry copper tract 142pCu7208
- Other porphyry copper tracts
- Porphyry copper prospects associated with other tracts

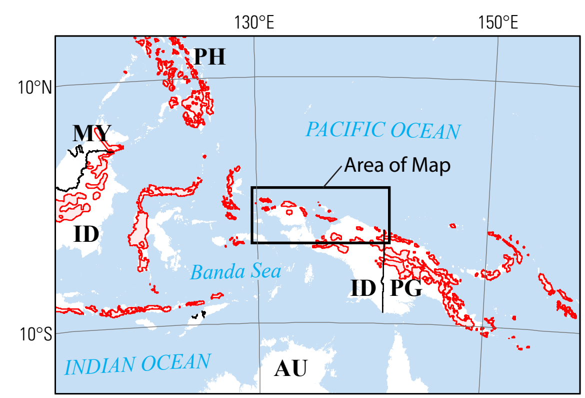


Figure R1. Map showing the location of permissive tract 142pCu7208, Inner Melanesian Arc Terranes I—Papua and West Papua, Indonesia. AU, Australia; ID, Indonesia; PG, Papua New Guinea; PH, Philippines; MY, Malaysia.

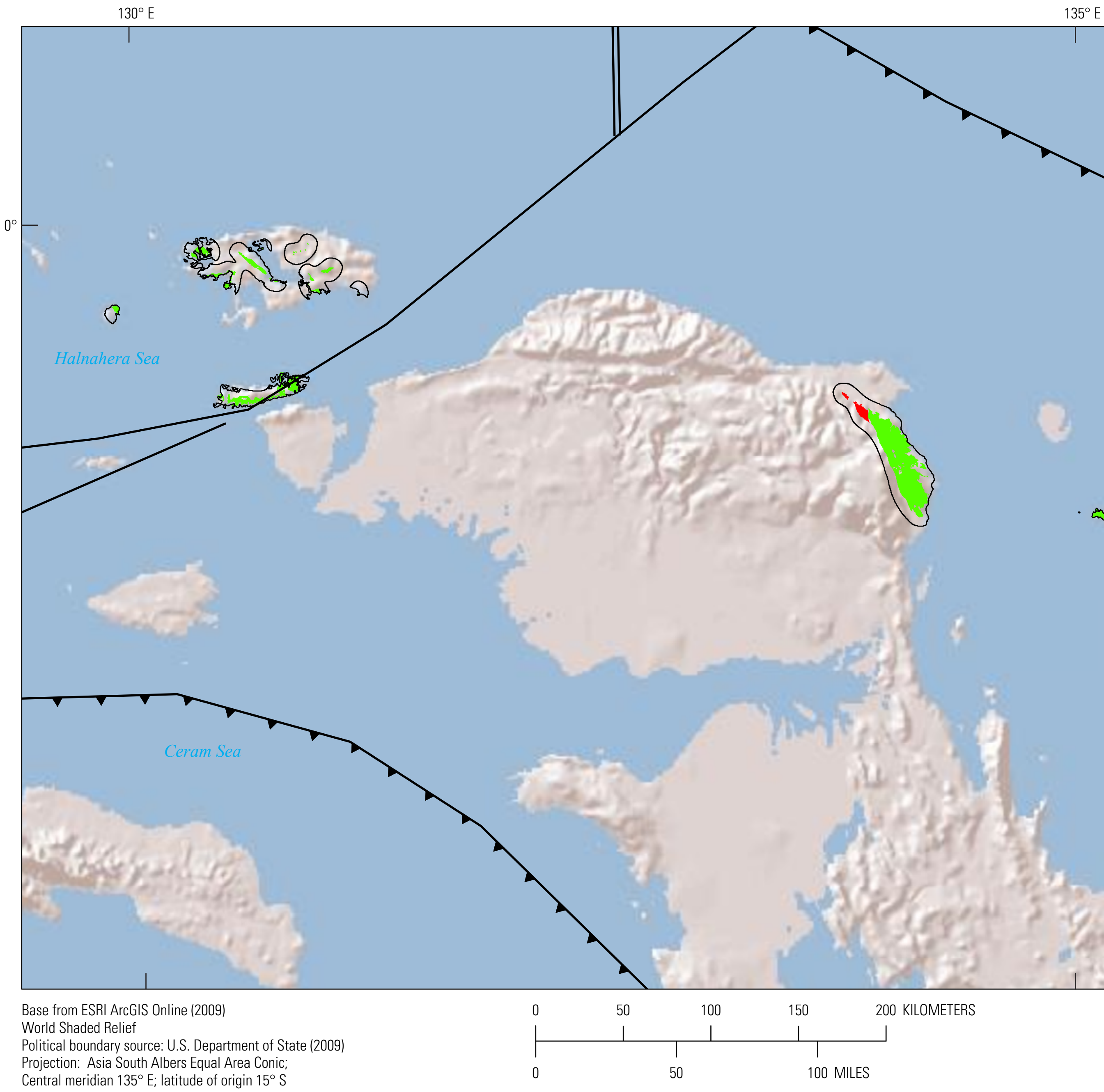
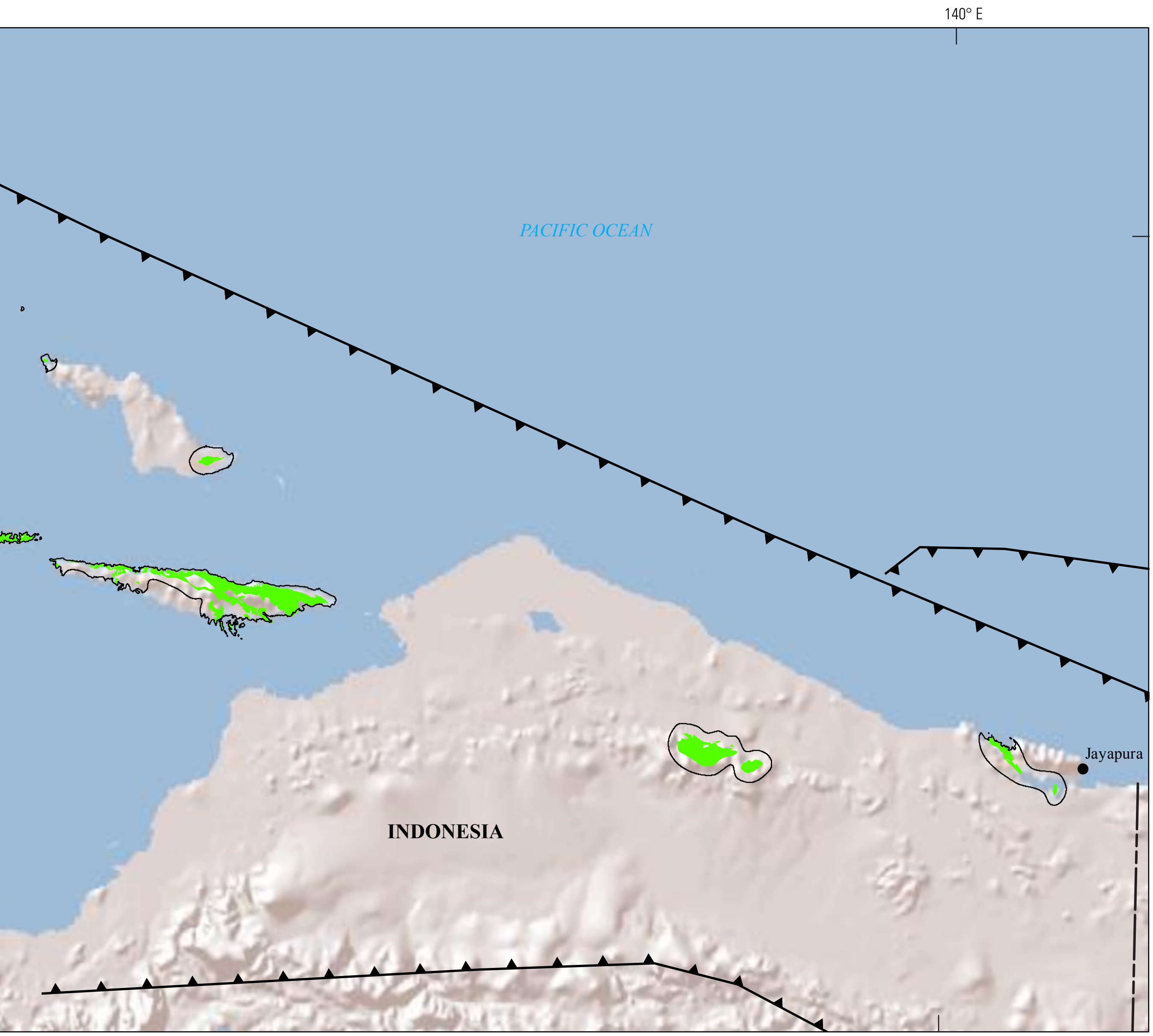


Figure R2. Map showing igneous rocks used to delineate tract 142pCu7208, Inner Melanesian Arc Terranes I—Papua and West Papua, Indonesia.



EXPLANATION

- Assessed porphyry copper tract 142pCu7208
- Permissive intrusive rock
- Permissive volcanic rock
- Subduction and suture zone
- Spreading center
- Strike-slip fault

Appendix S. Porphyry Copper Assessment for Tract 009pCu7208, Inner Melanesian Arc Terranes II—Northern New Guinea Island, Papua New Guinea

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[4], Arthur A. Bookstrom[5], and Michael L. Zientek[5], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[4]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010)

A permissive tract is delineated based on permissive rock types depicted on 1:250,000-scale geologic maps. Insufficient information was available to the assessment team members for them to complete a probabilistic assessment of the tract area. Summary information is listed in table S1.

Table S1. Summary of selected resourceassesment results for tract 009pCu7208, Inner Melanesian Arc Terranes II—Northern New Guinea Island, Papua New Guinea.

[km, kilometers; km^2, square kilometers; t, metric tons; n.d., no data]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)
February 2010	1	29,140	n.d.

Location

The tract includes the northern margin of the island of New Guinea, Papua New Guinea (fig. S1).

Geologic Feature Assessed

Eocene-Oligocene to early Miocene accreted Inner Melanesian magmatic arc terranes of New Guinea Island.

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Menlo Park, California, United States.
[5]U.S. Geological Survey, Spokane, Washington, United States.

Delineation of the Permissive Tract

Tectonic Setting

The Inner Melanesian Arc tract outlines parts of the Inner Melanesian Arc, a 1,000-km-long calc-alkaline arc that developed in the Eocene to early Oligocene from southwestward subduction of the Pacific Plate. The tract segments represent accreted Paleogene arcs preserved in the Bewani-Torricelli Mountains, Adelbert, and Finisterre Ranges (fig. 7). The accreted terranes are not well-understood; however, they all include Paleogene volcanic rocks and may represent remnants of the Philippine Sea Plate that were fragmented by strike-slip faulting since 25 Ma (Ali and Hall, 1995).

The tract corresponds with the Melanesian Arc terrane as defined by Cloos and others (2005). The region of northeastern New Guinea north of the Ramu-Markham Fault and New Britain Island are considered to be part of a single volcanic arc (Bain, 1973). No porphyry copper deposits have been reported on the New Guinea island-arc segment (Singer and others, 2008; Titley and Heidrick, 1978) although the rocks are age-equivalent to tract 009pCu7209 on New Britain Island. The fragmented, accreted arc segments on New Guinea Island are more poorly characterized and less well-explored, and therefore, they were delineated as a separate tract.

Geologic Criteria

The tract is delineated on the extent of permissive Paleogene to early Miocene igneous rocks shown on 1:250,000-scale geologic maps along the northern margins of the island of New Guinea in Papua New Guinea (fig. S2, table S2). The westernmost tract segments primarily are based on exposures of about subequal amounts of intrusions and volcanic rocks (fig. S2). The eastern tract segments include accreted parts of the Finisterre-Adelbert Arc along the northern margin of Papua New Guinea, where the tract is based primarily on the distribution of the Oligocene to early Miocene Finisterre Volcanics, which were described as a thick (perhaps as much as 4,500 m) sequence of Oligocene to early Miocene island-arc rocks dominated by volcaniclastic potassic basalt and low-silica andesites that fall into two groups: shoshonite and high-K, high-Al basalt (Jaques, 1976).

The tract was constructed in a GIS. Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, all igneous rocks of Eocene to early Miocene were selected. Ophiolites, ultramafic rocks, and basaltic units were deemed nonpermissive and are omitted from the tract. Map units included in the tract are listed in table S2.

The final tract boundaries were established by a GIS processing and editing. The processing steps included (1) buffering permissive map units with a 5-km concentric buffer; (2) unioning buffered permissive map units and other polygon features that comprise the framework of the tract; (3) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2, a step done to group closely spaced permissive areas; (4) manually aggregating and adjusting tract areas; and (5) smoothing polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing; tracts were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral-occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

Known Deposits

None.

Prospects, Mineral Occurrences, and Related Deposit Types

Alluvial gold workings are present in the eastern parts of the Toricelli Intrusive Complex in northern Papua New Guinea. Map unit Tlv (table S2) includes skarn.

Exploration History

Parts of the tracts, especially the westernmost tract segment in the Toricelli Mountains, overlap exploration tenement areas. The assessment team is unaware of any porphyry copper exploration targets within the tract area.

Sources of Information

Principal sources of information used by the assessment team are listed in table S3.

Qualitative Assessment

Permissive tract 009pCu7208 was delineated to recognize that Paleogene to early Miocene igneous rocks that are permissive for the occurrence of porphyry copper deposits occur in northern New Guinea Island, Papua New Guinea. The presence of coeval volcanic and plutonic rocks suggest that, at least in some areas, the erosion levels may be appropriate for preservation of deposits. However, the team members had too little information available to make resource estimates. The Finisterre Volcanics may be too thick to preserve any associated porphyry systems; they were included based on similarities to coeval rocks on New Britain within the same arc to the east, where porphyry copper deposits are known.

Table S2. Map units that define tract 009pCu7208, Inner Melanesian Arc Terranes II—Northern New Guinea Island, Papua New Guinea.

[Map unit, age range, and principal lithologies are based on a attributes in a digital compilation of geologic maps of Papua New Guinea (Papua New Guinea Geological Survey, 2002). --, no map unit]

Map unit	Map symbol	Lithology	Age range
		Intrusive rocks	
Kui Tonalite	Tek, Tet, KITet	Tonalite (quartz diorite): quartz-oligoclase/andesine-hornblende rock	Late Paleocene to Eocene
Prince Alexander Complex	KTp	Crushed and mylonitized granodiorite, diorite, dolerite, amphibolite; orthogneiss; some schist, adamellite, porphyry dykes	Early Cretaceous to earliest Miocene (Some middle Jurassic
Torricelli Intrusive Complex	KTt	Medium-grained gabbro, dolerite, diorite, monzonite; some granodiorite, adamellite; minor pegmatitic and porphyritic equivalents, serpentinite; commonly sheared	Late Cretaceous to earliest Miocene
Imo Tonalite	Tei	Tonalite; some granophyric diorite	Eocene
		Volcanic rocks	
Bliri Volcanics	Tb	Basic, intermediate and minor acid volcanics and volcanically derived sediments; dolerite; minor limestone lenses; commonly sheared and altered	Paleocene? to earliest Miocene
Eia Beds	Tee	Andesitic and dacitic glassy tuff, breccia, lava, minor calcilutite, planktonic foraminifera	Eocene
--	Tl	Andesitic and dacitic porphyries, some granodiorite, gabbro	Early Eocene to Late Oligocene?
Okiduse Volcanics	Tlo	Andesite and basaltic andesite flows and tuffs, typically porphyritic; andesitic agglomerate; intrusive breccia	Early Tertiary
Lower Volcanics	Tlv	Basalt and basaltic andesite flows and tuffs, typically fine grained; pillow lavas, agglomerate, volcanic conglomerate, medium-grained mafic intrusions; shale, chert, limestone; monzonite porphyry intrusions; garnet and magnetite skarns	Early Tertiary
Finisterre Volcanics	Tof	Basalt and andesite flow breccia, indurated tuffaceous lithic greywacke, lithic and crystal tuff, paraconglomerate, peperite and peperitic breccia, palagonite breccia, lava, pillow lava, pillow breccia, agglomerate, argillite, minor limestone. Also includes shoshonites.	Early Oligocene to early Miocene
Kwama Volcanic Member	Tofk	Basaltic lava	Late Oligocene
Iauga Formation	Tomv	Augite-phyric basalt conglomerate, breccia and tuff, calcareous matrix; green tuff, agglomerate, siltstone; younger? poorly consolidated conglomerate and sandstone	Late Oligocene to early Miocene
--	Ts	Gabbro, andesitic porphyry, diorite	Early Miocene?

Table S3. Principal sources of information used for tract 009pCu7208, Inner Melanesian Arc Terranes II—Northern New Guinea Island, Papua New Guinea.

[NA, not applicable; CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Digital geologic map of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Geology of Papua New Guinea	1,1,000,000	Bain and others (1972)
	Page size maps in published papers.	NA	Garwin and others (2005), Hill and others (2002), Quarles van Ufford and Cloos (2005), and Cloos and others (2005)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital mineral occurrence database for Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Mineral deposits of Papua New Guinea	1:2,500,000	Granger (1973)
Exploration	Tenement maps, reports	NA	Papua New Guinea Mineral Resources Authority (2008a,b), Lole (2005)

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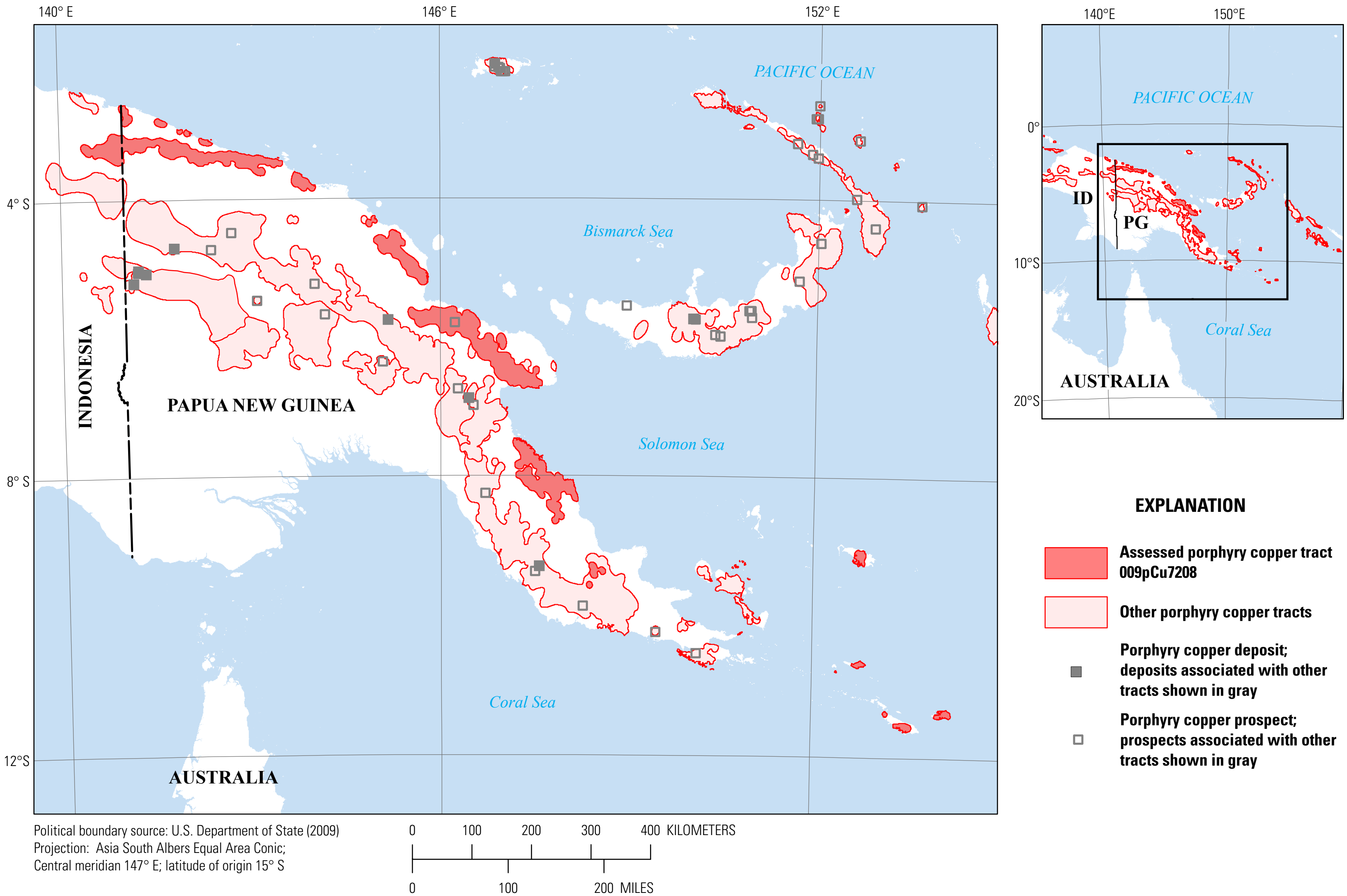

Figure S1. Map showing the location of permissive tract 009pCu7208, Inner Melanesian Arc Terranes II— Northern New Guinea Island, Papua New Guinea. ID, Indonesia; PG, Papua New Guinea.

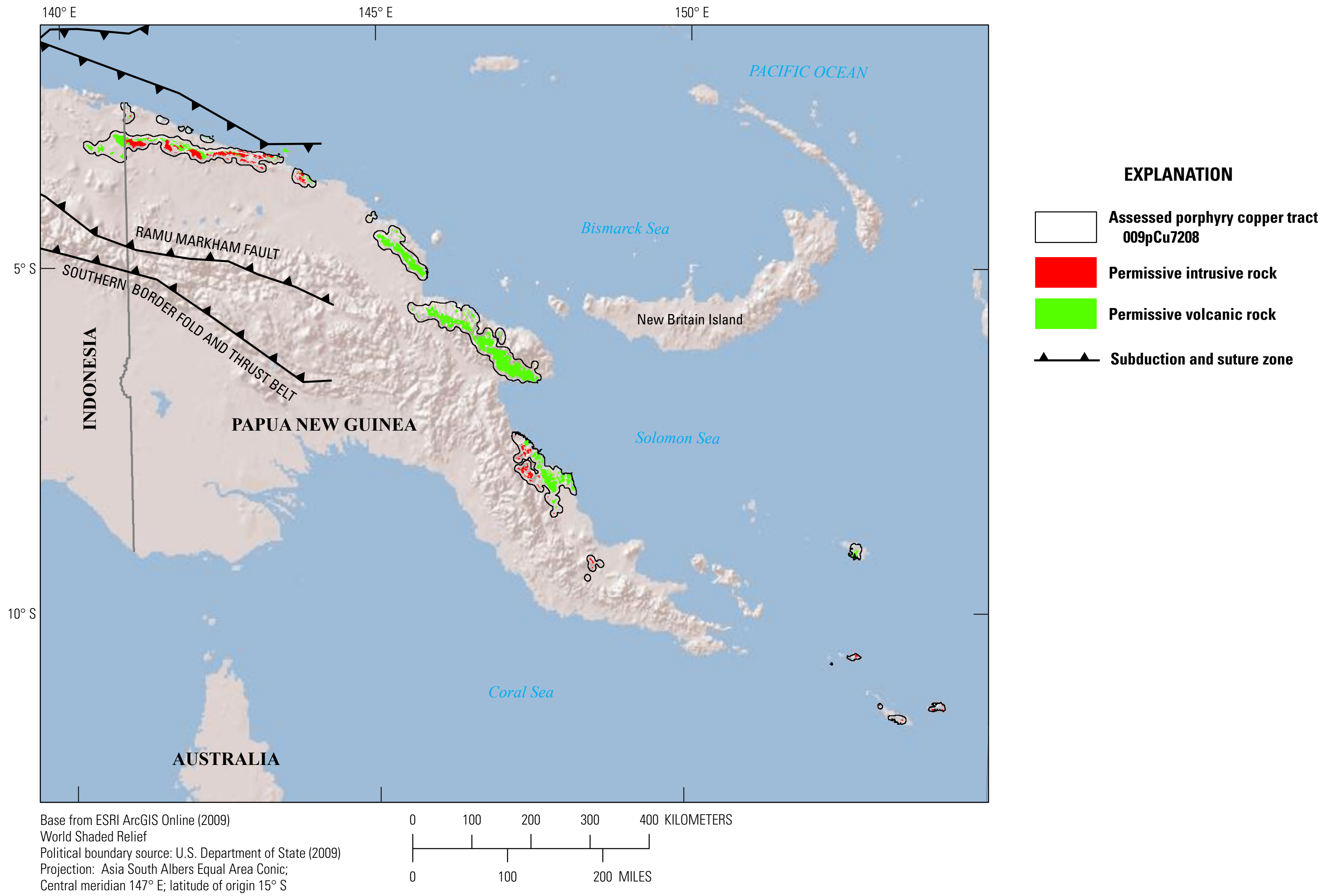

Figure S2. Map showing igneous rocks used to delineate tract 009pCu7208, Inner Melanesian Arc Terranes II— Northern New Guinea Island, Papua New Guinea.

Appendix T. Porphyry Copper Assessment for Tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[4], Arthur A. Bookstrom[5], and Michael L. Zientek[5], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[4]

Deposit Type Assessed: Porphyry copper

Descriptive model: Porphyry copper (Berger and others, 2008; Cox, 1986; Cox and others, 1986; John and others, 2010;)
Grade and tonnage model: Porphyry copper, general model (Singer and others, 2008)
Table T1 summarizes selected assessment results.

Table T1. Summary of selected resource assessment results for tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	17,990	720,000	8,500,000	3,200,000

Location

The tract is located on New Britain Island, Papua New Guinea.

Geologic Feature Assessed

Eocene to early Miocene Inner Melanesian Arc on New Britain Island.

Delineation of the Permissive Tract

Tectonic Setting

The New Britain tract represents part of the 1,000-km-long calc-alkaline Inner Melanesian Arc that developed in the Eocene to early Oligocene from southwestward subduction of the Pacific Plate along the New Britain Trench (fig. T2). Porphyry and high-sulfidation epithermal systems formed during plate reorganization at about 25 Ma, when New Britain was situated at the intersection of the South Caroline and Melanesian Arcs (Garwin and others, 2005).

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[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Menlo Park, California, United States.
[5]U.S. Geological Survey, Spokane, Washington, United States.

Table T2. Map units that define tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[Map unit, age range, and principal lithologies are based on attributes in a digital compilation of geologic maps of Papua New Guinea Indonesia (Papua New Guinea Geological Survey, 2002). Numbers and publication dates of 1:250,000-scale maps available from the Papua New Guinea Geological Survey are listed for reference. --, no map unit]

Map unit	Map symbol	Lithology	Age range	Map number	Map date
		Intrusive rocks			
- -	Ti	Leucogabbro, basic diorite, diorite, microdiorite, tonalite, granodiorite, monzonite and adamellite	Late Eocene to Miocene	B5602	1970
- -	Toi	Tonalite, gabbro, diorite, granodiorite, adamellite, monzonite, mangerite; related porphyries and microplutonic rocks	Late Oligocene	B5605	1971
- -	Toip	Intrusive-extrusive complex of rhyolite, dacite, andesite and tuff, rhyodacite porphyry	Late Oligocene	B5605	1971
		Volcanic rocks			
Kapuluk Volcanics	Tok	Zeolitic volcanic breccia, lapilli tuff and tuff, commonly maroon or green, basaltic and andesitic lavas, non-indurated marine sandstone and siltstone	Late Oligocene	B5508	1973
Baining Volcanics	Teb	Massive indurated highly jointed basaltic or andesitic lava, agglomerate, conglomerate, volcanic breccia, arenite, minor lutite, tuff, hypabyssal rocks, basic to intermediate lavas metamorphosed in some areas, minor recrystallized limestone	Late Eocene	B5602	1970
Andewa Volcanic Complex	Qs	Anedsitic, basaltic, and dacitic lavas and pyroclastics, andesite porphyry, microdiorite	Pleistocene to Holocene	B5508	1973
Mungu Volcanics	Tpm	Dacite, rhyodacite, andesite, pumiceous tuff	Pliocene	B5605	1971

Geologic Criteria

The tract is delineated on the extent of permissive late Eocene to early Miocene igneous rocks shown on 1:250,000-scale geologic maps of New Britain Island. The tract was constructed in a GIS. Map units were classified into generalized units by age and lithologic class (igneous volcanic, igneous plutonic). From this digital database of geologic lithology and age attributes, all Eocene to early Miocene igneous rocks were selected. Map units included in the tract are listed in table T2.

The final tract boundaries were established by a GIS processing and editing. The processing steps included (1) buffering permissive map units with a 5-km concentric buffer; (2) unioning buffered permissive map units and other polygon features that comprise the framework of the tract; (3) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2, a step done to group closely spaced permissive areas; (4) manually aggregating and adjusting tract areas; and (5) smoothing polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing; tracts were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral-occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

The tract terminates at the Bismarck Sea on the north and the Solomon Sea on the south. Parts of the island in the west, north, and northeast were not included in the tract because they contain Quaternary sediment estimated to be thicker than 1 km, based on examination of cross-sections shown on 1:250,000-scale geologic maps. Other data used to construct the tract includes the 1:2,000,000-scale regional geologic map (Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP) and Geological Survey of Japan, 1997), the 1:1,000,000-scale geologic map of Papua New Guinea, and local and regional mineral-occurrence databases (Bain and others, 1972; Granger, 1973; Hughes, 1990).

The geology of New Britain consists of Neogene sedimentary rocks and Paleogene felsic volcanic and sedimentary rocks, which are intruded locally by Eocene and Oligocene felsic plugs (fig. T2). The lowlands on the north and west and east ends of the island are composed of Quaternary mafic volcanic rocks. Mineralized areas contain intrusive bodies of aplite, diorite porphyry, granodiorite, quartz porphyry, gabbro, tonalite, dacite porphyry, granodiorite porphyry, and quartz diorite porphyry. Volcanic equivalents of these rocks are breccia, andesite, agglomerate, basalt, and rhyolite tuff. Country rocks consist of hornfels, limestone, and limestone breccia (Hine and Mason, 1978). Late Miocene and Pliocene volcanic rocks represent cover in some parts of the tract.

Porphyry prospects on New Britain have been dated at 24–25 Ma (Whalen and McDougall, 1980; Page and Ryburn, 1977). Three major intrusive episodes accompanied development of the of the Uasilau-Yau Yau intrusive complex in the central part of the island: Group 1 rocks (gabbro and quartz diorite) are at least 30 million years old, Group 2 intrusions (quartz diorite, tonalite, and granodiorite) formed at about 28.4 Ma, and Group 3 tonalite formed at about 23.5 Ma (Whalen and McDougall, 1980). These intrusive events were followed by hydrothermal alteration, copper mineralization, and quartz-feldspar porphyry emplacement. Copper prospects associated with this intrusive complex include Uasilau and Yau Yau (fig. T1). K-Ar ages for Pleysumi (24.5 Ma), Kulu (22.6 Ma), and Esis (<25 Ma) were reported by Titley (1978), Page and Ryburn (1977), and Hine and others (1978). Based on their study of the Uasilau-Yau Yau area, as well as age determinations on other prospects, Whalen and McDougall (1980) suggested that all of the New Britain porphyry copper deposits formed in the late Oligocene-early Miocene.

Known Deposits

Simuku is the only porphyry copper deposit on New Britain Island that has reported tonnage and grade information (table T3), with inferred resources of 200 Mt at 0.36 percent copper, 0.07 g/t gold, 0.0076 percent molybdenum, and 2 g/t silver (Coppermoly, Ltd., 2009). Drilling in 2010 identified broad zones of copper mineralization south of the area delineated for inferred resources, as well as mineralized skarn along the western margins of the deposit (Coppermoly, Ltd., 2011).

Prospects, Mineral Occurrences, and Related Deposit Types

Several porphyry copper systems are present in the mountain ranges of central New Britain Island (Garwin and others, 2005; Singer and others, 2008). These include partially explored deposits at Esis, Mount Nakru, and Plesyumi (fig. T1); no resource estimates are available for these deposits (table T4). Ore minerals include bornite, chalcopyrite, galena, molybdenite, and sphalerite. Pyrite, stannite, and cassiterite also have been reported. Supergene minerals include chalcocite, copper, covellite, cuprite, gold, goethite, and jarosite (Hine and others, 1978; Titley, 1978).

The geology of the Esis prospect was first described by Hine and others (1978). Copper mineralization is hosted in quartz diorite and magnetite breccias exposed on a west-northwest-trending ridge on the western side of a granitoid complex. Esis is within the Likuruanga exploration license area (Frontier Resources, Ltd., 2008, 2011), where recent drilling intercepted copper (>0.2 weight percent) over the entire length of six shallow drill holes; previous drilling established a supergene copper zone (152.6 m of 0.39 percent copper, 24 ppm molybdenum). Surface-rock sampling, magnetic data, and radiometric potassium data outline the Esis porphyry target area, as well as a gold-zinc-lead-copper epithermal-vein prospect and a gold-zinc skarn exploration target to the north of Esis (Frontier Resources, Ltd., 2011).

The Kulu prospect, located about 4 km southeast of Simuku, is in early Miocene dacite porphyry, porphyritic andesite, and microdiorite near a contact with the late Oligocene Kulu batholith (Hutchison and Swiridiuk, 2006). Kulu lies within the exploration license areas for the Simuku property.

The Pleysumi porphyry copper-gold prospect in central New Britain is associated with a large, multiphase igneous complex. Post-mineral ash and sediments cover parts of the area; erosion at Pleysumi exposes the prospect. Mount Nakru, also located in the central New Britain exploration area, is a caldera structure with copper-gold-molybdenum breccias (New Guinea Gold Corporation, 2009, 2011).

The Sinivit gold mine (quartz-alunite epithermal system) in East New Britain Province in the northeastern part of the island exploits an oxide cap which contains gold, and telluride and copper minerals. The deposit is localized along a 1 by 10 km structural zone (Lindley, 1990; New Guinea Gold Corporation, 2009; Stagg, 2006). Porphyry-style alteration (potassic, argillic, sericitic, propylitic) is associated with the composite Magiabe Valley porphyry intrusion, west of the Mount Sinivit gold deposit. The porphyry intrudes coeval volcanic rocks (late Oligocene to early Miocene) (Lindley, 1998). Disseminated chalcopyrite and bornite occur in potassic alteration zones in micromonzodiorite and monzonite and in a propylitic halo characterized by chlorite, calcite, epidote, and pyrite (Stagg, 2006). Alluvial gold probably is derived from a sericitized pebble breccia. Surface exposures are depleted in copper and silver because of tropical weathering, which formed a 25-m-thick oxide zone, with a possible copper-enrichment zone (chalcocite) below. The Magiabe intrusion was interpreted by Stagg (2006) as having potential for a porphyry-style copper-gold deposit, albeit one in the early stages of unroofing.

The Andewa gold-copper prospect in western New Britain has indications of early porphyry mineralization overprinted by a telescoped epithermal gold system in the caldera of the extinct calc-alkaline Mount Andewa stratovolcano. Phyllic alteration is associated with andesite and diorite dikes. Anomalous copper (400–600 ppm to 0.3–0.4 percent) encountered in

Table T3. Known porphyry copper deposits in tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; Cu-Mo subtype, deposits that have Au/Mo ratios <3 or average Mo grades >0.03%; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (percent). *, Inferred resources based on drilling; open (Coppermoly, 2009; Singer and others, 2008)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage	Grade				Contained Cu (t)	Reference
						Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)		
Simuku*	–5.733	150.033	NA	24	200	0.36	0.008	0.07	2	720,000	Coppermoly, Ltd. (2009), Hutchison, and Swiridiuk (2006), Singer and others (2008)

drilling the Komsen epithermal gold target, mineralized porphyry float, and an IP anomaly consistent with a possible large sulfide-bearing systems in the subsurface are the only indications of a possible porphyry system to date (Frontier Resources, Ltd., 2010). The prospect appears to be associated with the Pleistocene to Holocene Andewa Volcanic Complex, unlike the other porphyry systems on New Britain, which all appear to have formed in the late Oligocene to early Miocene.

Exploration History

Exploration has taken place around the Plesyumi, Esis, and Kulu (~3.5 km from Simuku) porphyry copper systems and a nearby epithermal gold occurrence. Plesyumi was discovered in 1968. The Esis porphyry copper prospect was discovered in 1971 based on anomalous copper in stream sediments and identification of sulfide minerals in float (Hine and others, 1978); 1970s exploration ceased when copper prices dropped. Frontier Resources, Ltd., started to re-evaluate Esis in 2008 (trench, rock-chip, soil sampling) for a hypothetical exploration target on the order of >150 Mt grading 0.4 percent copper or more, based on historical data. Previous exploration included 4 diamond drill holes (150 m each) and 15 shallow holes; the best drill intercepts included 152.6 m grading 0.39 percent copper and 24 ppm molybdenum. No resource estimates are available for Esis; preliminary work by Frontier reportedly confirmed previous copper and gold assays (Frontier Resources, Ltd., 2010). Exploration by Esso Minerals and CRA on New Britain in the 1980s identified gold and copper anomalies in rock chips; these exploration areas are included in MIL Resources' New Britain Project. MIL Resources 5,000-m drilling program was slated to begin in April of 2011 at the Esis porphyry copper-gold prospects within the Likuruanga Exploration Licenses area; drill targets are based on magnetic data and surface-rock sampling (Frontier Resources, Ltd., 2011).

Sources of Information

Principal sources of information used by the assessment team for delineation of 009pCu7209 are listed in table T5.

Grade and Tonnage Model Selection

Simuku, with a gold/molybdenum ratio of 10, meets the criteria of Singer and others (2008) for the general type of porphyry copper deposit (Cu-Au-Mo) rather than a copper-gold (Cu-Au) subtype. ANOVA tests of the reported tonnage and grade for Simuku do not reject the general or Cu-Au subtype models for tonnage, copper, or molybdenum; however, gold is significantly different from both models at the 1-percent test level (table 6). Partial exploration data for the Esis and Plesyumi porphyry copper prospects suggest that both gold and molybdenum may be present; anomalous gold and copper values in stream sediments near Esis contribute to its current status as an exploration target (Frontier Resources, Ltd., 2011). Garwin and others (2005) described the deposit style in the Inner Melanesian Arc as porphyry copper-gold, associated with oceanic crust. Model selection for this tract is problematic based on available information. The general global Cu-Au-Mo model of Singer and others (2008) was chosen based on the reported grades for Simuku and as a default model.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The tract contains one deposit with reported inferred resources. Three other potential deposits have been known since the 1960s. The extensive volcanic cover (fig. T3), remoteness, heavy vegetation, and incomplete exploration are factors that lead to the conclusion that additional undiscovered porphyry copper deposits may be present in the tract. The proportions of permissive volcanic rocks versus intrusions suggest that the level of erosion is appropriate and that additional intrusions may be present under shallow cover. Porphyry systems are known in the vicinity of the Sinivit gold deposit (Lindley, 1998). The Uasilau-Yau Yau

Table T4. Significant prospects and occurrences, tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[Rank 4=Prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Plesyumi	−5.967	150.383	24	Intersections 44 m at 0.85% Cu; 110 m at 0.31% Cu; and 101 m at 0.2% Cu.	Singer and others (2008), Christopher (2002), Hine and Mason (1978), Mason and McDonald (1978), Titley (1975,1978), Vangold Resources, Ltd. (2006)	4
Esis	−5.176	151.709	25	Breccia-related porphyry copper prospect associated with Uasilau-YauYau intrusive complex. Mineralization in quartz diorite and magnetite-bearing breccias. Primary mineralization: 6 shallow drill holes with weighted copper average >0.2%; 1,400 m by 400–1,000 m zone of copper mineralization; open.	Hine and Mason (1978), Hine and others (1978), Singer and others (2008), Frontier Resources, Ltd. (2008, 2011)	4
Mount Nakru	−5.983	150.467	24	Intersections: 94 m at 0.43% Cu, 0.46 g/t Au; 205 m at 0.4% Cu; 54 m at 0.18 g/t Au.	Christopher (2002), Lole (2005), Vangold Resources Ltd. (2006), Singer and others (2008)	4
Uasilau	−5.611	150.942	24	NW end of a 9 km by 2 km long, 1–2 km wide zone of low-grade porphyry copper-type mineralization (<0.3% Cu) associated with quartz diorite and tonalite in an area of anomalous stream-sediment copper.	Whalen and McDougall (1980)	2
Yau Yau	−5.616	150.955	24	SE end of a 9 km by 2 km long, 1–2 km-wide zone of low-grade porphyry copper-type mineralization (<0.3% Cu)	Whalen and McDougall (1980)	2
Andewa	−5.547	148.964	n.d.	Indication of porphyry copper-gold system overprinted by a telescoped epithermal gold system in a Pleistocene-Holocene calc-alkaline caldera complex.	Frontier Resources, Ltd. (2010)	2
Sinivit (Magiabe Valley)	−4.623	152.047	n.d.	Disseminated chalcopyrite and bornite in potasically-altered composite intrusion (micromonzodiorite and monzonite); phyllic altered pebble breccia; explored based on magnetic anomaly.	Lindley (1998), New Guinea Gold Corporation (2009), Stagg (2006)	1
Pelapuna	−5.709	150.963	n.d.	Copper prospect	Papua New Guinea Geological Survey (2002)	1
Unnamed Cu prospect	−5.613	150.918	n.d.	Copper prospect	Papua New Guinea Geological Survey (2002)	1
Kulu	−5.743	150.065	23	Porphyry copper prospect associated with Uasilau-YauYau intrusive complex.	Whalen and McDougall (1980)	1

Table T5. Principal sources of information used for tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[NA, not applicable; CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Geology of Papua New Guinea	1;1,000,000	Bain (1972)
	Digital geology of Papua New Guinea	1:250,000	Papua New Guinea Geological Survey (2002)
	Geologic quadrangle maps	1:250,000	Bureau of Mineral Resources, Geology and Geophysics, and Geological Survey of Papua New Guinea (1970, 1973, 1974)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology of the Mineral Deposits of Australia and Papua New Guinea	1;35,000,000	Hughes (1990)
	Mineral deposits of Papua New Guinea	1:2,500,000	Granger (1973)
	Digital geology of Papua New Guinea (mineral occurrence point file)	1:250,000	Papua New Guinea Geological Survey, 2002
Exploration	Company Web sites	NA	Frontier Resources, Ltd. (2008, 2010), New Guinea Gold Corporation (2011), Coppermoly, Ltd. (2009, 2011), MIL Resources Limited (2010)
	Papua New Guinea Mineral Resources Authority reports and tenement map, exploration reviews	NA	Mineral Resources Authority of Papua New Guinea (2008), Legge (1999) , Lole (2005)
	CCOP country report	NA	Dulcie Saroa (oral commun., 2010)

trend has not been fully explored. The tract includes about 20 reported copper prospects or occurrences (Papua New Guinea Geological Survey, 2002). Most of the tract area was under exploration license in 2008. On the basis of this information, the team estimated a 90-percent chance of one or more deposits, a 50-percent chance or two or more deposits, and a 10-percent chance of four or more deposits (table T6). Although the tract area is small (~16,000 km^2), the presence of significant prospect areas within the tract and the gap of approximately 20 years in exploration suggest that a 10-percent chance of four or more deposits is not an unreasonable estimate. This distribution results in a mean of 2.2 deposits with a low coefficient of variation (C_v%=54).

Probabilistic Assessment Simulation Results

Undiscovered resources for tract 009pCu7209 were estimated by combining consensus estimates for numbers of undiscovered porphyry copper-gold deposits with the porphyry copper-gold model using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table T7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. T3). The simulation predicts a mean of 8.5 Mt of copper and a median of 3.2 Mt of copper. Identified resources within the tract are 720,000 tons of copper.

Table T6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	2	4	4	4	2.2	1.2	54	1	3.2	17,990	18

Table T7. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	180,000	3,200,000	18,000,000	32,000,000	8,500,000	0.24	0.07
Mo	0	0	38,000	500,000	1,000,000	230,000	0.20	0.27
Au	0	0	62	520	820	210	0.26	0.23
Ag	0	0	350	5,800	11,000	2,700	0.20	0.37
Rock	0	45	730	3,700	6,400	1,700	0.26	0.07

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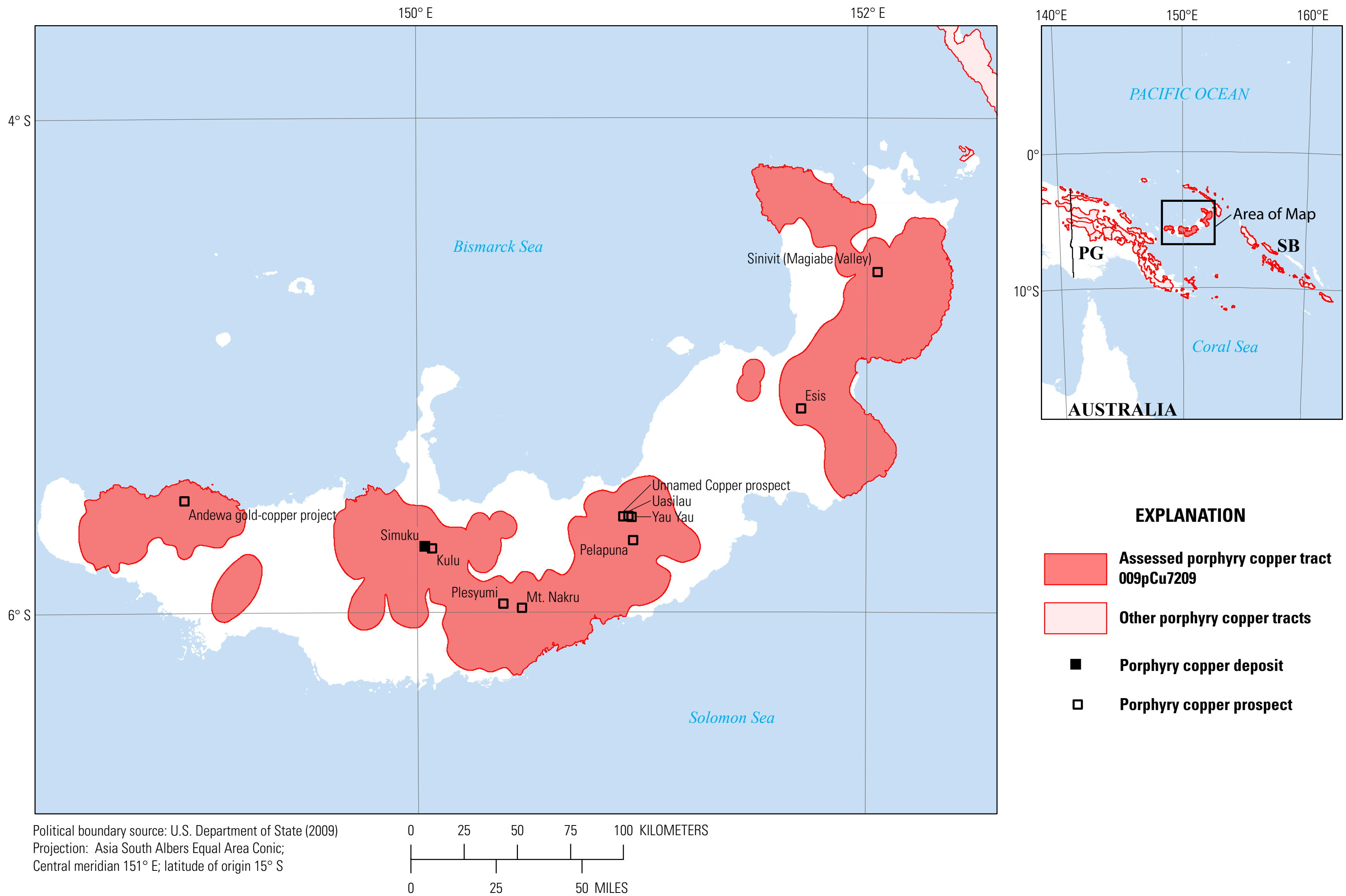

Figure T1. Map showing the location, known deposits, and significant prospects and occurrences for permissive tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea. PG, Papua New Guinea; SB, Solomon Islands.

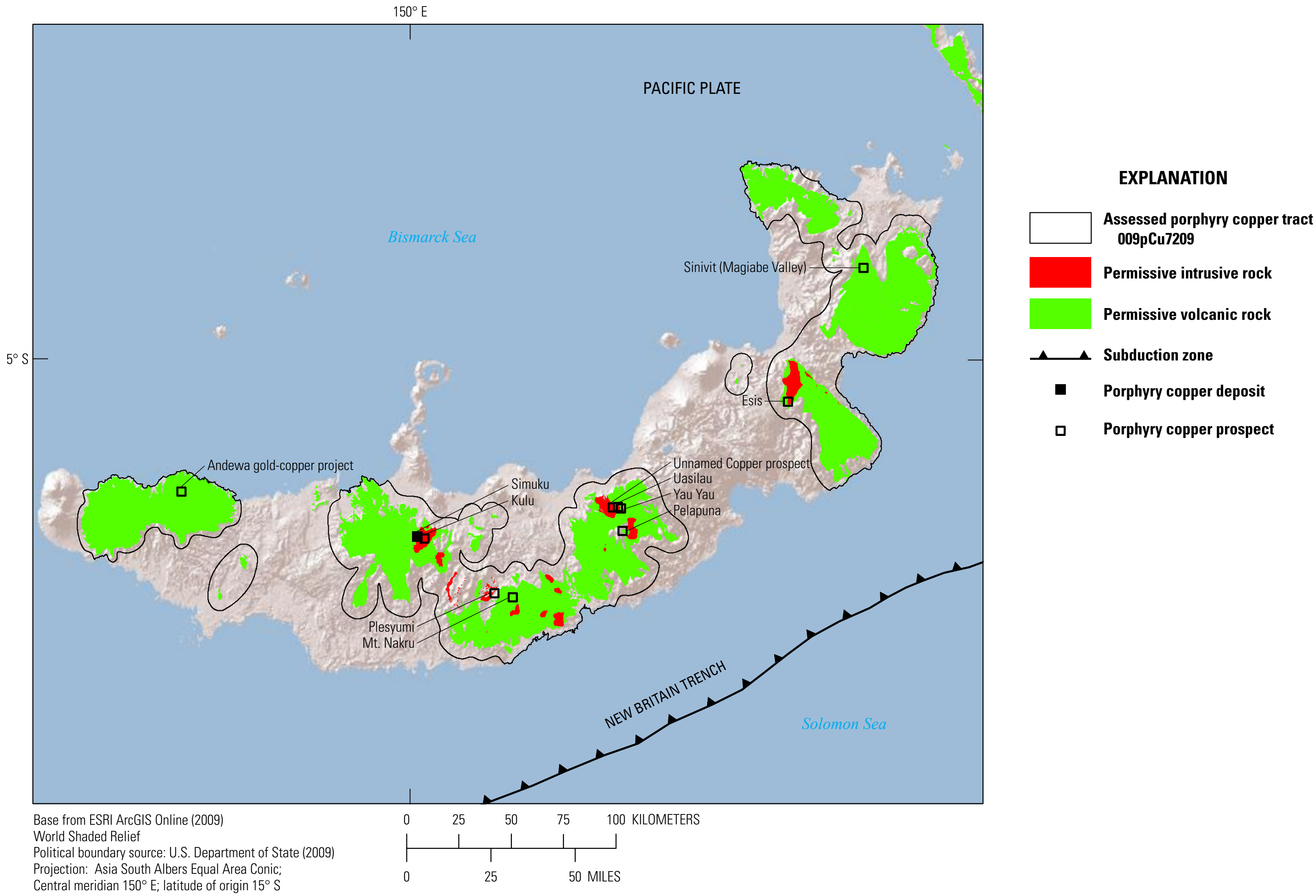

Figure T2. Map showing igneous rocks used to delineate tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea.

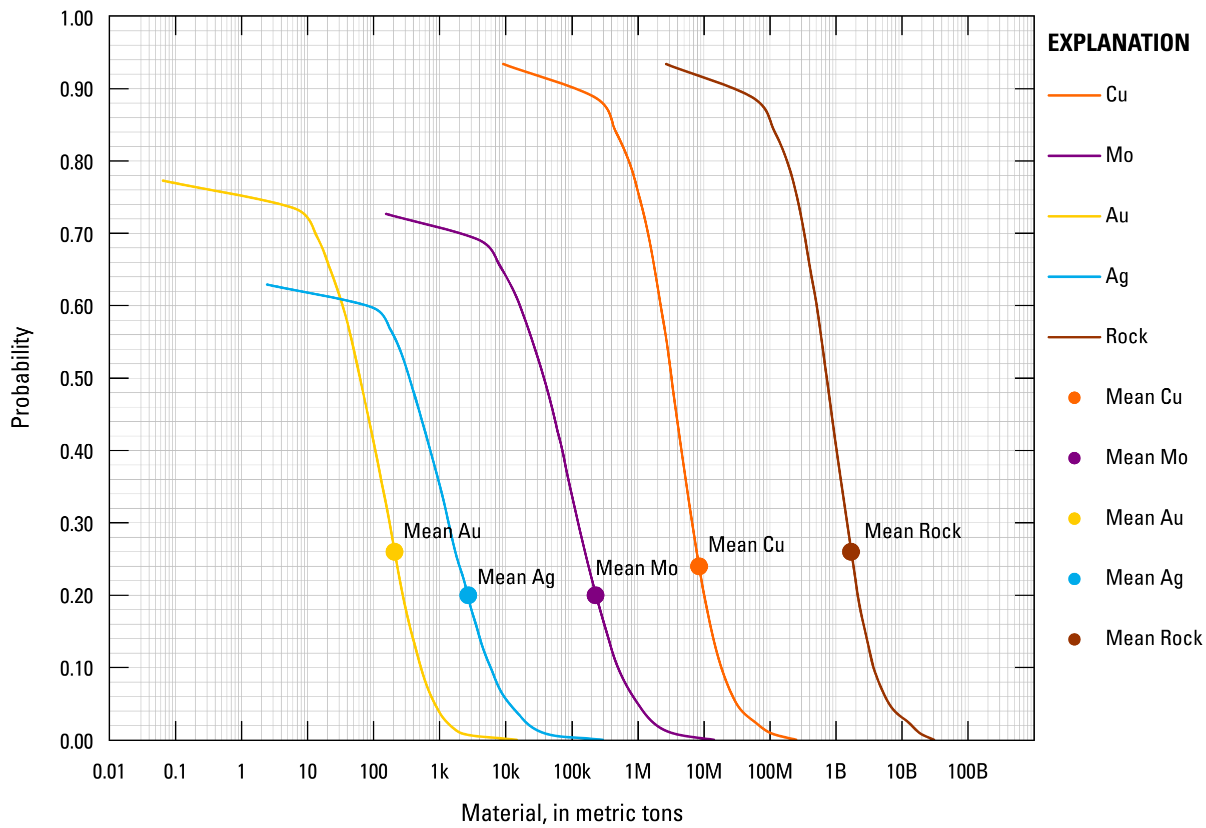

Figure T3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 009pCu7209, Inner Melanesian Arc—New Britain, Papua New Guinea. k, thousands; M, millions; B, billions.

Appendix U. Porphyry Copper Assessment for Tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea

By Jane M. Hammarstrom[1], Dulcie Saroa[2], Bambang Tjahjono Setiabudi[3], Dwi Nugrono Sunuhadi[3], Gilpin R. Robinson, Jr.[1], Connie L. Dicken[1], Steve Ludington[4], Arthur A. Bookstrom[5], and Michael L. Zientek[5], with contributions from Gwaibo Kopi[2] and Dennis P. Cox[4]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table U1 summarizes selected assessment results.

Table U1. Summary of selected resource assessment results for tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
February 2010	1	16,830	7,131,000	17,000,000	9,800,000

Location

The tract includes the following islands of Papua New Guinea: Manus, New Ireland, Bougainville, and the Bismarck archipelago (Tabar-Lihir-Feni Islands) (fig. U1).

Geologic Feature Assessed

Eocene to Holocene Outer Melanesian magmatic arc, Papua New Guinea.

Delineation of the Permissive Tract

Tectonic Setting

The tract outlines exposed segments of the >800 km Outer Melanesian Arc in Papua New Guinea. The oceanic Outer Melanesian Arc (fig. 2 of main report, no. 15) is the northern extension of the Solomon Arc that formed starting in the Eocene-

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]Mineral Resources Authority, Papua New Guinea.
[3]Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.
[4]U.S. Geological Survey, Menlo Park, California, United States.
[5]U.S. Geological Survey, Spokane, Washington, United States.

Oligocene as a consequence of southwesterly subduction of the Pacific Plate (Garwin and others, 2005). The term "Outer Melanesian Arc" is used in this report to refer to the system of arcs that extends from Papua New Guinea to Tonga, following the use of the term by Hill and Hall (2003). The arc system south of Papua New Guinea (Solomon Islands, Vanuatu and Fiji) is described in tract 009pCu7210.

The northernmost islands of the Outer Melanesian Arc, Manus and New Ireland, host Miocene porphyry copper prospects. In the early Pliocene, there was a reversal in subduction polarity caused by establishment of northeasterly directed subduction of the New Britain slab beneath the Inner and Outer Melanesian Arcs. The strike and dip of the subducting New Britain slab varies throughout the Melanesian Arcs, as does the age and character of the magmatism. Bougainville hosts Pliocene porphyry copper deposits associated with calc-alkaline diorite to granodiorite stocks. The Tabar-Feni-Lihir Islands (New Ireland offshore islands), which lie about 400 km above the subducting New Britain slab, represent a series of uplifted and eroding Pliocene to Holocene stratovolcanoes that have a shoshonitic K-alkaline geochemical signature interpreted as reflecting a contribution from subducted mantle material (Garwin and others, 2005). Lindley (2006) noted that major, generally northerly, structural corridors localized the emplacement of mineralized Tertiary intrusions in New Britain, New Ireland, and Manus Island. These structural corridors are oblique to major morphotectonic features, such as the New Britain Trench. High-angle structures predominate in the region, resulting in vertical uplift of crustal blocks, such as the north-trending horst blocks that comprise the basement in the New Ireland offshore island chain (Lindley, 2006; Garwin and others, 2005).

Geologic Criteria

The tract was delineated in a GIS by selecting Eocene to Pliocene or Quaternary (depending on subarea) igneous rocks from the digital 1:250,000-scale geologic map of Papua New Guinea (Mineral Resources Authority of Papua New Guinea, 2002). Igneous rocks used for the basis of the tract are shown in figure U2. A 5-km buffer area was created around the permissive units to extend the permissive area under younger cover. The final tract boundaries were established by a GIS processing and editing. The processing steps included (1) buffering permissive map units with a 5-km concentric buffer; (2) unioning buffered permissive map units and other polygon features that comprise the framework of the tract; (3) aggregating unioned polygons using an aggregation distance of 15 km and a minimum hole size of 1,000 km^2, a step done to group closely spaced permissive areas; (4) manually aggregating and adjusting tract areas; and (5) smoothing polygons. Preliminary tracts were cleaned to remove necking and thinning introduced by processing; tracts were compared with source maps to ensure that original permissive boundaries and buffer distances were honored. Regional and local mineral-occurrence, geochemical, and isotopic-age data were plotted and used to constrain or expand tract boundaries; in particular, a database of isotopic ages of igneous rocks for Indonesia compiled by the Southeast Asia Research Group provided additional controls on distributions of permissive rocks (Malaihollo and others, 2002). Tract boundaries were clipped at shorelines (U.S. Department of State, 2009).

The area of permissive rocks on individual islands and the size of some entire islands can be quite small; however, the Outer Melanesian Arc represents a geologic feature that hosts important porphyry copper deposits. We assessed the arc in Papua New Guinea as a whole, but we describe the permissive rocks (table U2), known deposits (table U3), and prospects (table U4) within each arc segment. Much of the arc may be submerged; however, the assessment is limited to island areas.

A. Manus Island.—On Manus Island the tract was delineated on igneous rocks that are exposed in the central highlands of Manus Island, the largest of the Admiralty Islands. The porphyry copper prospects on Manus Island are associated with middle Miocene calc-alkaline intrusive rocks. Solomon (1990) noted that development of these porphyry systems, as well as those on New Britain Island, preceded post-Miocene subduction related to the New Britain Trench.

The tract extends to the island's south margin at the Bismarck Sea and northern coast on the South Pacific Ocean. Western Manus Island is dominated by Quaternary mafic volcanic rocks (Pleistocene basalts) and Pliocene agglomerates. Neogene rocks spatially associated with porphyry copper mineralization are andesite agglomerate, basalt, basaltic pyroclastics, conglomerate, limestone, tuffaceous sandstone, and tuffaceous siltstone (Mason and McDonald, 1978). The known porphyry copper occurrences are Miocene in age (Jaques and Webb, 1975). Eastern parts of the island are dominated by sedimentary rocks, middle Miocene to Pliocene basalts, and Pleistocene to Holocene gravels, sands, and silts.

B. New Ireland Island.—The tract includes early or middle Oligocene and middle Miocene intrusive rocks of the Lemau Intrusive Complex and younger diorite and quartz diorite, including porphyry. The Legusulum porphyry copper prospect is associated with diorite, diorite porphyry, gabbro, granodiorite and associated agglomerate and pyroclastic rocks (Mason and McDonald, 1978). Host rocks include volcanic and sedimentary rocks. The southern part of New Ireland Island is dominated by Paleogene volcanic rocks, the central part by Neogene sedimentary rocks, and the northern part by Quaternary sediments.

C. Bismarck Archipelago (Tabar, Lihir, Tanga, and Feni Islands).—Tabar, Lihir, Tanga, and Feni are four volcanic island groups (listed from north to south) that form a chain parallel to the east coast of New Ireland Island. The tract includes rocks mapped as Quaternary volcanic rocks of predominantly andesitic composition, cut by hypabyssal intrusions. Five stratovolcanoes of high-K igneous rocks are described on Lihir Island; compositions range from porphyritic trachybasalt through trachyandesite to latite cut by monzodiorite stocks (Müller and others, 2001). The Feni Islands also represent eroded calderas with epithermal systems overprinting porphyry copper-gold systems. Active hydrothermal systems are present on some islands, including Lihir.

Table U2. Map units that define tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[Map unit, age range, and principal lithologies are based on a attributes in a digital compilation of geologic maps of Papua New Guinea Indonesia (Papua New Guinea Geological Survey, 2002). Numbers and publication dates of 1:250,000-scale maps available from the Papua New Guinea Geological Survey are listed for reference. - -, no map unit]

Map unit	Map symbol	Lithology	Age range	Map number	Map date
		Intrusive rocks on Manus Island			
Yirri Intrusive Complex	Tmy	Quartz monzodiorite, quartz diorite, quartz monzonite, tonalite with porphyry phases of microdiorite, microtrondhjemite, quartz micromonzodiorite, quartz microdiorite, dacite, and andesite	Late early to middle Miocene	A5510	1975
Yirri Intrusive Complex (alunitic phase)	Tmyd	Pyritic quartz-alunite-zeolite breccia; altered and brecciated porphyritic quartz micromonzonite, micromonzodiorite, and andesite pyroclastics and lava	Late early to middle Miocene	A5510	1975
Yirri Intrusive Complex (Dremsel alunitic phase)	Tmyp	Porphyritic quartz micromonzonite, micromonzodiorite, microdiorite, andesite	Late early to middle Miocene	A5510	1975
		Volcanic rocks on Manus Island			
Tinniwi Volcanics	Tot	Indurated, veined, andesite and basalt agglomerate, and lapilli tuff, lava breccia and lava; indurated tuffaceous lithic greywacke; some limestone lenses near top	Late Eocene to early Miocene	A5510	1975
		Intrusive rocks on New Ireland Island			
Lemau Intrusive Complex	Tomb	Gabbro, norite, diorite (mostly leucocratic), rhyodacite plugs	Early or middle Oligocene and middle Miocene	A5614, B5603	1973
Lemau Intrusive Complex	Toma	Granodiorite, tonalite, trondhjemite	Early or middle Oligocene and middle Miocene	A5614, B5603	1973
- -	Tmi	Diorite, quartz diorite, porphyritic microdiorite	Late? Miocene to early Pliocene	A5609	1973
		Volcanic rocks on New Ireland Island			
Jaulu Volcanics	Toj	Porphyritic andesitic and minor basaltic lapilli tuff, agglomerate; minor welded ash-flow tuff, amygdaloidal and pillow lava, lava breccia; tuffaceous limestone	Early to middle (or early late) Oligocene	A5609, A5614, B5603	1973
Lavongai Volcanics	Tmv, Tmvb	Porphyritic basaltic andesite, dacite, agglomerate, lapilli tuff, lava, lava breccia, bentonite; minor intercalated volcanic conglomerate and sandstone; minor porphyritic micromonzonite, microdiorite, andesite and dacite dykes, pebble dykes and stocks	Late? Miocene to early Pliocene	A5609	1973

Table U2. Map units that define tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.—Continued

Map unit	Map symbol	Lithology	Age range	Map number	Map date
Intrusive rocks on New Ireland Island					
Rataman Formation	Tmr	Andesitic and dacitic crystal-lithic tuff, volcanolithic arenite and lutite, foraminiferaI marl and limestone	Late Miocene	A5614, B5603	1973
Intrusive rocks on Bougainville					
- -	Czd	Microdiorite, diorite, monzonite, granodiorite, syenite, granophyre	Oligocene? to Pleistocene?	B5608, B5612	1966
Volcanic rocks on Bougainville					
Balbi Volcanics	Czb	Andesite, tuff, agglomerate, derived fan deposits	Pliocene? to Holocene	B5608, B5612	1966
Emperor Range Volcanic Beds	Cze	Andesite, basalt, agglomerate, tuff, derived fan deposits	Pliocene? to Holocene	B5608	1966
Bagana Volcanics	Czg	Andesite; Undifferentiated pyroclastics and derived fan deposits	Pliocene? to Holocene	B5612	1966
Bakanovi Volcanics	Czk	Andesite, tuff, agglomerate	Pliocene? to Holocene	B5612	1966
Taroka Volcanics	Czl	Andesite; Undifferentiated agglomerate, tuff, andesite (?), derived fan deposits	Pliocene? to Holocene	B5612	1966
Billy Mitchell Volcanics	Czm	Tuff, agglomerate, andesite (?), derived fan deposits	Pliocene? to Holocene	B5608, B5612	1966
Numa Numa Volcanics	Czn	Tuff, agglomerate, andesite (?)	Pliocene? to Holocene	B5608, B5612	1966
Tore Volcanics	Czo	Undifferentiated andesite, pyroclastics, derived fan deposits	Pliocene? to Holocene	B5608	1966
Reini Volcanics	Czr	Andesite, pyroclastics, derived fan deposits	Pliocene? to Holocene	B5612	1966
Takuan Volcanics	Czt	Undifferentiated tuff, agglomerate, andesite, derived fan deposits	Pliocene? to Holocene	B5612	1966
Bougainville Group	Czt>v	Andesite and dacite	Pliocene? to Holocene	B5612	1966
- -	Czu	Andesite, basalt, dacite, agglomerate, tuff	Miocene? to Pliocene?	B5608, B5612	1966
Kieta Volcanics	Tk	Agglomerate, tuff; sandstone, siltstone and conglomerate composed of volcanic material; andesite, basalt, pillow lava	Oligocene? to early Miocene?	B5612	1966
Volcanic rocks on Tabar-Lihir-Tanga-Feni Islands					
- -	Czv	Undifferentiated volcanics	Pliocene to Pleistocene	A5610	1973
Quaternary volcanics	Qv8, Qv7	Mainly volcanics. Predominantly andesitic pyroclastic rocks and lavas; dacites, basalts, and rhyolites	Quaternary	1:1M scale map	1971

Table U3. Known porphyry copper deposits in tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; Cu-Mo subtype, deposits that have Au/Mo ratios <3 or average Mo grades >0.03%; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (%)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Grade				Contained Cu (t)	Reference
						Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)		
A. Manus Island											
Arie	–2.047	146.870	NA	15	165	0.32	n.d.	0.10	1.70	528,000	ACA Howe International Limited (2010), Anonymous (1978), Jaques and Webb (1975), Mason and McDonald (1978), Rogerson and McKee (1990), Rogerson and others (1986)
D. Bougainville											
Panguna	–6.318	155.493	Cu-Au	3	1,420	0.47	0.005	0.57	1.1	6,603,000	Andrew (1995), Baldwin and others (1978), Clark (1987, 1990), Eastoe (1978), Ford (1978), Fountain (1972), Mining Journal (2009), Page and McDougall (1972), Tarkian and Stribrny (1999)

Table U4. Significant prospects and occurrences, tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[Ma, million years. Rank 4=Prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with < 20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers, m, meters. Names listed in italics are known epithermal gold deposits that are included because they have indications of associated porphyry-style mineralization]

Name	Latitude	Longitude	Ag (Ma)	Comments	Reference	Rank
				A. Manus Island		
Mount Kren	–2.116	146.95	13.5	Trench samples:120 m at 0.12% Cu including 25 m at 0.3%; rock chip assay ≤0.6 g/t Au and ≤2.5% Cu.	Jaques and Webb (1975), Mason and McDonald (1978), Rogerson and McKee (1990), Rogerson and others (1986), Triple Plate Junction Plc. (2006), Singer and others (2008)	4
Aniwea	–2.091	146.873	n.d.	Cu prospect.	Mineral Resources Authority of Papua New Guinea (2002)	1
Wytar	–2.102	146.926	n.d.	Cu prospect.	Mineral Resources Authority of Papua New Guinea (2002)	1
Njekel	–2.156	146.997	n.d.	Cu prospect, epithermal Au prospect; defined by multi-element drainage anomalies.	Mineral Resources Authority of Papua New Guinea (2002), Triple Plate Junction Plc. (2006)	1
Wamatja	–2.161	147.03	n.d.	Cu prospect.	Mineral Resources Authority of Papua New Guinea (2002)	1
Manus Island gold/copper project	–2.16	146.969	n.d.	Exploration project along 12 km belt of prospects targeting a porphyry copper-epithermal gold system defined by Mt. Kren Kren(Cu)-Njekel-Kisi (Au) -and East Worei prospects.	Pacrim Energy Limited (2009)	2
				B. New Ireland Island		
Legusulum (West Lihir copper-gold project)	–3.184	151.654	24	Oligocene-Miocene Lemau dioritic intrusive complex.	MIL Resources, Ltd. (2008); Singer and others (2008)	4
New Hanover	–2.622	150.142	n.d.	Reconnaissance exploration identified Cu-bearing breccias associated with epithermal gold target areas. Feldspar porphyry intrusion with quartz-sulfide-carbonate stockwork at core of 19 km^2 area of argillic alteration. Cu in brecciated quartz veins and in narrow intercepts in drillcore in oxide zone epithermal Au target.	Papuan Precious Metals (2011)	1
Palabong copper/gold project	–3.98	152.599	n.d.	Porphyry copper-gold and epithermal gold exploration target area.	MIL Resources, Ltd. (2008), Titan Metals Limited (2008)	2

Table U4. Significant prospects and occurrences, tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.—Continued

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
				B. New Ireland Island		
Weitin River copper/ gold project	–4.397	152.9	n.d.	Weitin River Caldera is a large circular structure approximately 5 km in diameter; anomalous stream sediment copper geochemistry with samples assaying 35 to 200 ppm copper.	MIL Resources, Ltd. (2008), Titan Metals Limited (2008)	2
New Ireland - unworked deposit 1	–3.388	151.977	n.d.	Unworked copper deposit~ 30 km SE of Legusulum, as noted in MRA database.	Mineral Resources Authority of Papua New Guinea (2002)	1
New Ireland - unworked deposit 2	–3.341	151.888	n.d.	Unworked copper deposit~ 40 km SE of Legusulum, as noted in MRA database.	Mineral Resources Authority of Papua New Guinea (2002)	1
				C. Tabar-Lihir-Tanga-Feni-Islands		
Feni (Kabang)	–4.067	153.633	n.d.	Epithermal Au prospect may be overprinting porphyry copper-gold.	PACCOM Ventures (2003)	1
Ladolam (Lihir Island)	–3.313	152.633	n.d.	Epithermal gold deposit in an inactive volcanic crater (active mine). Early stage porphyry possibly related to very low-grade porphyry copper style mineralization.	LGL Gold (2009), Corbett and Leach (1998), Müller and others (2003)	1
Tatua gold/copper project	–2.82	151.94	n.d.	Gold and copper exploration within collapsed calderas.	Allied Gold Limited (2009)	1
Simberi (Tabar Island)	–2.631	152.002	n.d.	Epithermal gold deposits; gold produced starting in 2008 from an open pit mine in oxide zone ores; ongoing exploration includes drilling at the Pigibo and Pigiput prospects.	Allied Gold Limited (2009)	1
Tabar Island	–2.817	151.967	n.d.	Gold and copper exploration within collapsed calderas.	Allied Gold Limited (2009)	1

D. Bougainville Island.—Bougainville consists of a northwest-trending zone of Neogene and Paleogene sedimentary rocks intruded by Neogene and Quaternary felsic to intermediate plugs. Mafic volcanic rocks on the northern and southern parts of the island locally are covered by Quaternary sediments. The area around the Bougainville porphyry copper mineralized zone contains breccia, diorite, feldspar porphyry, granodiorite, quartz diorite, and volcanic rocks consisting of basalt, dacite, and andesite. Late Cenozoic sediments are grits and limestones (Fountain, 1972; Baldwin and others, 1978). Age of mineralization is Pliocene (Page and McDougall, 1972).

Known Deposits

A. Manus Island.—The 15 Ma Arie porphyry copper deposit (165 Mt at 0.32 wt. percent copper) is hosted in breccia and porphyritic diorite (Singer and others, 2008). Resources are based on drilling by Kennecott in the 1980s and are not compliant with modern NI43-101 reporting criteria. The 13.5 Ma Mount Kren prospect, located about 12 km southeast of Arie (fig. U1), has a noncompliant estimated resource of 20 Mt at 0.3 percent copper, based on drilling in the 1970s. The team includes Arie as a known deposit because it was included in the porphyry copper grade and tonnage model used for the assessment (Singer and others, 2008). The historical data should be considered preliminary pending outcomes of current exploration on Manus Island.

D. Bougainville.—The Panguna (Bougainville) mine produced 2 percent of world copper supply at one time. The mine operated from 1972 until 1989 when political unrest caused a shutdown. Panguna is interpreted as part of a stratovolcano, where the Panguna Andesite was intruded by the Kaverong Quartz Diorite and related differentiates (granodiorite, breccias). The 3.4 Ma Panguna (Bougainville) porphyry copper-gold deposit lies in the south central part of Bougainville Island. Ore minerals are present in quartz veinlets and as disseminations of bornite, chalcopyrite, galena, gold, molybdenite, and sphalerite; stannite and tetrahedrite/tennantite also are reported. Supergene ore minerals include chalcocite and covellite, along with iron-oxide minerals (Baldwin and others, 1978; Clark, 1990; Tarkian and Stribrny, 1999). Mill concentrate from the mine contained up to 8 ppb platinum and 40–52 ppb palladium. Grade and tonnage for the deposit in the database of Singer and others (2008) are cited as 1,420 Mt at 0.465 percent copper, 0.005 percent molybdenum, and 0.57 g/t gold. The mine produced 3 Mt of copper and 9.3 million ounces of gold from 675 Mt of milled ore during the 18 years of mine operation. At closure, ore reserves were cited as 497 Mt at 0.42 percent copper and 0.55 g/t gold, with additional material that could be upgraded to 691 Mt of mill feed at 0.40 percent copper and 0.47 g/t gold (Bougainville Copper Limited, 2009). In preparation for reopening the mine, an updated total resource (indicated and inferred) was estimated based on historical data: 1,064 Mt at 0.33 percent copper and 0.37 g/t gold (Bougainville Copper Limited, 2009). In 2010, efforts were underway between the Boungainville government, the government of Papua New Guinea, and landowners to resolve issues related to the future of the mine, including lifting a moratorium on new exploration and mining (Bougainville Copper Limited, 2011).

Prospects, Mineral Occurrences, and Related Deposit Types

A. Manus Island.—Pacrim's Manus Island project targeted a 12-km-long belt of prospects that include the Mount Kren copper prospect, as well as epithermal gold targets (Njekel, Kisi and East Worei). Soil copper anomalies at Mount Kren overlie rock where rock-chip sampling confirmed a 600-m-long shallow dipping zone of anomalous copper (0.12–0.3 percent and up to 0.22 g/t gold). Ore minerals are veinlets and disseminations of bornite, chalcopyrite, molybdenite, and gold, accompanied by pyrite, gold, zeolite and sulfur. Minor gold, silver, and molybdenum values are reported in the ores. Supergene assemblages contain alunite and kaolinite. Alteration minerals associated with the Arie and Mount Kren porphyry systems include biotite, sericite, chlorite, carbonate minerals, epidote, magnetite, and kaolinite. The entire tract area in central Manus is under exploration for high-sulfidation epithermal deposits, deeper-seated porphyry systems, and low-sulfidation epithermal veins and limestone replacements (ACA Howe International Limited, 2010).

B. New Ireland Island.—The West Lihir exploration target is the Legusulum porphyry copper prospect, a prominent diorite ridge covering an area of more than 1 km^2, with reported chalcopyrite, bornite, chalcocite and molybdenite and a 70-m-thick leached cap overlying the deposit (Titan Metals Limited, 2008). Other prospect areas under exploration for porphyry copper-gold and epithermal gold deposits on New Ireland include Palabong and Weitin River, a caldera structure with geochemical anomalies for copper (MIL Resources, Ltd., 2010).

C. Tabar-Lihir-Tanga-Feni Islands.—Alluvial gold was worked by artisanal mining, mainly before World War II. The area was explored for porphyry copper deposits in the 1970s and 1980s, which led to the discovery of the world-class Ladolam deposit on Lihir Island. Ladolam is an epithermal gold deposit with total ore reserves of 330.8 Mt at 2.71 g/t gold (LGL Gold, 2009). The Ladolam gold deposit on Lihir Island is developed in the floor of the alkaline Luise Caldera, where sector collapse at 0.3 Ma resulted in telescoping of the hydrothermal system and superposition of an epithermal gold system on early stage, weak porphyry gold-copper mineralization (Müller and others, 2003). Ladolam has been described as an atypical gold deposit related to alkaline rocks formed in a postsubduction extensional setting (Sillitoe, 2002). Ladolam is the youngest (<1 Ma) known intrusion-related gold deposit and the first documented example of a low-sulfidation epithermal system triggered by sector collapse of a volcano that overprints a pre-collapse porphyry system (Sillitoe, 2002). Gold is mined from an epithermal deposit on Simberi in the northernmost Tabar Islands.

Exploration History

Prospecting on Manus Island led to the discovery and development of Arie and Mount Kren. A digital compilation of historical exploration data for Manus Island was compiled as part of a World Bank project for the Papua New Guinea Department of Mining and released in 2003 (Beams and Jenkins, 2003). The data set includes more than 30,000 records of stream-sediment, rock-chip, soil, and drill data and provides an inventory of tenements held and related exploration activities. As of 2008, the permissive-tract area was under active exploration license (Mineral Resources Authority of Papua New Guinea, 2008). Pacrim/Triple Plate PLC remapped the central Manus region, reinterpreted geophysical data, identified structural controls on mineralization, identified epithermal mineralization associated with porphyry copper mineralization, and performed detailed studies at the Kisi epithermal gold prospect, and at the Kren, Njekei, and East Worei prospects in the southern part of the island (Pacrim Energy Limited, 2009; ACA Howe International Limited, 2010). In 2010, Manus Island exploration was in progress through a joint venture between Triple Plate Junction PLC and Newcrest Mining Limited, subject to approval by the Papua New Guinea government (Newcrest Mining Limited, 2010).

Swiss Aluminium Mining Australia explored the New Ireland area in the 1970s, using shallow drilling into the limonite cap at Legusulum. ESSO flew airborne magnetics in the early 1980s and determined that Legusulum may contain significant copper mineralization. Exploration targets include breccia pipes and porphyry deposits under recent volcanic cover and limestone (Titan Metals, 2008).

Exploration for porphyry copper deposits in the Tabar-Lihir-Tanga-Feni island chain in the 1970s and 1980s led to the discovery of the world-class Ladolam deposit. That 1982 discovery sparked exploration for epithermal gold and related deposit types associated with the eroded calderas that comprise the chain. Ongoing drilling to characterize epithermal gold mineralization at the prospects on Simberi Island, the northernmost of the Tabar Islands, identified copper (~170 ppm) associated with gold and arsenian pyrite; host rocks are tuffs and a porphyritic intermediate intrusive. No exploration or mining has occurred on Bougainville since 1989 because of limitations on site access.

Sources of Information

Principal sources of information used by the assessment team for delineation of 009pCu7207 are listed in table U5.

Grade and Tonnage Model Selection

Panguna is a copper-gold porphyry (Au/Mo ratio >30). Gold and molybdenum grades are not reported for the Arie deposit. T-tests for tonnage and copper for both deposits are compatible with either a general or Cu-Au subtype (table 6). Exploration activities are targeting copper-gold porphyry deposits and epithermal gold systems. On the basis of Panguna, the island-arc setting, and the regional characteristics of porphyry deposits, the copper-gold subtype grade and tonnage model was selected for this assessment.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The team concluded that data for the Mount Kren prospect and additional exploration areas on Manus Island supported an estimate for at least one undiscovered deposit on the island, in addition to the Arie deposit. On New Ireland, the Legusulum porphyry copper-gold prospect and the association of copper with epithermal gold systems indicates porphyry copper potential, perhaps at depth below associated epithermal systems. Similarly, porphyry systems may be associated with collapsed calderas that host epithermal gold in the islands of the Bismarck Archipelago. Although Bougainville has not been explored for many years, the presence of permissive rocks and its location between prospective areas in New Ireland to the north, and in the Solomon Islands to the south, suggest that undiscovered deposits may be present. Recognition of porphyritic intrusions within the predominantly volcanic terrane suggests that levels of erosion may be appropriate to preserve porphyry copper deposits.

The team estimated a 90-percent chance of at least two undiscovered deposits, a 50-percent chance of five or more deposits, and a 10-percent chance of 10 or more based on the data in table U4 and the recent resurgence in exploration activity. The mean number of deposits based on these estimates is 5.5, with a coefficient of variation of 54 percent (table U6). That is, about a third of the 16 prospect areas listed in table U4, as well as areas that are yet to be identified through exploration, might represent undiscovered deposits. The team considered the fact that the area was underexplored for many years, and that new drilling to confirm previously identified geochemical anomalies and geophysical targets is likely to document new resources comparable to those in the grade and tonnage model, although the shallow, gold-rich epithermal parts of any porphyry systems are most likely to be developed in the foreseeable future.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered

Table U5. Principal sources of information used for tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[NA, not applicable; CCOP, Coordinating Committee for Geoscience Programmes in East and Southeast Asia]

Theme	Map or title	Scale	Citation
Geology	Digital geologic map of East and Southeast Asia	1:2,000,000	CCOP and Geological Survey of Japan (1997)
	Geology of Papua New Guinea	1:1,000,000	Bain and others (1972)
	Digital geology of Papua New Guinea	1:250,000	Mineral Resources Authority of Papua New Guinea (2002)
	SE Asia Radiometric Ages: GIS Database	NA	Malaihollo and others (2002)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology of the mineral deposits of Australia and Papua New Guinea	1;35,000,000	Hughes (1990)
	Mineral deposits of Papua New Guinea	1:2,500,000	Granger (1973)
	Mineral resources on-line spatial data	NA	U.S. Geological Survey (2010)
	Digital geology of Papua New Guinea (mineral occurrence point file)	1:250,000	Mineral Resources Authority of Papua New Guinea (2002)
Exploration	Company Web sites	NA	Various (see table U4)
	Papua New Guinea Mineral Resources Authority reports and tenement map, exploration reviews		Mineral Resources Authorityof Papua New Guinea (2008), Legge (1999)
	CCOP country report		Dulcie Saroa (oral commun., 2010)

Table U6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km^2, area of permissive tract in square kilometers; N_{total}/100k km^2, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
2	5	10	10	10	5.5	3	54	2	7.5	16,830	45

porphyry copper deposits with the global porphyry copper-gold subtype model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table U7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. U3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper contained in undiscovered porphyry copper deposits within the tract (17 Mt) represents about 2.4 times the amount of copper reported in identified resources within the tract (~7 Mt).

Table U7. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea.

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount based on the Cu-Au subtype model						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	260,000	1,200,000	9,800,000	42,000,000	61,000,000	17,000,000	0.32	0.04
Mo	0	0	27,000	260,000	470,000	95,000	0.25	0.19
Au	26	110	830	3,000	3,900	1,200	0.35	0.04
Ag	0	0	2,000	13,000	27,000	5,400	0.23	0.12
Rock	59	290	2,100	8,800	12,000	3,400	0.34	0.04

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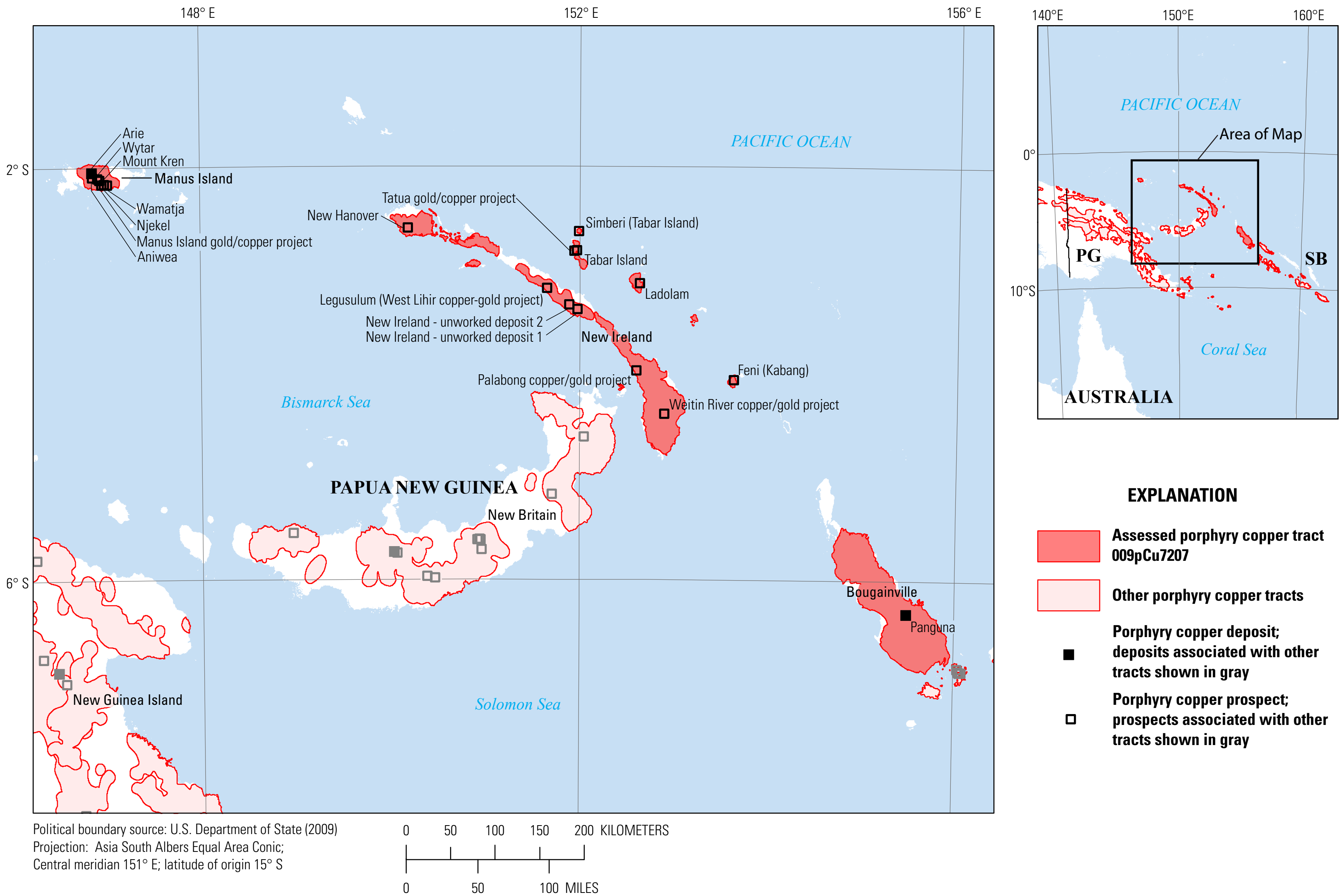

Figure U1. Map showing the location, known deposits, and significant prospects and occurrences for of permissive tract 009pCu7207, Outer Melanesian Arc I— Papua New Guinea. PG, Papua New Guinea; SB, Solomon Islands.

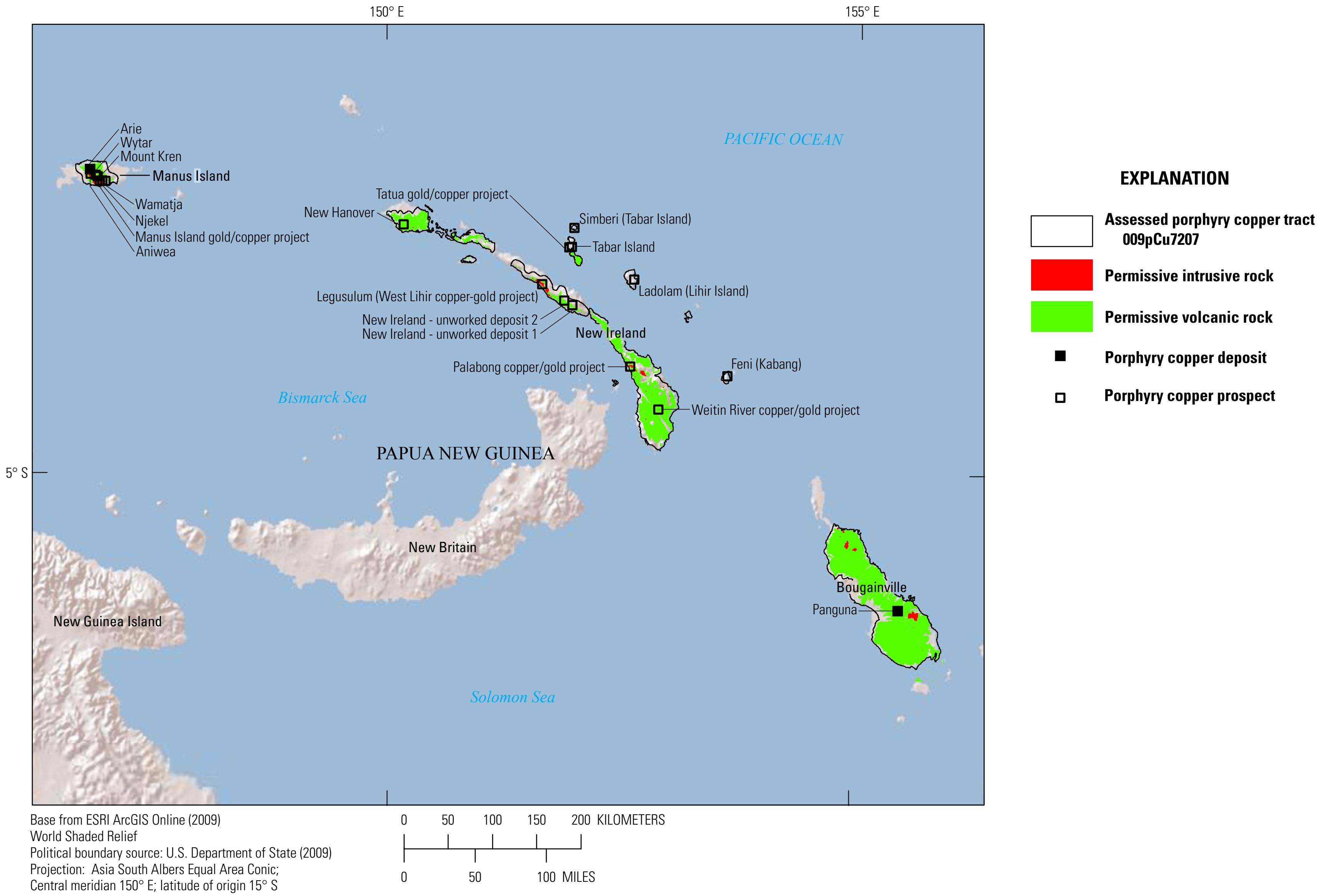

Figure U2. Map showing igneous rocks used to delineate tract 009pCu7207, Outer Melanesian Arc I— Papua New Guinea.

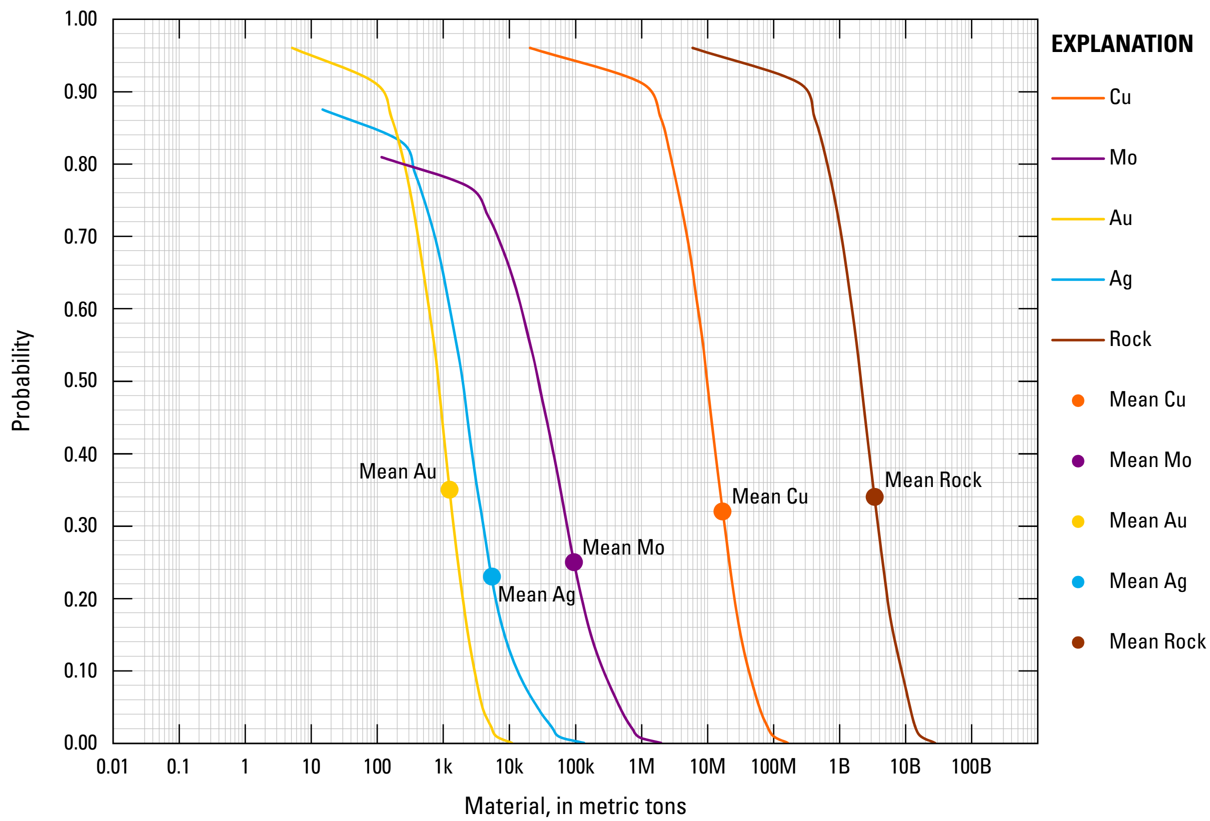

Figure U3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea. k, thousands; M, millions; B, billions; Tr, trillions.

Appendix V. Porphyry Copper Assessment for Tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji)

By Jane M. Hammarstrom[1], Connie L. Dicken[1], Gilpin R. Robinson, Jr.[1], and Arthur A. Bookstrom[2]

Deposit Type Assessed: Porphyry copper, copper-gold subtype

Descriptive model: Porphyry copper (Berger and others, 2008; John and others, 2010); Porphyry copper-gold (Cox, 1986; Cooke and others, 1998)
Grade and tonnage model: Porphyry copper, copper-gold subtype (Singer and others, 2008)
Table V1 summarizes selected assessment results.

Table V1. Summary of selected resource assessment results for tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[km, kilometers; km^2, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
January 2011	1	38,180	6,887,900	16,000,000	9,100,000

Location

The tract covers the central and southern portions of Melanesia, including the archipelago countries of Solomon Islands, Vanuatu (formerly New Hebrides), and Fiji (fig. V1). The northernmost parts of the Outer Melanesian Arc are described in tract 009pCu7207, Outer Melanesian Arc I—Papua New Guinea, which covers the islands north of the Solomon Islands (Bougainville, New Ireland, the Bismarck archipelago, and Manus Island).

Geologic Feature Assessed

Eocene-Oligocene to late Miocene-Pliocene-Pleistocene Outer Melanesian magmatic arc and Melanesian borderlands in the Solomon Islands, Vanuatu, and Fiji.

Delineation of the Permissive Tract

Tectonic Setting

The Outer Melanesian Arc has a protracted history of arc development, starting with southwest-dipping subduction of the Pacific Plate beneath the Indo-Australian Plate along the Vitiaz-Tonga Trench system (fig. 6) by Eocene time (Schellart and

[1]U.S. Geological Survey, Reston, Virginia, United States.
[2]U.S. Geological Survey, Spokane, Washington, United States.

others, 2006). A single semicontinuous arc system, known as the Vitiaz Arc, included New Ireland and Bougainville in Papua New Guinea, the Solomon Islands, Vanuatu, and Fiji. The Vitiaz Arc persisted as the Pacific Plate subducted beneath a passive Indo-Australian Plate margin until the Miocene. Early to middle Miocene collision of the Ontong Java Plateau (fig. 9) with the Solomon Arc segment of the Vitiaz Arc system led to a reversal in subduction polarity, initiation of eastward subduction of the Indo-Australian Plate along the New Britain-Cristobel and Vanuatu (New Hebrides) Trench systems (west of the Vitiaz Arc system), and subsequent fragmentation of the Vitiaz Arc. The 1,900,000 km^2 Ontong Java Plateau is an anomalously thick (>30 km), probably plume-related, Cretaceous oceanic plateau on the Pacific Plate that continues to interact with an active subduction zone as its southwestern margin subducts at the North Solomon Trench (fig. 6; Mann and Taira, 2004). Extensive offshore drilling of the Ontong Java Plateau and sampling of obducted plateau material in the eastern Solomon Islands along the southern margin of the Plateau demonstrated that plateau lavas are low-K tholeiitic basalts with limited compositional variability (Tejada and others, 2004). The plateau basalts are geochemically distinct from both ocean island basalts (OIB) and normal mid-ocean-ridge basalt (Pacific N-MORB), as indicated by their flat normalized incompatible element- and rare-earth patterns (Tejada and others, 2004). The collision of the Ontong Java Plateau disrupted the Vitiaz Arc system and had a profound effect on the tectonic setting of the region because it triggered reversals in subduction polarity. Such reversals may be a factor that controls development of some porphyry Cu-Au systems (Solomon, 1990).

Between 8 and 5 Ma, the Vanuatu Arc rotated clockwise as the North Fiji back-arc basin opened and the Fiji Platform rotated in a counterclockwise direction. The modern Fiji Platform, bordered by the Fiji Fracture Zone and the North Fiji Basin to the north, and the Hunter Fracture Zone to the south, is situated between the eastward-subduction zone that defines the modern eastward subducting Vanuatu Arc and the westward subduction zone of the Tonga-Kermadec Arc system. The modern southern part of the Melanesian Arc system is a collage of microplates (North Fiji, Solomon Sea, Bismarck, and Woodlark Basins) and trenches (San Cristobal-Vanuatu, Vitiaz, Tonga) along the boundary zone between the Australian and Pacific Plates (fig. 6).

Tract Segments

On the basis of the vast extent of the now-segmented Outer Melanesian Arc, the assessment team subdivided the tract into three segments to facilitate discussion: Solomon Islands, Vanuatu, and Fiji. The probabilistic assessment applies to the whole tract.

Solomon Islands

About 1,000 islands comprise the independent nation of Solomon Islands and have a land mass of approximately 28,400 km^2. The islands trend northwest-southeast from the Shortland Islands and the island of Choiseul, just south of Bougainville, Papua New Guinea, to the island of Makira (fig. V2*A*). The Solomon Islands represent a collage of "terrains"[3] formed in an intra-oceanic arc setting since the Cretaceous (Petterson and others, 1999). Building on the framework for the Solomon Arc developed by Coleman (1962, 1980) and Coleman and Kroenke (1981), Petterson and others (1999) constructed a terrain map of the Solomon Islands which defined five crustal units based on lithology, age, geochemistry of basement, and presence or absence of arcs (fig. V2*A*). Permissive terrains for porphyry copper deposits preserve Paleocene/Eocene to early Miocene (stage 1) arc volcanism related to southwest-directed subduction of the Pacific Plate along the Vitiaz Trench and (or) late Miocene to Holocene (stage 2) volcanism and plutonism. Stage 2 magmatism is related to northeast-directed subduction of the Australian Plate beneath the Solomon block. During stage 2, the San Cristobel Trench developed following the polarity reversal initiated by docking of the Ontong Java plateau. Both arc stages are preserved in the South Solomon MORB Terrain on Guadalcanal and Choiseul; stage 2 arc magmatism formed the New Georgia Terrain, and stage 2 rocks also occur in the Shortland Islands, Choiseul, Guadalcanal, and in some of the smaller islands of the archipelago (fig. V2*A*). Stage 1 arc activity formed the basement of the Central Solomon terrain, which has variable development of stage 2 arc (Petterson and others, 1999). Stage 1 arc assemblages include ultramafic rocks, basic to ultrabasic island-arc basalts, back-arc basalts, and alkali basalts, as well as calc-alkaline andesites and dacites. Stage 2 arc assemblages include late Miocene calc-alkaline basalt-rhyolite rocks, sodic basalt-dacite, shoshonitic rocks, high-Mg basalt-andesite, picrites, diorite, and microgranites related to northeast-directed subduction of the Australian Plate. These rocks form the New Georgia Group and also occur in the Shortland Islands, on Choiseul, and on Guadalcanal.

Vanuatu (New Hebrides)

The Republic of Vanuatu, known as the New Hebrides prior to independence in 1980, is a y-shaped archipelago composed of 83 island groups that trend north-south for a distance of 1,300 km, with a total land area of about 12,500 km^2 (fig. V2*B*). Vanuatu lies 800 km west-southwest of Fiji and 500 km northeast of New Caledonia. The main islands are Espiritu Santo, Malekula, Efate, and Erromango.

Vanuatu is described as an island-arc ridge composed of three parallel belts (Macfarlane and others, 1988). The western belt is composed of late Oligocene to middle Miocene volcanic rocks that formed part of the relict Vitiaz Arc prior to subduction reversal (fig. 9). The volcanic rocks, up to 7,000 m thick, were uplifted, deformed, and intruded by calc-alkaline mafic to intermediate intrusions associated with northeast-striking faults (Vanuatu Department of Geology, Mines, and Water Resources,

[3]Petterson and others (1999) proposed the term "terrain" to describe the geodynamic framework of the Solomon Islands. Terrains are distinguished from one another based on geology, tectonic history, and age. The term "terrane" sensu stricto refers to fault-bounded areas that have unique geological histories.

1995). The deep trenches that characterize the North and South Vanuatu (New Hebrides) Trench are absent in the parts of the arc adjacent to the western belt, where Pliocene onset of collision of the d'Entrecasteaux ridge (on the Indo-Australian Plate) with the Vanuatu Arc caused rapid uplift and tilting on Espiritu Santo and Malekula (Collot and Fisher, 1991). This uplift may have exposed the upper parts of porphyry systems.

The central belt of Vanuatu, active since the late Miocene subduction reversal, hosts 11 major volcanoes. Volcanic-rock compositions are mafic and highly variable, ranging from low-K tholeiites to high-K alkaline rocks, including high-K picrites and ankaramites (Vanuatu Department of Geology, Mines, and Water Resources, 1995). The late Miocene to early Pliocene eastern belt of Vanuatu is composed of submarine basaltic to andesitic volcanic and volcaniclastic rocks, unconformably deposited on tilted, block-faulted Miocene volcanic rocks. Obduction of ophiolite complexes accompanied late Pliocene uplift and erosion; rapid (2.7 mm/yr) Pleistocene uplift led to development of coral reef terraces (Vanuatu Department of Geology, Mines, and Water Resources, 1995). Permissive rocks and known prospects for porphyry copper deposits are confined to the western belt of Vanuatu.

Fiji

The island nation of Fiji, about 2,000 km northeast of the North Island of New Zealand, is an archipelago of more than 300 islands with a total land area of 18,300 km^2. Fiji is situated on the Lau Ridge between the opposing Vanuatu and Tonga-Kermadec convergence zones and is bordered by the extensional Lau and North Fiji back-arc basins (figs. 6, 8). The geology of the Fiji islands preserves a record of the growth, evolution, and fragmentation of an island-arc system (Fiji Ministry of Lands and Mineral Resources, 2010). The evolution of Fiji is characterized by 4 stages: (1) early arc stage (35–12 Ma) characterized by primitive, low-K thloeiites with pre-Miocene volcanism associated with subduction along the Vitiaz Trench; (2) mature arc stage (12–7 Ma) represented by the Colo Plutonic Suite, which is referred to as the Tholo Suite in some references; (3) early arc rifting stage (7–3 Ma) associated with tholeiitic to calc-alkalic rocks; and (4) late arc rifting stage (3 Ma to Holocene), associated with ocean-island basalts and on some islands, high-K andesites. Porphyry systems are associated with the mature arc and early extensional (rifting) stages (Colley and Greenbaum, 1980; Fiji Ministry of Lands and Mineral Resources, 2010). Epithermal gold-telluride systems, such as the Emperor deposit, are associated with calderas of the early rifting stage (Fiji Ministry of Lands and Mineral Resources, 2010).

Calc-alkaline rocks permissive for porphyry copper deposits occur on the two main islands: Viti Levu and Vanua Levu (fig. V2*C*). Ages range from 12.5 Ma to about 7 Ma. The main plutons of the Colo (Tholo) Suite are tonalite and gabbro, with marginal facies, including trondhjemite, diorite, and hornblende andesite-microdiorite; coeval volcanic rocks are absent. Colley and Greenbaum (1980) noted 7 porphyry-type copper ±molybdenum prospects associated with plutons of the Colo (Tholo) orogeny, as well as copper skarns; no economic deposits are associated with these rocks. The Yavuna stock in western Viti Levu, dated at 33 Ma, and the Mbotenaulu stock in central Viti Levu are mapped as first phase, pre-Miocene, synorogenic intrusions of the Colo (Tholo) plutonic suite, whereas the other plutons of the Colo (Tholo) suite are mapped as second-phase, late Miocene (7–11 Ma) synorogenic intrusions.

Major porphyry copper and epithermal gold deposits are associated with mature arc (12–7 Ma) and early rifting stage (~7–3 Ma) tholeiitic to calc-alkaline rocks on Viti Levu and Vanua Levu. The early rifting stage produced the Namosi Andesite, which covers much of southeastern Viti Levu; these rocks are associated with the porphyry copper, skarn, and epithermal-vein systems in the Namosi district.

Geologic Criteria

Permissive rocks for porphyry copper deposits include late Eocene-early Miocene island-arc volcanic rocks and intrusions related to the Vitiaz Arc, as well as late Miocene-Pliocene-Pleistocene rocks associated with post-collision arc magmatism and subduction reversal (stage 1 and 2 arcs of Petterson and others, 1999). Igneous rock ages are not well-constrained throughout the Melanesian islands. Calc-alkaline to alkaline intrusive and extrusive igneous rocks that are permissive for porphyry copper deposits are associated with both early and late phases of arc evolution. On Guadalcanal in the Solomon Islands, the Poha and Mbetilonga porphyry copper prospects are associated with Oligocene diorite-tonalite-andesite complexes; the Koloula porphyry copper deposit and epithermal gold prospects are associated with the Pliocene-Pleistocene Koloula Igneous Complex (mainly quartz diorite, tonalite, andesite) and eroded calderas. Permissive rocks on Vanuatu are confined to the western belt of the archipelago, where late Miocene diorite, microdiorite, and andesite stocks intrude Miocene volcanic rocks. In Fiji, porphyry-type prospects are associated with orogenic and post-orogenic magmatism on Viti Levu and with post-orogenic magmatism on Vanua Levu (Colley and Greenbaum, 1980).

The 2,700-km-long southeast-trending archipelagos that comprise the fragmented, Paleogene-Neogene Outer Melanesian Arc system south of Papua New Guinea are delineated as a single permissive tract for several reasons: (1) both early and late stages of arc evolution are preserved in close spatial proximity on some islands, (2) insufficient age information is available to subdivide the tract by age, (3) dioritic intrusions and andesitic volcanic rocks permissive for porphyry copper deposits occur throughout the evolution of the arc, (4) the likelihood of occurrence of undiscovered porphyry copper deposits is uniform throughout the tract area, and (5) the availability and quality of geologic mapping and mineral occurrence data is consistent throughout the study area. Because of the large extent of the tract, the arc is discussed in three segments: Solomon Islands, Vanuatu, and Fiji.

A preliminary permissive tract was delineated by compiling a master digital geology file of igneous rocks in a GIS. Source data included digital geologic data at 1:1,000,000 for the Solomon Islands and 1:250,000-scale data for the two main islands of Fiji, Viti Levu and Vanua Levu. Selected map units were digitized from georectified paper maps of islands within the Solomon and Vanuatu (New Hebrides) Archipelagos at scales ranging from 1:250,000 to 1:100,000. Detailed geologic map coverage is not available for all islands; where available, the more detailed maps were consulted and the units represented on those maps are listed in table V2. Each map unit was attributed by source, age, and lithology and coded as "permissive_extrusive" or "permissive_intrusive."

Permissive igneous rocks are present on islands that host Eocene-early Miocene stage 1 and (or) late Miocene-Pleistocene stage 2 island-arc rocks in the Solomon Islands (Petterson and others,1999) and in the late Oligocene to middle Miocene volcanic complexes of the western belt of Vanuatu (Mitchell and Warden, 1971).

In the Shortland Islands in the northernmost Solomon Islands, an older late Oligocene to early Miocene tholeiitic basement sequence is intruded by younger (probably pre-Pliocene) small calc-alkaline intrusions. These include the Tuana Microdiorite, Fauro Dacite, and Hisiai Complex (Turner and Ridgway, 1982).

In Vanuatu, igneous ages are not well-constrained; however, the igneous rocks of the western belt islands are mainly Miocene in age (Macfarlane and others, 1988). The oldest igneous rocks (possibly as old as 37–39 Ma) are reportedly the andesites on the Torres Islands; three early to early middle Miocene intrusive episodes are recognized on Espiritu Santo; and quartz diorite and microdiorite intrusions in northern Malekula have been dated at 20–14 Ma.

Permissive rocks in Fiji include 35–7 Ma pre- and syn-Colo (Tholo) orogeny tholeiitic and calc-alkaline rocks and 7–3 Ma post-orogenic rift-related alkaline and shoshonitic rocks. Synorogenic, elongate, tonalite-trondhjemite intrusions core anticlines formed during the late Miocene Tholo orogeny. Post-orogenic calc-alkaline volcanic rocks include the Namosi Andesite, Vatia Andesite, and Navosa Group, as well as alkaline/shoshonitic Plio-Pleistocene volcanic centers.

The tract excludes map units designated as nonpermissive for porphyry copper deposits [oceanic basement rocks, pillow basalts, ophiolite complexes, and oceanic basalts, such as occur on the easternmost Solomon Islands and in the central, active volcanic, and eastern block-faulted volcanic (>1,000 m thick) and ophiolite complexes of Vanuatu]. Many of the islands include sequences of mixed volcaniclastic-sandstone-limestone units that exceed 1,000 m in thickness. These cover rocks are excluded from the permissive tract because porphyry copper deposits are unlikely to be preserved within 1 km of the surface. Map units included as permissive rocks are listed in table V2.

Modern, reduced-to-pole aeromagnetic data are available for parts of western Vanuatu. Preliminary results were interpreted by the Vanuatu Mineral Exploration Initiative (Vanuatu Department of Geology, Mines, and Water Resources, 1995) as indicating the following: (1) high magnetic intensity associated with shallow (<500 m) and deep (>500 m) features correlates with mafic to intermediate complexes; (2) magnetic highs are associated with basalt flows, mafic dikes, and small, probably mafic, intrusive bodies and many of these areas are concealed; and (3) magmatic complexes are associated with northwest-trending (Malekula) to north-northwest-trending (Espiritu Santo) fracture and fault zones. A 1:1,000,000 page-size map of total magnetic intensity of south Espiritu Santo and Malekula was georectified and brought into a GIS for comparison with the geologic map. Most of mapped small intrusive bodies and prospect areas appear to coincide with magnetic low areas rather than magnetic highs. The texture of the aeromagnetic data suggests the presence of numerous small, circular, magnetic bodies in the shallow subsurface. The map-based tract boundaries were expanded to encompass these areas on western Espiritu Santo and Malekula.

Most of the intrusive units exposed throughout the Melanesian islands crop out as very small stocks, plugs, and dikes within andesites; some geologic maps simply indicate areas within volcaniclastic breccia-sedimentary units that contain abundant andesitic intrusions. Cross sections show the form of the many stocks as steep-sided, vertically extensive, pencil-shaped bodies. Intrusions in Malekula and western Espiritu Santo in Vanuatu are porphyritic. The final permissive tract was defined by using GIS tools to add a 2-km buffer around permissive extrusive map unit boundaries to account for uncertainty in mapping extensions beneath overlapping cover rocks or alluvium. The buffered tract boundaries were smoothed, edited, and clipped to a world shoreline data set (U.S. Department of State, 2009).

Known Deposits

The study area contains three Pliocene porphyry copper deposits (table V3): the 50 Mt Koloula deposit on Guadalcanal in the Solomon Islands and the 1.8 Gt Namosi and 23 Mt Waivaki deposits on Viti Levu, Fiji. No deposits are known in Vanuatu. The northern part of the Outer Melanesian in Papua New Guinea (tract 009pCu7207) contains the 1.4 Gt Pliocene Panguna deposit on Bougainville and the 165 Mt Miocene Arie deposit on Manus Island.

Solomon Islands

The 50 Mt Koloula deposit is associated with the multiphase Koloula Igneous Complex on Guadalcanal (fig. V2*A*). Koloula was discovered in 1967 by geophysical exploration and was characterized by 3 diamond drill holes by Utah International; the best drill intercept reported 114 m of 0.35 percent copper. The property was abandoned in 2002 and subsequently explored as part of Solomon Gold's Guadalcanal Joint Venture (Solomon Gold, 2010). The resource data cited by Singer and others (2008) dates from the 1970s and should be considered

Table V2. Map units that define tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[Map unit, age range, and principal lithologies are based on attributes in source maps cited; NA, not applicable; ?, no age indicated on map. Note ages are reported as listed on source maps. Ma, million years]

Map unit	Lithology	Age range	Source map	Source map scale
		Intrusive rocks		
		Solomon Islands		
NA	Intrusives & Plutonic Rocks	Eocene and Oligocene	Geological Survey Division of the Ministry of Natural Resources (1969)	1:1,000,000
Alpha	Minor basaltic and andesitic intrusives	Age unknown—Oligocene to Pliocene	Turner (1978)	1:100,000
D, Dh	Diorite (undifferentiated), hornblende diorite	?	Abraham and others (1987)	1:250,000
Delta	Hisiai complex (diorite)	Age unknown—Oligocene to Pliocene	Turner (1978)	1:100,000
Delta	Guadalcanal gabbro	Upper Mesozoic and Eocene	Institute of Geological Sciences, London (1978)	1:150,000
Delta 2	Tauna microdiorite	Age unknown—Oligocene to Pliocene	Turner (1978)	1:100,000
Delta 2	Delta 2	Delta 2	Institute of Geological Sciences, London (1978)	1:150,000
Delta 4	Koloula diorite	Plio-Pleistocene	Institute of Geological Sciences, London (1978)	1:150,000
Delta prime	Tiaro Bay Porphyrites	Plio-Pleistocene	Institute of Geological Sciences, London (1978)	1:150,000
Gm	Micro gabbro, olivine bearing	?	Abraham and others (1987)	1:250,000
Phi	Fauro dacite	Age unknown—Oligocene to Pliocene	Turner (1978)	1:100,000
T	Hornblende biotite tonalite	?	Abraham and others (1987)	1:250,000
		Vanuatu		
Alpha1	Ora-Navaka Complex	Lower Miocene	New Hebrides Geological Survey (1977)	1:100,000
Alpha2	Apuna Complex	Lower Miocene	New Hebrides Geological Survey (1977)	1:100,000
Alpha3	Woke Complex	Lower Miocene	New Hebrides Geological Survey (1977)	1:100,000
NA	Zones with numerous intrusion of various andesites; isolated dikes and other minor intrusions of andesite and basalt	Lower and middle Miocene	New Hebrides Geological Survey (1977)	1:100,000
TM1	Matanui Group containing abundant leucocratic hornblende andesite and microdiorite, mesocratic andesites and basalts as dikes, sills, and irrgegular intrusions	Tertiary	New Hebrides Geological Survey (1972)	1:100,000

Table V2. Map units that define tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).—Continued

Map unit	Lithology	Age range	Source map	Source map scale
		Intrusive rocks		
		Solomon Islands		
NA	Nakvaka Gabbro	Lower Miocene	New Hebrides Geological Survey (1977)	1:100,000
		Fiji		
SoA1	Yavuna Stock: Syn-Orogenic Intrusive Rocks, Tholo Plutonic suite, (predominantly tholeitic), First phase-Pre Miocene (>30 Ma)	33 Ma approximate K-Ar	Metallogenic map of Viti Levu (Mineral Resource Division, Fiji, 1978)	1:250,000
SoB2	Singatoka Stock: Syn-Orogenic Intrusive Rocks, Tholo Plutonic suite, (predominantly tholeitic), Second phase-late Miocene (~7-11Ma)	8 Ma approximate K-Ar	Metallogenic map of Viti Levu (Mineral Resource Division, Fiji, 1978)	1:250,000
NA	Hornblende andesite plugs and breccias	Early to mid-Pliocene	Geological Survey Department, Fiji (1965)	1:500,000
		Volcanic rocks		
		Solomon Islands		
NA	Volcanics mainly andesitic	Oligocene and Eocene (in part Mesozoic)	Geological Survey Division of the Ministry of Natural Resources (1969)	1:1,000,000
NA	Volcanics mainly andesitic	Pliocene	Geological Survey Division of the Ministry of Natural Resources (1969)	1:1,000,000
NA	Volcanics mainly basaltic	Pliocene	Geological Survey Division of the Ministry of Natural Resources (1969)	1:1,000,000
NA	Gallego Type Volcanics. Andesitic	Pleistocene	Geological Survey Division of the Ministry of Natural Resources (1969)	1:1,000,000
Ah	Hornblende andesite	Pleistocene	Abraham and others (1987)	1:250,000
Ahi	Gallego Type Volcanics. Hornblende andesite	Pleistocene	Abraham and others (1987)	1:250,000
Ahx-Box, Box-Ahx	Polymictic breccia with clasts of hornblende andesite	Plio-Pleistocene	Institute of Geological Sciences, London (1978); Dunkley and Philip (1986)	1:250,000
Ahy, Ahyx	Hypersthene andesite lava, breccia	?	Abraham and others (1987)	1:250,000
Alpha	Kamaleai pyroxene andesite	Age unknown—Oligocene to Pliocene	Turner (1978)	1:100,000

Table V2. Map units that define tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji). —Continued

Map unit	Lithology	Age range	Source map	Source map scale
		Volcanic rocks		
		Solomon Islands		
Alpha	Suta volcanics	Miocene-Oligocene	Institute of Geological Sciences, London (1978)	1:150,000
Alpha h	Hypersthene-augite high silica andesite	Pliocene	Abraham and others (1982)	1:100,000
Alpha hx	Andesitic tuff-breccia	Pliocene	Smith and others (1982)	1:100,000
Alpha i Beta x	Polymictic volcanic breccia; with andesite, basaltic andesite and basalt clasts	Pliocene	Smith and others (1982)	1:100,000
Alpha t	Andesite tuff; hornblende bearing	Pliocene	Smith and others (1982)	1:100,000
Alpha x	Andesitic volcanic breccia	Pliocene	Smith and others (1982)	1:100,000
BAhy-Ahy	Hypersthene basaltic and hypersthene andesite lava	Pleistocene and Pliocene	Booth and Strange (1987)	1:100,000
Beta	Mbiro volcanics	Upper Mesozoic	Institute of Geological Sciences, London (1978)	1:150,000
Beta Alpha x	Basaltic volcanic breccias with some andesitic volcanic breccias and tuffs	Pliocene	Abraham and others (1982)	1:100,000
i Alpha	Basaltic andesite and andesite lava, hornblende-phyric, brecciated in part	Pliocene	Smith and others (1982)	1:100,000
i Beta x	Basaltic andesite and basaltic volcanic breccia	Pliocene	Smith and others (1982)	1:100,000
		Vanuatu		
Tm	Volcaniclastic breccias and minor sandstones	Lower Miocene	New Hebrides Geological Survey (1977)	1:100,000
Tom	Torres Volcanics	Early Oligocene and early Miocene	New Hebrides Geological Survey (1975)	1:100,000
		Fiji		
NA	Natewa Volcanics: basic andesite to basalt brecia, flows, grits, tuffs	Late Miocene to early Pliocene (late or post-orogenic)	Geological Survey Department, Fiji (1965)	1:500,000

Table V3. Porphyry copper deposits in tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, gram per metric ton; n.d., no data. Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × Cu grade (%)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Grade				Contained Cu (t)	Reference
						Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)		
						Solomon Islands					
Koloula (Guadalcanal Joint Venture)	−9.797	160.022	NA	2.0	50	0.170	n.d.	n.d.	n.d.	85,000	Chivas (1978), Chivas and McDougall (1978), Chivas and Wilkins (1977), Lum and Calicutt (1989), United Nations (1985), Solomon Gold plc (2011)
						Fiji					
Namosi	−18.002	178.165	NA	5.6	1,792	0.370	0.014	0.120	n.d.	6,630,400	Andrew (1995), Colley and Flint (1995), Colley and Greenbaum (1980), Ellis and others (1997), Imai and others (2007), Legge (1998), Leggo (1977), Lum and Calicutt (1989), Spry (2007), Newcrest Mining Limited (2010)
Waivaka	−18.056	178.187	Cu-Au	n.d.	23	0.750	n.d.	0.250	n.d.	172,500	Colley and Flint (1995), Colley and Greenbaum (1980), Leggo (1977), Lum and Calicutt (1989)

preliminary; recent exploration indicates that the deposit is probably larger and gold-rich.

The Koloula Igneous Complex includes an older cycle of >2.5 Ma pyroxene andesite dikes, granodiorite, quartz diorite, and gabbro and a younger (1.7–2.4 Ma) cycle of quartz diorite, tonalite and pyroxene-hornblende andesite dikes (Chivas and McDougall, 1978). Hydrothermal alteration occurred from 4.5–1.4 Ma, making the Plio-Pleistocene deposit one of the youngest known island-arc porphyry systems (Chivas, 1978). The complex is exposed over a distance of 38 km^2. Copper is associated with two stages of hydrothermal alteration (A, potassic-propylitic and B, composite early potassic alteration overprinted by sericitic and chloritic) associated with late tonalite phases of the Imamumu Zoned Pluton. Disseminated and veinlet chalcopyrite and bornite occur with pyrite and magnetite in a quartz core in the mineralized intrusions. Molybdenite is present in molybdenite-pyrite-quartz veins centered on trondhjemite dikes that may post-date copper-gold mineralization (Chivas, 1978). Although no molybdenum or gold grades were available, gold is more important than molybdenum in the Koloula system, based on a range of metal ratios from drill core. The silver to gold ratio is about 14 (Chivas, 1978). The deposit formed at a depth of about 3 km; the depth of oxidation ranges from 10 to 50 m, and supergene enrichment is limited (Chivas, 1978; Chivas and Wilkins, 1977).

The Koloula deposit lies along a northeast-trending corridor that includes the Chikora porphyry, Koloula, the Sutakiki and Central prospect areas, and extends for 25 km from Koloula to the Gold Ridge epithermal gold deposit (fig. V2*A*). Drilling at the Chikora prospect in 2009 intersected disseminated copper and gold in potassically-altered porphyry.

Fiji

The Namosi district of Viti Levu includes the Waisoi area and the Waivaka Corridor (fig. V2C), where more than 15 major porphyry copper and gold prospects have been explored since the early 20th century (Imai and others, 2007). Porphyry copper prospects are associated with diorite and quartz diorite intrusions into late Oligocene to middle Miocene metamorphosed basaltic and andesitic rocks of the Wanimala Group and middle Miocene to Pliocene andesites and pyroclastic rocks of the Medrausucu Group (Namosi andesite). The main deposit in the Namosi district is at Waisoi, where two zones of bornite-chalcopyrite are recognized, Waisoi West and Waisoi East. Namosi is an advanced porphyry copper-gold exploration project on a 72,000 ha mining tenement on southern Viti Levu (Newcrest Mining Limited, 2010). The Namosi project includes Waisoi, where Newcrest Mining Limited holds probable reserves of 570 Mt at 0.43 percent copper and 0.14 g/t gold, and total resources (indicated and inferred) of 1,253 Mt at 0.37 percent copper and 0.12 g/t gold. These figures represent 70 percent of the ore reserves and resources of the deposit held by Newcrest (Newcrest Mining Limited, 2010).

The 6.7–5.8 Ma diorite porphyry intrusion associated with bornite-chalcopyrite zones in the Waivaka corridor is slightly younger than the 11.9–7.4 Ma K-Ar ages for diorite porphyry at Waisoi (Tanaka and others, 2010). Porphyry copper mineralization has not been identified at three other quartz diorite intrusions in the Namosi district. The 23 Mt Waivaka deposit is located about 7 km southeast of Waisoi. Geochemical studies comparing Waisoi and the Waivaka corridor intrusions suggest that crustal contamination and higher oxidation states in the Waivaka corridor magmas led to gold-poor porphyry systems in the Waivaka area (Tanaka and others, 2010).

Prospects, Mineral Occurrences, and Related Deposit Types

Porphyry copper prospects and mineral occurrences that may be associated with porphyry systems are listed in table V4.

Solomon Islands

Active exploration projects are targeting porphyry copper systems in the Solomon Islands on Fauro Island, in the New Georgia Islands, and on Guadalcanal (fig. V2A) The Ballyorlo prospect on Fauro Island is associated with the Pliocene (?) Fauro dacite. The porphyry target was identified by geochemical anomalies and an aeromagnetic high. The porphyry target is situated between epithermal gold targets that have been the focus of drilling to date (table V4). The Mase, Tirua, and Kele exploration targets on New Georgia Island are associated with Plio-Pleistocene multiphase porphyry intrusions and eroded andesitic stratovolcanoes. Drill intercepts with anomalous copper and gold grades are compatible with porphyry copper systems. The Poha and Mbetilonga prospects on Guadalcanal are associated with Oligocene intrusions. The Poha prospect was explored in 1997; 11 copper and (or) gold prospects were identified in association with altered diorite-tonalite. The Mbetilponga prospect, situated in a nested caldera, was explored in the 1970s and is currently within the Guadalcanal Joint Venture project targeting a low-grade, high tonnage porphyry copper deposit with a supergene-enriched cap (table V4).

Vanuatu

Copper- and iron sulfide-bearing porphyritic andesite and diorite intrusions (fig. V2B) up to 2 km across are present on Espiritu Santo (~25 Ma), Malekula, and in the Torres Islands (39 Ma) (Mitchell and Warden, 1971). Some of the composite fault-controlled high-level late Miocene intrusions in western Espiritu Santo and central and northern Malekula may represent upper parts of porphyry copper systems (Vanuatu Department of Geology, Mines, and Water Resources, 1995). Indications of porphyry mineralization include proximity of intrusions to major faults; association with oxidized, magne-

Table V4. Significant prospects and occurrences in tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[Rank 4=prospect in global database of Singer and others (2008) or >16,000 t contained copper; Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ppm, parts per million; Ma, million years]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
				Solomon Islands		
Ballyorlo	-6.869	156.066	Pliocene?	Fauro Island. Porphyry copper exploration target of Solomon Gold plc (2010). Trench results: 16 m at 450 ppm Cu. Aeromag high. Cu, Mo, Au, Se signature. Gold slightly anomalous in rock chips; high in BLEG samples.	Solomon Gold plc (2010)	2
Meriguna	-6.834	156.043	Pliocene?	Solomon Gold exploration target. Epithermal signature (Au-Ag-Cu-Te-As-Hg-Sb-Pb-Zn). Location = drill hole FDDH001 - drilled 2010, 9,900 m diamond drilling program; expected to intersect argillic-altered brecciated dacite porphyry, Gold-bearing quartz sulfide veins at surface. Trenching over 400 by 250 m area; up to 20 m at 4.3 g/t Au.	Solomon Gold plc (2010)	2
Kiovokase	-6.863	156.052	Pliocene?	Solomon Gold exploration target ~2 km W of Ballyorlo porphyry copper target on Fauro Island. Epithermal signature (Au-Ag-Cu-Te-As-Hg-Sb-Pb-Zn).	Solomon Gold plc (2010)	2
Fauro	-6.871	156.087	Pliocene?	Minor disseminations of sphalerite (?) and chalcopyrite in microdiorite on east central coast of Fauro Island. Minor occurrence in internediate intrusive rocks—possibly porphyry-type.	Geological Survey Division of the Ministry of Natural Resources (1980), United Nations (1985), Turner (1978)	1
Mase	-8.083	157.517	3.6 Ma	XDM Resources (2011): Porphyry Cu-Au system with overprinted epithermal Au within the Mase Caldera on northern New Georgia Island. Mineralized area >5 km^2. Along intersection of major arc normal and arc parallel structures. Initial drilling reported broad intersections of anomalous Au and Cu associated with reactivated intrusion margin structures. Assays up to 0.5 m of 4.02 g/t Au and 0.42% Cu. Gold in trench and float samples. Adjacent Pudakona crater may be a similar setting.	United Nations (1985) , XDM Resources (2011)	2
Tirua	-8.474	157.793	Plio-Pleistocene	XDM Resources (2011): Porphyry Cu-Au and epithermal system centered on a 15-km-wide caldera of a basaltic stratovolcano on southern New Georgia Island; 8 km of sector collapse; airborne magnetics and sampling indicate alteration zones up to 5 km^2. Previous drilling by Newmont indicated 62 m at 0.45% Cu; 3 m at 2.52 g/t Au. Anomalous Au in trenches and rock chip	XDM Resources (2011)	3

Table V4. Significant prospects and occurrences in tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).—Continued

Name	Latitude	Longitude	Age	Comments	Reference	Rank
				samples; 1 km long silica-pyrite ridge; Cu-Au-Mo soil anomalies correlate with magnetic high anomalies; Cu-Au porphyry type mineralization in a 10 km^2 hydrothermally altered area associated with magnetic lows.		
Kele	−8.753	158.074	Plio-Pleistocene	XDM Resources (2011): Porphyry Cu-Au and epithermal system within deeply eroded andesitic to balsaltic Kele stratovolcano assocated with muliphase porphyry intrusions (granodiorite, porphyry diorite, microdiorite) along long-lived arc normal and arc parallel fault intersections. Drill intercepts: 25 m of 0.15% Cu, 1.84 g/t Au and 53 m of 0.20% Cu and 0.80 g/t Au. Cu and Au in trench sampling.	XDM Resources (2011)	3
Hidden Valley	−9.367	159.733	2.6 Ma	Veins, shears, disseminations	United Nations (1985)	
Poha	−9.433	159.833	24.4 Ma	Diorite-tonalite 24.4 Ma age. Explored by Leigh Resources Corp. 1997: 11 Cu and/or Au prospects identified; heavy vegetation; altered diorite and volcaniclastic rocks; massive magnetite-pyrite-chalcopyrite skarn;	Chivas and McDougall (1978), Lum and Calicutt (1989), United Nations (1985), Leigh Resources Corporation (1998)	2
Mbetilonga (Guadalcanal Joint Venture)	−9.612	160.164	31.3 Ma	Exploration license area targeting low grade, high tonnage porphyry copper with a copper-rich oxide cap. Soil copper >0.1% Cu over an area of 3 km^2 outlines and trenched; 155 m at 1.33% Cu (2005). Prospect is within a large nested caldera structure 15 km S of Honiara, Guadalcanal. Exploration by Utah in 1970s showed widespread high Cu in soils; rock chip float samples with >1% Cu.	United Nations (1985)	2
				Vanuatu		
Espiritu Santo skarn prospect area 2	−15.442	166.818	n.d.	Fe-Cu skarn in andesite near gabbro; location digitized from S Santo 1:100K geologic map	New Hebrides Geological Survey (1977)	1
Espiritu Santo skarn prospect area 1	−15.467	166.827	n.d.	Fe-Cu skarn in andesite near gabbro; location digitized from S Santo 1:100K geologic map	New Hebrides Geological Survey (1977)	1
Espiritu Santo skarn prospect area 3	−15.386	166.803	n.d.	Fe-Cu skarn in andesite near gabbro; location digitized from S Santo 1:100K geologic map	New Hebrides Geological Survey (1977)	1

Table V4. Significant prospects and occurrences in tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).—Continued

Name	Latitude	Longitude	Age	Comments	Reference	Rank
N Malakula prospect area?	-15.999	167.254	n.d.	Porphyry copper-gold prospect :Island Arc Resources (Business Wire, 1997). Diorite intrusion with anomalous gold; up to 0.44 g/t gold in grab samples occurs two kilometers to the south. This trend lies four kilometers east of the Mt. Wingtar copper-gold porphyry prospect.	New Hebrides Geological Survey (1977), Business Wire (1997)	2
				Fiji		
Savundrondro Creek	-16.749	179.392	n.d.	Pyritic disseminated deposit, copper, porphyry-type	Mineral Resource Division, Fiji (1978b), Colley and Greenbaum (1980)	1
Vunda	-17.681	177.496	n.d.	Porphyry copper type; epigenetic, irregular or unknown form.	Mineral Resource Division, Fiji (1978a)	1
Tuvatu (Kingston Mine)	-17.696	177.599	Pliocene	Porphyry copper type; epigenetic, irregular or unknown form. Tuvatu : Low-sulfidation epithermal gold deposit on Viti Levu overprinting low-grade porphyry copper system.	Mineral Resource Division, Fiji (1978a), Lion One Metals (2011)	2
Tawaravi Creek	-17.702	177.530	n.d.	Porphyry copper type; epigenetic, irregular or unknown form.	Mineral Resource Division, Fiji (1978a)	1
Nuku	-17.798	178.207	n.d.	Porphyry type (orogenic); pyritic disseminated deposit.	Colley and Greenbaum (1980), Mineral Resource Division, Fiji (1978a)	1
Wainivau	-17.877	177.941	n.d.	Major disseminated mineral occurrence; porphyry type (orogenic).	Colley and Greenbaum (1980), Mineral Resource Division, Fiji (1978a)	1
Nathilenga	-17.995	177.366	n.d.	Porphyry type (orogenic); pyritic disseminated deposit.	Colley and Greenbaum (1980), Mineral Resource Division, Fiji (1978a)	1
Kule	-18.023	177.367	n.d.	Porphyry type (orogenic).	Colley and Greenbaum (1980), Mineral Resource Division, Fiji (1978a)	1
Rama Creek	-18.023	177.832	n.d.	Porphyry type (orogenic); disseminated.	Colley and Greenbaum (1980), Mineral Resource Division, Fiji (1978a)	1
Emperor	-17.509	177.855	Pliocene	Low-sulfidation epithermal gold deposit on Viti Levu overprinting low-grade porphyry copper system.	Mineral Resource Division, Fiji (1978a)	2

tite-bearing intrusions; alteration types (propylitic, sericitic, locally potassic); placer gold occurrences; anomalous copper, gold, and other base metals in stream sediments and soils; disseminations, stockworks and veins of pyrite±chalcopyrite pyrrhotite associated with intrusions; and gold-bearing skarns in limestone adjacent to intrusions. The western belt also is prospective for epithermal gold (prospects on Espiritu Santo, Malekula, and northern Efate) and for "Porgera-style" gold, described as gold in brecciated diorite porphyry without copper or porphyry-type alteration, in northwestern Espiritu Santo (Vanuatu Department of Geology, Mines, and Water Resources, 1995).

Fiji

In their study of mineral deposits of the Fiji platform, Colley and Greenbaum (1980) described 11 prospect areas as porphyry-type [10 on Viti Levu including the Waivaka and Namosi (Waisoi) deposits, and one prospect on Vanua Levu] in addition to a number of copper skarn and epigenetic vein occurrences. Low-sulfidation epithermal gold deposits overprint low-grade porphyry copper systems at the Emperor and Tuvatu deposits on Viti Levu (fig. V2C). These systems lie along the Viti Levu lineament, a prominent east-northeast-trending structure formed by extension related to onset of Vanuatu Trench subduction that extends to Vanua Levu and localizes 7 Pliocene shoshonitic and high-K calc-alkaline volcanic centers (Spry and others, 2003). The three major epithermal gold deposits of Fiji lie along the lineament. The low-sulfidation epithermal gold deposits at Emperor and Tuvatu on Viti Levu are related to monzonite intrusions that host low-grade porphyry copper systems; the high-sulfidation epithermal Mount Kasi deposit on Vanua Levu is not known to be associated with a porphyry system (Scherbarth and Spry, 2006).

Exploration History

The Solomon Islands were mapped and explored by the British Geological Survey prior to independence of the nation in 1980. Guadalcanal was prospected for alluvial gold in the 1930s. Geochemical reconnaissance surveys of beach sands and stream sediments were done as part of the 1965–68 United Nations Development Program, which also produced a 1:2,000,000-scale atlas of prospects and mineral occurrences (United Nations, 1985). Utah Development Company explored Guadalcanal from 1969 to 1974 (Chivas, 1978). Exploration throughout the 1990s led to development of an epithermal gold deposit that went into production as the Gold Ridge Mine on Guadalcanal in 1998. Political and ethnic violence in 2000 led to mine closure and cessation of exploration activities (Lyday, 2001); Gold Ridge was scheduled to reopen in 2011. Since 2005, exploration for epithermal gold and porphyry copper-gold targets in the Solomon Islands has increased, and some areas identified in the 1990s are being revisited, such as the Mbetilonga and Koloula intrusive complexes on Guadalcanal and Fauro Island in the Shortland Islands.

Decline in copper prices in the 1960s, followed by periods of political change (independence for the Solomon Islands and Vanuatu in 1980), subsequent periods of political and social unrest, and disruptions caused by earthquakes and tsunamis have had a negative impact on mineral exploration and development. However, since approximately 2005, exploration activity in the Solomon Islands has increased, and drilling operations were initiated at a number of prospects in 2010.

Placer Pacific explored the Waisoi area of Fiji from 1991 to 1995, completed a feasibility study, and delineated a total resource of 900 Mt at 0.43 percent copper and 0.14 g/t gold as amenable to open-pit mine development. Subsequent exploration in the district in the 2000s identified an 8 by 1.5 km corridor of porphyry copper-gold mineralization at Waivaka, about 7 km south of Waisoi.

Sources of Information

Most of the data used for the assessment was derived from published geologic maps, journal articles, and Web searches for recent information on exploration activities.

The British Geological Survey (BGS) participated in United Nations Development Programs in the Solomon Islands in the 1960s and completed mapping and geochemical sampling projects from 1976 to 1983, which produced 1:100,000-scale maps of some islands and identified epithermal gold exploration targets. Bibliographic references to Solomon Islands project results, including references to unpublished reports that were not readily available for this study, are cited at http://www.bgs.ac.uk/geochemcd/solomon/sol6.htm.

Information on mining and geology in Fiji, including mining tenement and mineral prospect locations maps is available on-line from the Mineral Resources Department Web site (http://www.mrd.gov.fj/gfiji/).

Data sources used in this assessment are listed in table V5.

Grade and Tonnage Model Selection

The three known deposits in the permissive tract area (table V3) fit either a general model or a copper-gold subtype model based on t-tests of reported tonnages and grades (table 6). Waivaka is classified as a copper-gold porphyry deposit based on an average gold grade of 0.25 g/t gold. Namosi, with an average reported grade of 0.14 g/t gold and 0.014 percent molybdenum, falls within the Au/Mo ratio range that Singer and others (2008) defined as the grade range for the general type of porphyry copper deposit. No gold or molybdenum grades are reported for Koloula. Porphyry copper deposits in island-arc settings tend to be gold-rich (Kesler, 1973). Based on the geologic setting, available gold

Table V5. Principal sources of information used for tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[NA, not applicable]

Theme	Map or title	Scale	Citation
Geology	Geology of the British Solomon Islands	1:1,000,000	Geological Survey Division of the Ministry of Natural Resources (1969)
	Geological map of Guadalcanal	1:150,000	Institute of Geological Sciences, London (1978)
	Geology of New Georgia Group,	1:250,000	Abraham and others (1987)
	New Georgia Geological Map Sheet NG 6	1:100,000	Dunkley and Philip (1986)
	New Georgia Geological Map Sheet NG 7	1:100,000	Booth and Strange (1987)
	New Georgia Geological Map Sheet NG 1	1:100,000	Smith and others (1982)
	Shortland Islands Geological Map Sheet SH 1A	1:100,000	Turner (1978)
	Geology of Ranongga, Simbo, and Ghizo Islands	1:100,000	Abraham and others (1982)
	Geology of Malekula	1:100,000	New Hebrides Geological Survey (1972)
	Geology of South Santo	1:100,000	New Hebrides Geological Survey (1977)
	Geology of the Torres Islands	1:100,000	New Hebrides Geological Survey (1975)
	Geological map of the New Hebrides Condominium	1:1,000,000	British Directorate of Overseas Surveys (Mallick, 1975)
	Geological map of Fiji	1:500,000	Geological Survey Department, Fiji (1965)
	Reconnaissance geology of Vanua Levu	1:200,000	Geological Survey Department ,Fiji (1963)
	Metallogenic map of Viti Levu and Vanua Levu	1:250,000	Mineral Resource Division, Fiji (1978a,b)
Geophysics	Aeromagnetic map of southern Espiritu Santo and Malekula, Vanuatu	1:1,000,000	Vanuatu Department of Geology, Mines, and Water Resources (1995)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Mineral occurrences map of the British Solomon Islands	1:1,000,000	Geological Survey Division of the Ministry of Natural Resources (1980)
	Metallic mineral deposits of Fiji	NA	Colley and Greenbaum (1980)
	Solomon Islands Atlas of Mineral Resources	1:2,000,000	United Nations (1985)
	Fiji mineral occurrences	1:250,000	Mineral Resource Division, Fiji (1978a,b)
Exploration	Solomon Islands exploration	NA	Solomon Gold (2010)
	Vanuatu exploration	NA	Vanuatu Department of Geology, Mines, and Water Resources (1995)
	Fiji exploration	NA	Lion One Metals (2011), Newcrest Mining Limited (2010)

Table V6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; km², area of permissive tract in square kilometers; N_{total}/100k km², deposit density reported as the total number of deposits per 100,000 km². N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km²)	Deposit density (N_{total}/100k km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
1	5	10	10	10	5.2	3.2	61	3	8.2	38,180	21

Table V7. Results of Monte Carlo simulations of undiscovered resources for tract 009pCu7210,Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji).

[Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	480,000	9,100,000	40,000,000	60,000,000	16,000,000	0.32	0.07
Mo	0	0	21,000	270,000	470,000	92,000	0.24	0.23
Au	0	47	760	2,900	3,800	1,200	0.35	0.07
Ag	0	0	1,700	12,000	24,000	5,100	0.23	0.17
Rock	0	120	1,900	8,400	11,000	3,200	0.33	0.07

grades, proximity of many prospects to epithermal gold systems, statistical tests, and consistency with the model used for the Outer Melanesian Arc—Papua New Guinea tract (009pCu7207), the copper-gold subtype grade and tonnage model was selected as the appropriate model for the simulation of undiscovered resources.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The permissive tract contains three known porphyry copper deposits, 23 prospects (10 in the Solomon Islands, four in Vanuatu, nine in Fiji), four epithermal gold deposits, and additional epithermal gold prospects that may be associated with porphyry copper deposits at depth. Based on the prospect rankings listed in table V4, two prospects have drill-indicated intercepts of reasonable copper grades (rank 3); nine prospects have active or past exploration (rank 2), and more than 10 copper occurrences may be porphyry-related (rank 1).

The area is well-mapped and was explored in reconnaissance fashion in the 1960s. Exploration continues to expand the identified resources in the Namosi district, Fiji. Namosi, at the southern end of the permissive tract, and Panguna, in the adjoining tract to the north, are major porphyry copper deposits; the presence of these two deposits is an indication of resource potential within the overall arc system. Andesitic volcanic rocks are the dominant lithology exposed throughout the tract; intrusions mainly are small, steep-sided, stocks and dikes that intrude the volcanic rocks indicating that most of the tract area is at an appropriate level of depth of erosion where exposed intrusions may represent tops of porphyry systems. In addition, deposits may be preserved under shallow volcanic cover. Some prospects are associated with deeply eroded stratovolcanoes. The geologic setting of the tract, an area of protracted magmatism, arc reversal, and large-scale faulting and extension, is similar to other areas of the southwestern Pacific where numerous porphyry copper deposits have been found. The tract area and aspects of the geologic setting are similar to the Luzon Arc of the Philippines, which hosts 14 porphyry copper deposits.

On the basis of the available data, the team estimated a 90-percent chance of one or more undiscovered deposits, a 50-percent chance of five or more undiscovered deposits, and a 10-percent chance of 10 or more undiscovered deposits within the tract area (table V6). Preliminary drilling results for the Triua, Kele, and Mbetilonga prospects in the Solomon Islands (table V4) indicate that further characterization may lead to delineation of deposits. In addition, several other exploration target areas have favorable geochemical signatures. The abundance of small intrusions, hydrothermal alteration, and copper skarns in southern Espiritu Santo, Vanuatu, indicates a potential for a porphyry system. A porphyry prospect was explored on Malekula prior to 1997, but the location and results are not available. The presence of nine geographically dispersed porphyry-type prospects as well as the two porphyry systems associated with epithermal gold deposits at Emperor and Tuvatu are favorable factors for discovery of additional deposits.

The mean number of undiscovered deposits in the tract is 5.2, with a low coefficient of variation of 61 percent (table V6).

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the global porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected output parameters are reported in table V7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. V3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. Note that the estimates and simulation results apply to the entire tract, including all three sub-tract areas.

The mean amount of copper associated with undiscovered deposits in the tract is 16,000,000 metric tons; the median is 9,100,000 metric tons. The median value represents about twice the amount of identified copper resources (4,450,000 metric tons) in the three known deposits. The undiscovered estimate does not include extensions to identified resources; given that all three known deposits are undergoing additional exploration in 2011, the identified resources at known deposits are likely to increase in the near future.

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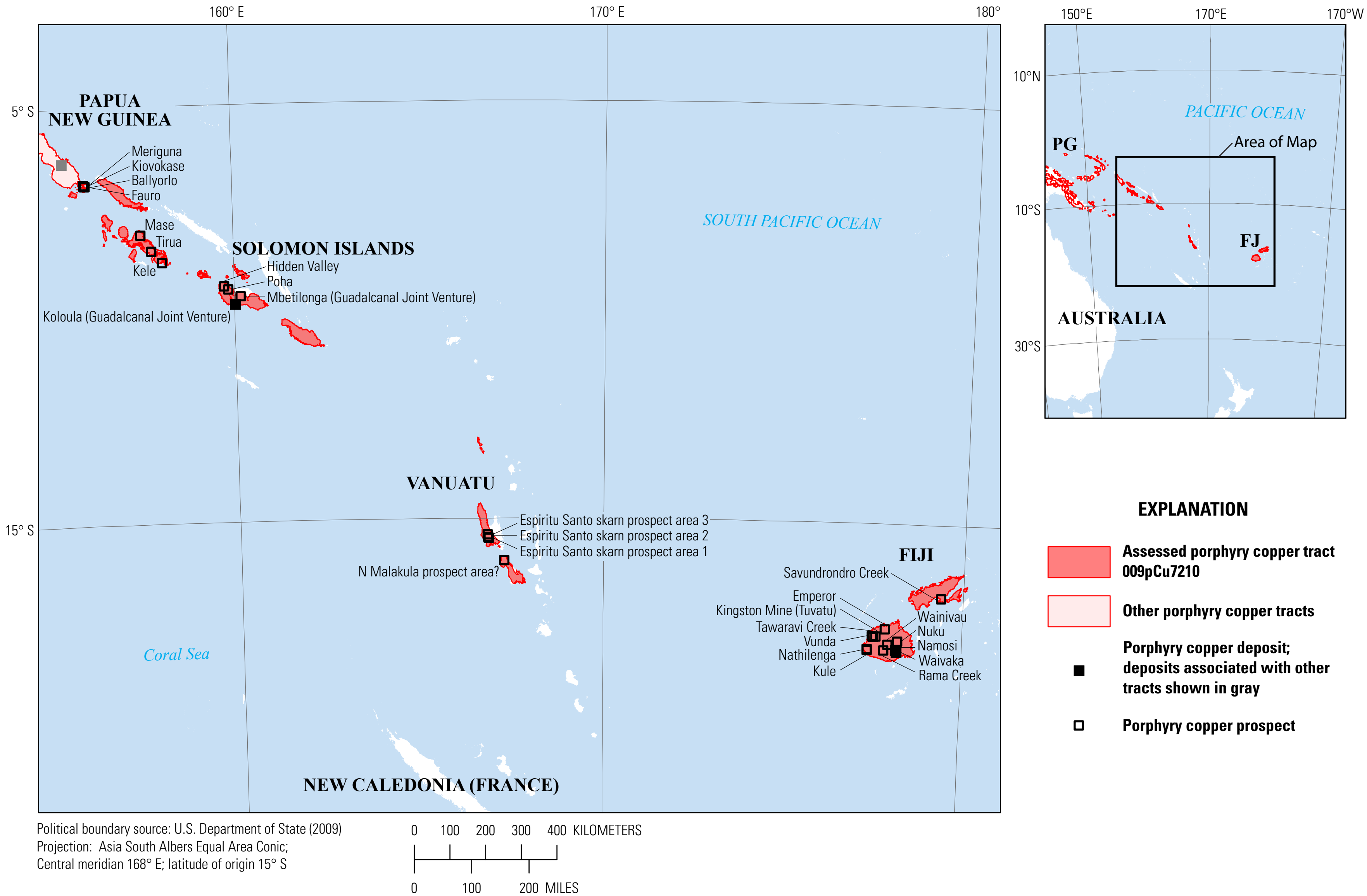
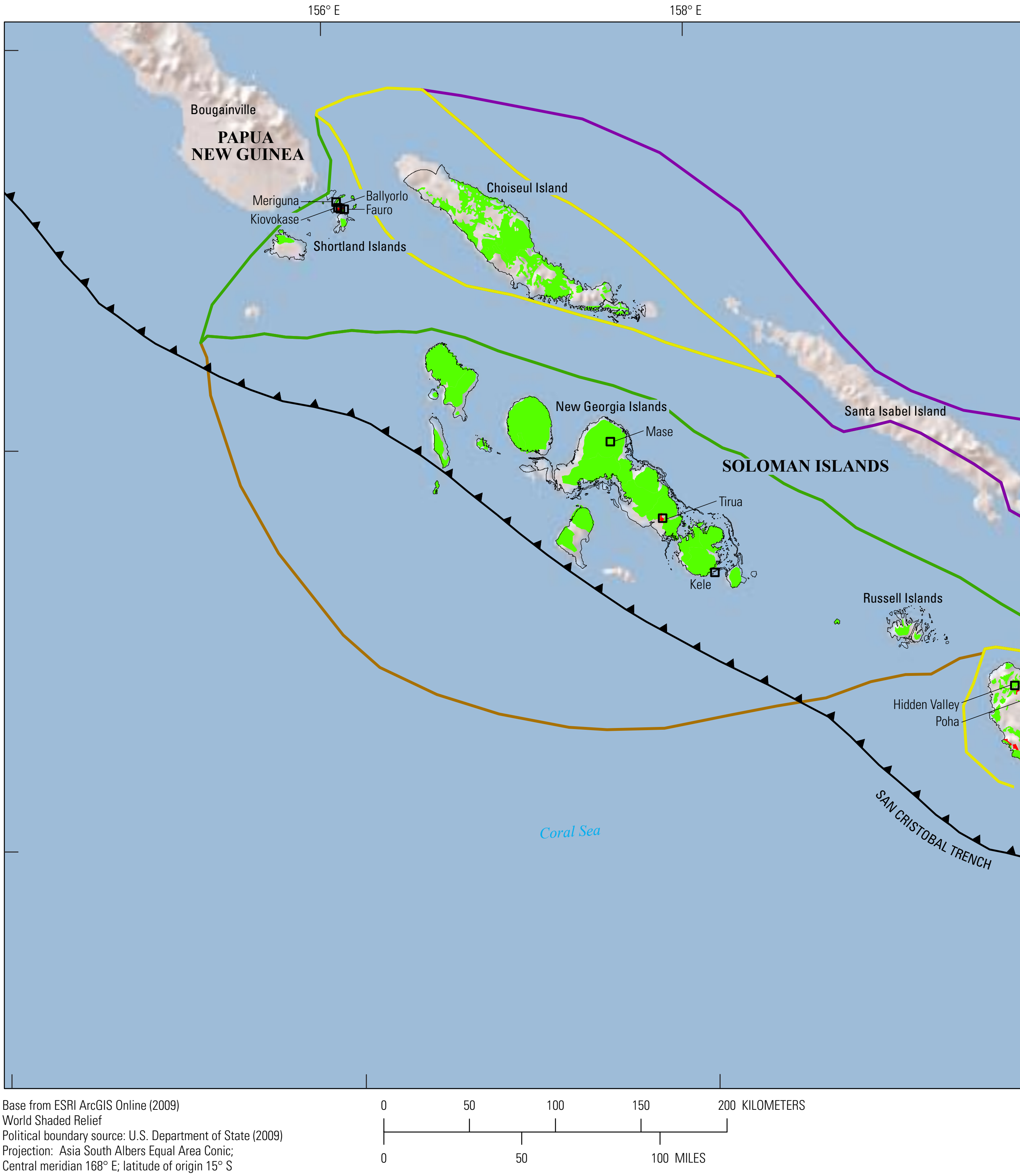


Figure V1. Map showing the location, known deposits, and significant prospects and occurrences for of permissive tract 009pCu7210, Outer Melanesian Arc I—Melanesia (Solomon Islands, Vanuatu, and Fiji). FJ, Fiji; PG, Papua New Guinea



Base from ESRI ArcGIS Online (2009)
World Shaded Relief
Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 168° E; latitude of origin 15° S

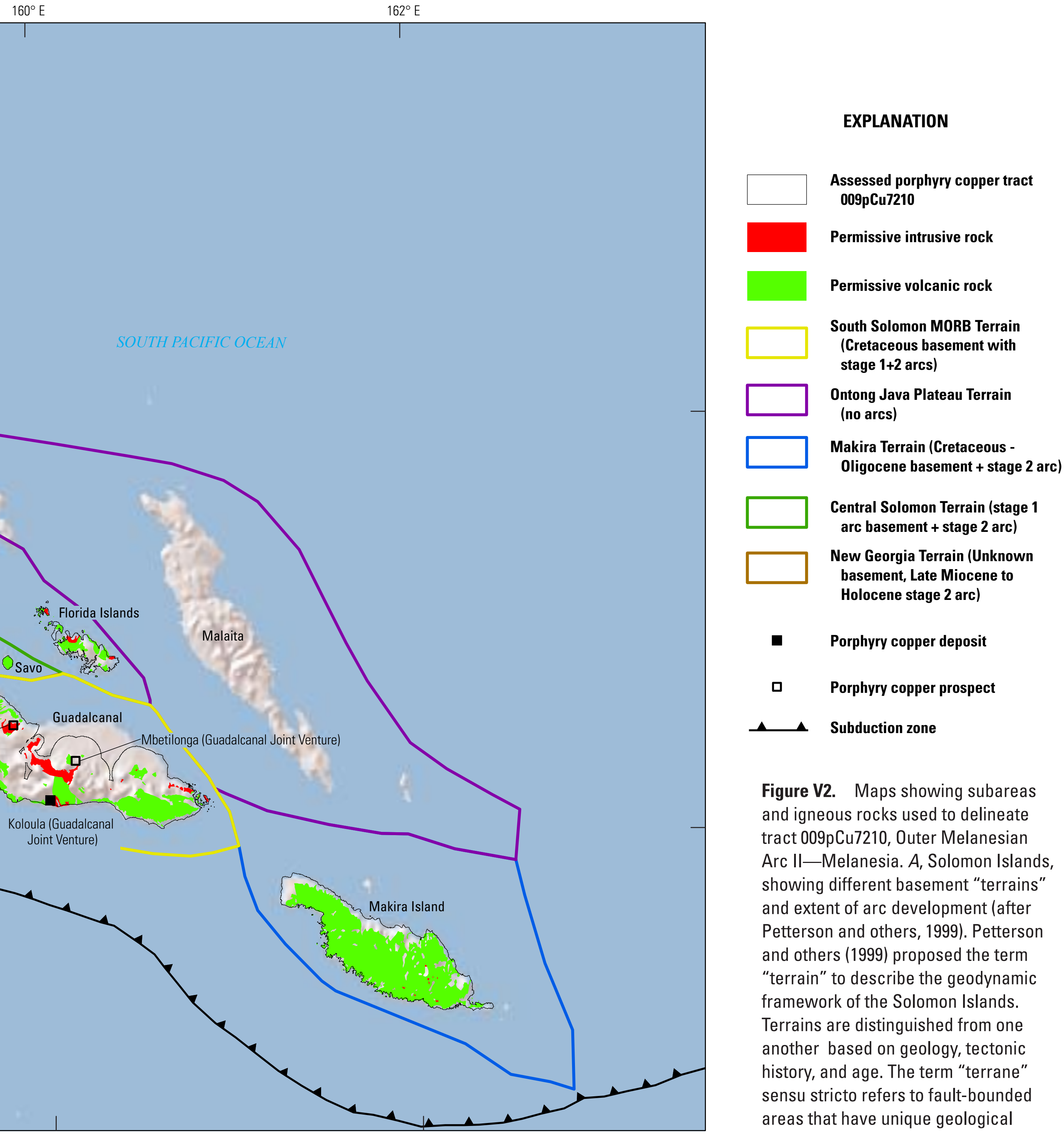
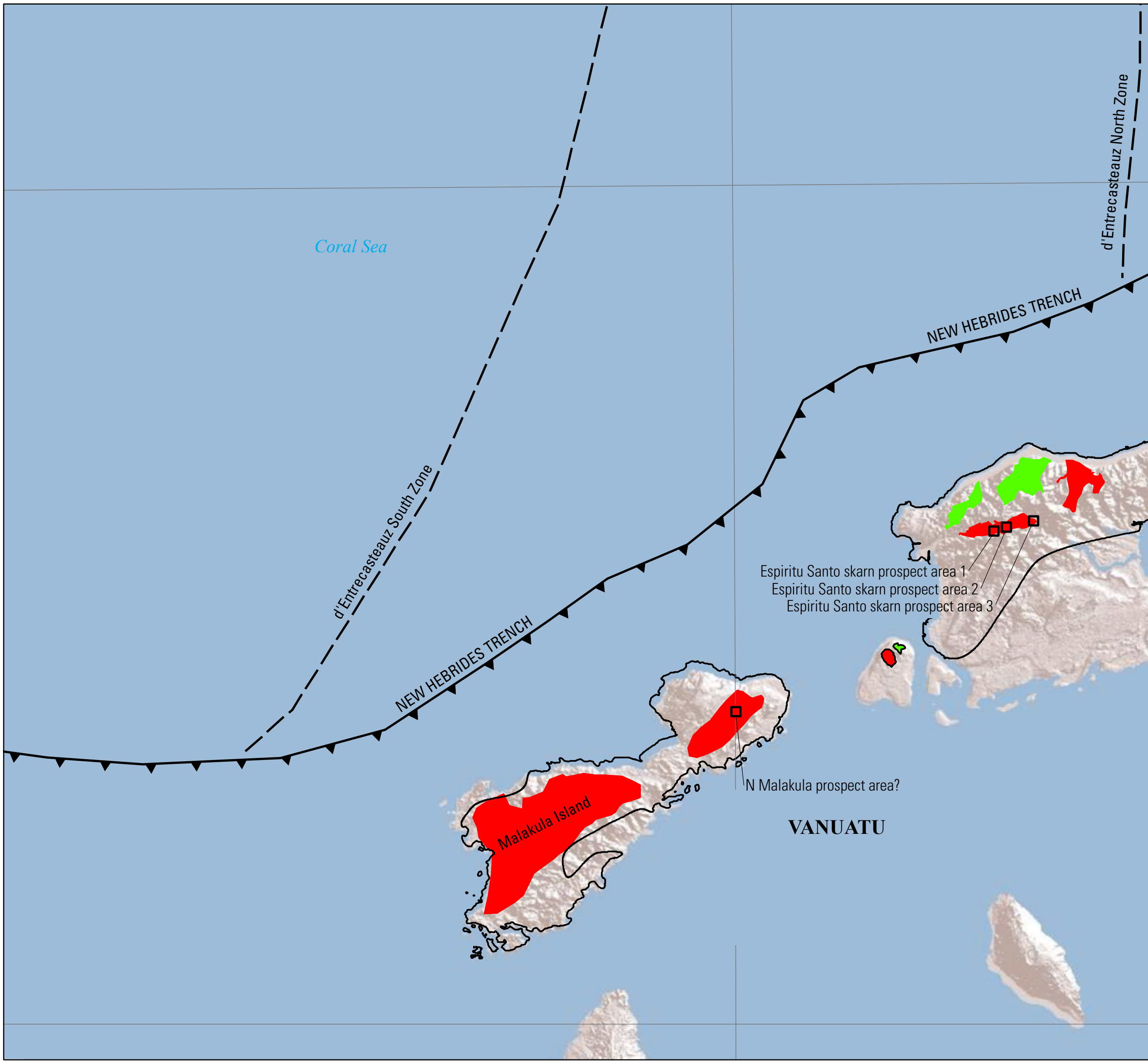


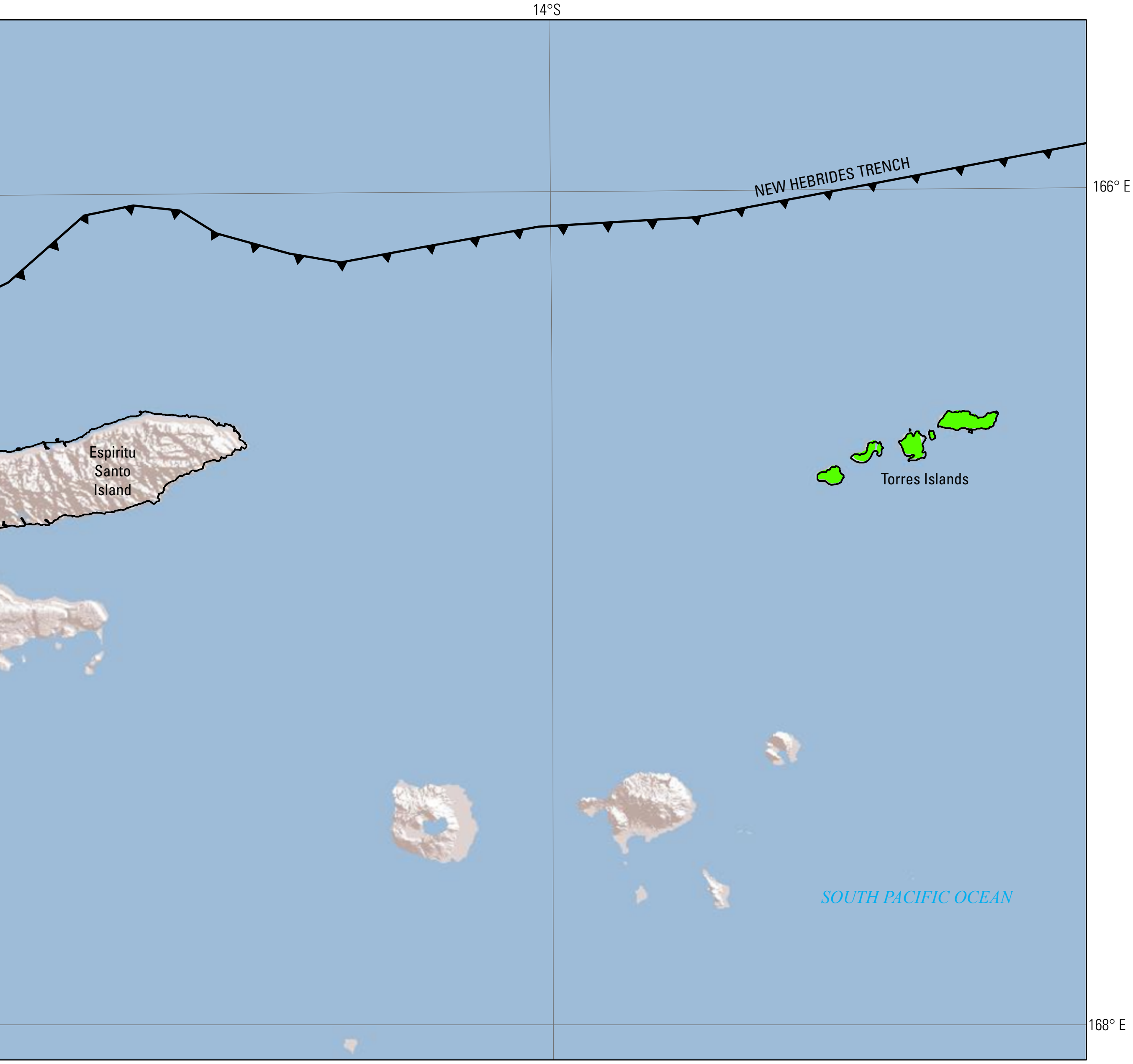
Figure V2. Maps showing subareas and igneous rocks used to delineate tract 009pCu7210, Outer Melanesian Arc II—Melanesia. *A*, Solomon Islands, showing different basement "terrains" and extent of arc development (after Petterson and others, 1999). Petterson and others (1999) proposed the term "terrain" to describe the geodynamic framework of the Solomon Islands. Terrains are distinguished from one another based on geology, tectonic history, and age. The term "terrane" sensu stricto refers to fault-bounded areas that have unique geological histories. *B*, Vanuatu. *C*, Fiji.

B

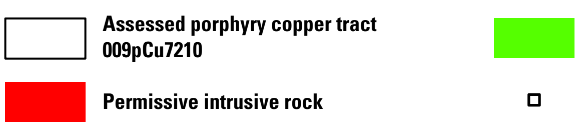


Base from ESRI ArcGIS Online (2009)
World Shaded Relief
Political boundary source: U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 168° E; latitude of origin 15° S

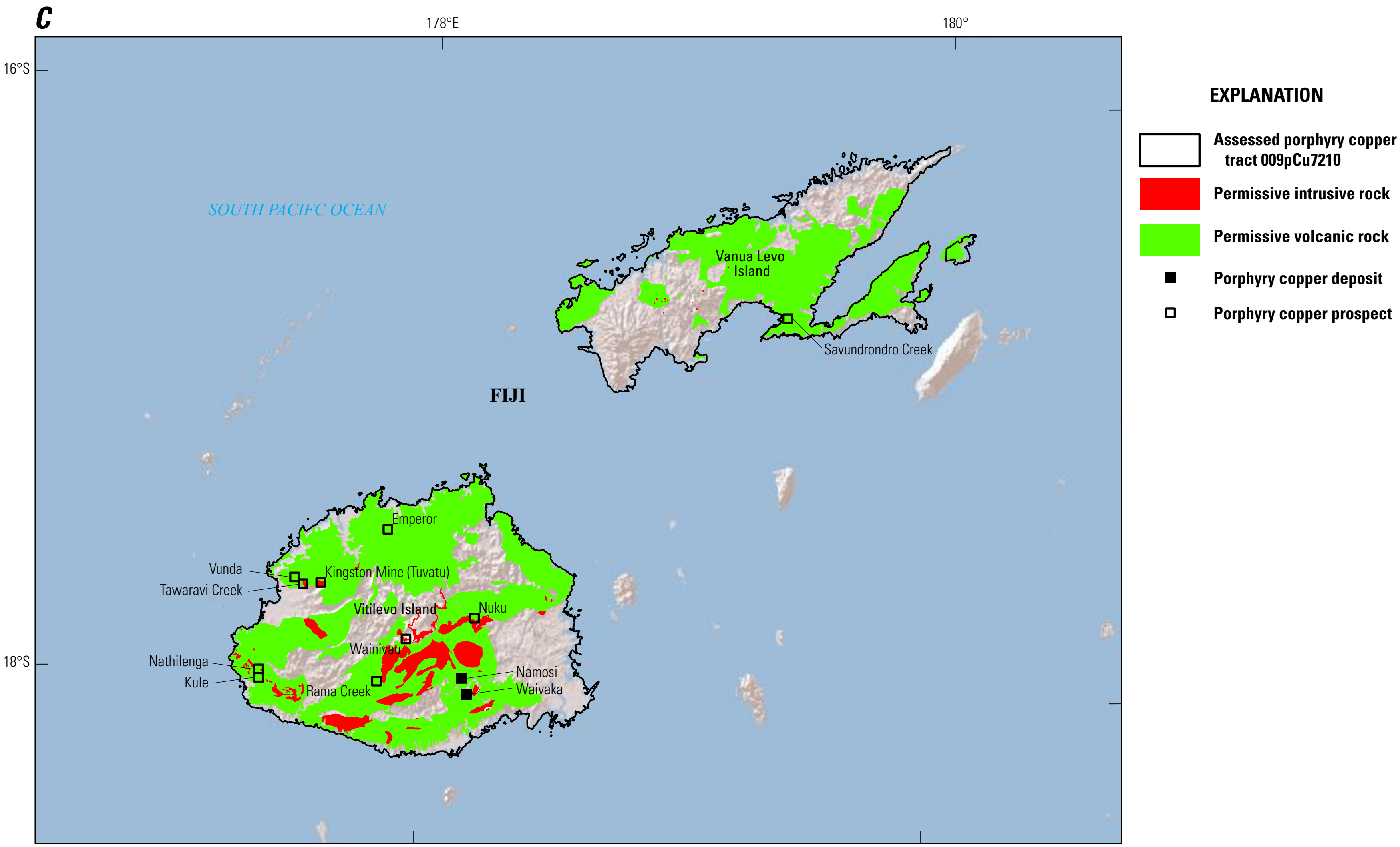
Figure V2.—Continued



EXPLANATION



- Assessed porphyry copper tract 009pCu7210
- Permissive volcanic rock
- Permissive intrusive rock
- Porphyry copper prospect



Base from ESRI ArcGIS Online (2009)
World Shaded Relief
Political boundary source U.S. Department of State (2009)
Projection: Asia South Albers Equal Area Conic;
Central meridian 168° E; latitude of origin 15° S

0 25 50 75 100 KILOMETERS
0 25 50 MILES

Figure V2.—Continued

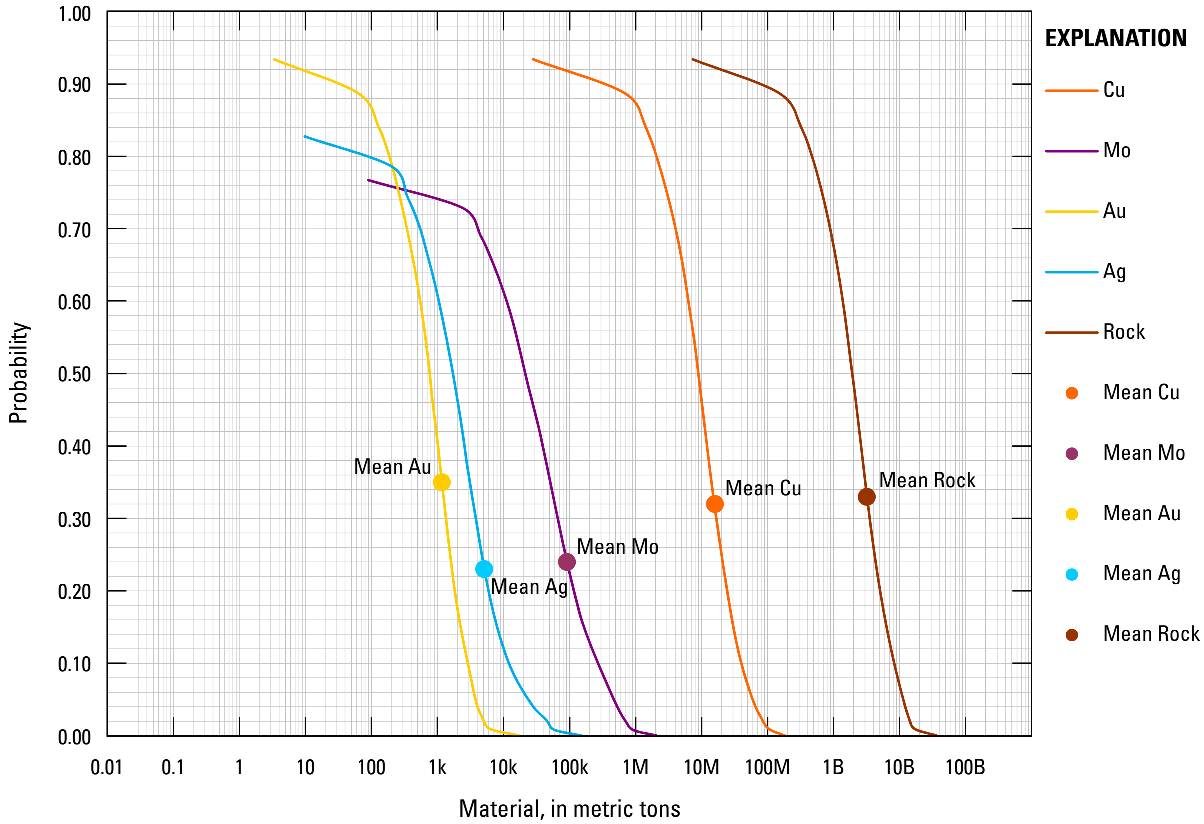


Figure V3. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 009pCu7210, Outer Melanesian Arc II—Melanesia (Solomon Islands, Vanuatu, and Fiji). k, thousands; M, millions; B, billions; Tr, trillions.

Appendix W. Description of GIS Files

Three ESRI shapefiles (.shp) and an ESRI map document (.mxd) are included with this report. These may be downloaded from the USGS Web site as zipped file **GIS_SIR5090-D.zip**.

The shapefiles are as follows:

SE_Asia_pCu_Tracts.shp is a shapefile of the permissive tracts. Attributes include the tract identifiers, tract name, a brief description of the basis for tract delineation, and assessment results. Attributes are defined in the metadata that accompanies the shapefile.

Probabilistic assessment results are included in two tables in the GIS project. Results table 1 shows quantiles for each tract. Results table 2 shows the mean amount for each commodity by tract. Note that separate results are included for sub-tracts of the Eastern Medial New Guinea magmatic belt (009pCu7203a and 009pCu7203b) and for sub-tracts of the Sunda-Banda Arc (142pCu7205a, 142pCu7205b, and 142pCu7205c). For the Outer Melanesian Arc II, a single assessment was made (reported as 009pCu7210) in the tables; the assessment applies to the three geographically separate areas that comprise the tract.

SE_Asia_pCu_Deposits_prospects.shp is a shapefile of point locations for known deposits (identified resources that have well-defined tonnage and copper grade) and prospects. Shapefile attributes include the assigned tract, alternate site names, information on grades and tonnages, age, mineralogy, associated igneous rocks, site status, comments fields, data sources and references. Attributes are defined in the metadata that accompanies the shapefile. Note that tonnage and grade information are numeric fields; entries of -9999 in these fields mean that no data are available. Entries of 0 in the Age_Ma field mean that no data are available.

SE_Asia _political_boundaries.shp is a shapefile showing the outline of the study area and the countries within and adjacent to the study area. The shapefile is extracted from the country and shoreline boundaries maintained by the U.S. Department of State (2009).

These three shapefiles are included in an ESRI map document (version 9.3): **GIS_SIR5090-D.mxd**.

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Appendix X. Assessment Team

Arthur A. Bookstrom, USGS Western Mineral and Environmental Resources Science Center, Spokane, Wash., United States. Economic geologist with expertise on porphyry copper and mineral resource assessment.

Dennis P. Cox, USGS Emeritus Scientist. Economic geologist with expertise on porphyry copper and mineral resource assessment.

Connie L. Dicken, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. GIS task leader for the USGS Global Mineral Resource Assessment Project.

Benjamin J. Drenth, USGS Central Mineral and Environmental Resources Science Center, Denver, Colo., United States. Geophysicist, USGS Global Mineral Resource Assessment Project.

Jane M. Hammarstrom, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. Co-chief, USGS Global Mineral Resource Assessment Project since 2007. Task leader, porphyry copper assessment.

Pairatt Jarnyaharn, CCOP representative for Thailand at the 2005 project workshop, is a geologist with the Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.

Gwaibo Kopi, CCOP[1] representative for Papua New Guinea.

Steve Ludington, USGS Western Mineral and Environmental Resources Science Center, Menlo Park, Calif., United States. Economic geologist with expertise on porphyry copper and mineral resource assessment.

Gilpin R. Robinson, Jr., USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. Dr. Robinson is a geologist, geochemist, and mineral-resources specialist working on mineral resource assessment and other projects, including geologic mapping, studies of the origin and genesis of metal and industrial-mineral deposits, and geochemical modeling.

Nguyen Thi Minh Ngoc, CCOP[1] representative for Vietnam at the 2010 Pusan workshop, serves as Officer of International Cooperation Division of the Department of Geology and Minerals of Vietnam in Hanoi, Vietnam.

Pichai Otarawanna, CCOP[1] representative for Thailand at the 2005 project workshop, geologist with the Thai Department of Mineral Resources, Bangkok, Thailand.

Chen Shick Pei, Director of the CCOP[1] Technical Secretariat in 2006. Former Director General of the Geological Survey of Malaysia.

Ung Phany, CCOP[1] representative for Cambodia at the 2010 Pusan workshop, Director, Cambodian National Petroleum Authority, Phnom Penh, Cambodia.

Nguyen Vay Quy, CCOP[1] representative for Vietnam, Department of Geology and Minerals, Hanoi, Vietnam.

Takehiro Sakimoto, CCOP[1] representative for Thailand, Senior Geologist at the Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.

Dulcie Saroa, CCOP[1] representative for Papua New Guinea at the 2010 Pusan workshop. Acting Manager, Geological Mapping and Mineral Exploration Branch, Geological Survey Division, Mineral Resources of Papua New Guinea, Port Moresby, Papua New Guinea.

Norberta Soares da Costa, CCOP[1] representative for Timor-Leste, Director of Geology and Mineral Resources, Secretary of State for Natural Resources, Dili, Timor-Leste.

Bambang Tjahjono Setiabudi, CCOP[1] representative for Indonesia, former Head of the Technical Support Division, Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia. Dr. Setiabudi has authored numerous papers on the geology and mineral deposits of Indonesia.

I.M. Sim, CCOP[1] representative for Cambodia, Department of Geology and Mines, Phnom Penh, Cambodia.

Sieng Sotham, CCOP[1] representative for Cambodia, Department of Geology and Mines, Phnom Penh, Cambodia.

Wudhikarn Sukserm, CCOP[1] representative for Thailand, is the Senior Geologist at the Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.

Dwi Nugroho Sunuhadi, CCOP[1] representative for Indonesia is the Senior Geologist at the Center for Geological Resources, Geological Agency of Indonesia, West Java, Indonesia.

Alexander Yan Sze Wah, CCOP[1] representative for Malaysia, is Director of the Minerals and Geoscience Department of Malaysia, Sabah, Malaysia. He participated in all of the project workshops.

Nguyen Nhu Trung, CCOP[1] Technical Secretariat, Geo-Resources Sector Coordinator, Bangkok, Thailand.

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[1]Coordinating Committee for Geoscience Programmes in East and Southeast Asia.

Somob Wongsomasak, CCOP[1] representative for Thailand at the 2005 project workshop, geologist with the Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.

Sewit Yenie, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. GIS and drafting assistant.

Boonsong Yokartt, CCOP[1] representative for Thailand at the 2005 project workshop, geologist with the Royal Thai Government Department of Mineral Resources, Bangkok, Thailand.

Khin Zaw, Professor, ARC Centre of Excellence in Ore Deposits, University of Tasmania. Khin Zaw is the author of numerous reports, including AMIRA projects reports on the geology, tectonics and metallogeny of Southeast Asia.

Michael L. Zientek, USGS Western Mineral and Environmental Resources Science Center, Spokane, Wash., United States. Co-chief, USGS Global Mineral Resource Assessment Project since 2007.

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