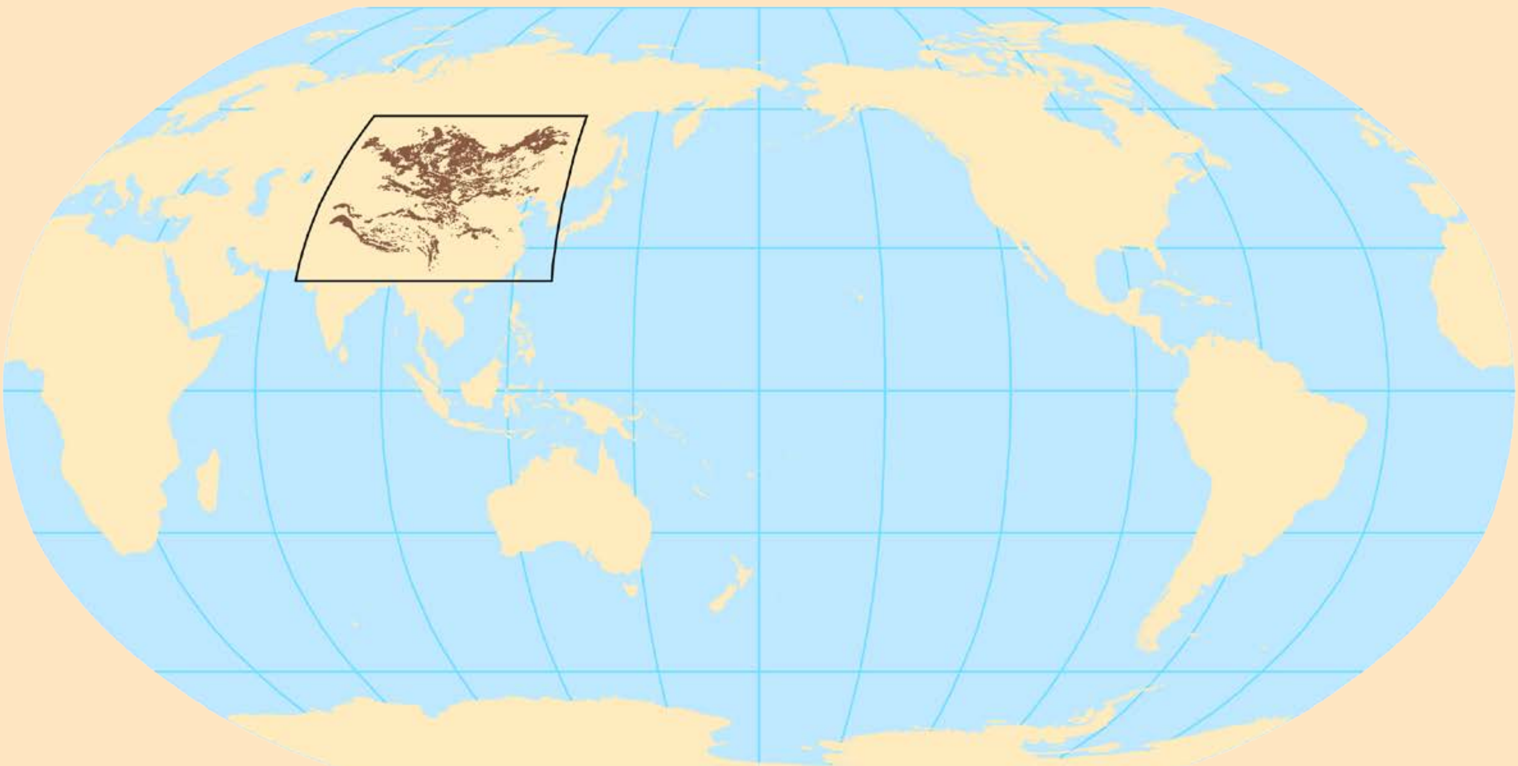
Global Mineral Resource Assessment

Porphyry Copper Assessment of the Central Asian Orogenic Belt and Eastern Tethysides—China, Mongolia, Russia, Pakistan, Kazakhstan, Tajikistan, and India



Prepared in cooperation with the China Geological Survey, the Centre for Russian and Central EurAsian Mineral Studies, and the Russian Academy of Sciences

Scientific Investigations Report 2010–5090–X

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

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

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U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors, Abbreviations and Acronyms, and Chemical Symbols

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
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, avoirdupois (oz)	28.35	gram (g)
ounce, troy (troy oz)	31.015	gram (g)
ounce, troy (troy oz)	0.0000311	megagram (Mg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	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)
kilograms (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	32,151	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

Multiply	By	To obtain
metric ton (t)	1	megagram (Mg)
troy ounce per short ton	34.2857	gram per metric ton (g/t)
percent (%)	10,000	part per million (ppm) or grams per metric ton (g/t)
percent metal	0.01 × metal grade, percent × ore tonnage, metric tons	metric tons of metal

Acronyms and Abbreviations Used

ANOVA	analysis of variance
CIS	Commonwealth of Independent States
GIS	geographic information system
g/t	grams per metric ton
kt	thousand metric tons
Ma	mega-annum/millions of years before the present
Mt	million metric tons
PGE	platinum-group elements
ppb	parts per billion
REE	rare-earth elements
SHRIMP	sensitive high resolution ion microprobe
SSIB	small-scale digital international boundaries
t	metric ton (tonne) or megagram (Mg)
USGS	U.S. Geological Survey
USSR	Union of Soviet Socialist Republics
VSEGEI	A.P. Karpinsky Russian Geological Research Institute

Chemical Symbols Used

Fe	iron
Hf	hafnium
Nb	niobium
Nd	neodymium
Sm	samarium
Sr	strontium

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Porphyry Copper Assessment of the Central Asian Orogenic Belt and Eastern Tethysides—China, Mongolia, Russia, Pakistan, Kazakhstan, Tajikistan, and India

By Mark J. Mihalasky[1], Steve Ludington[1], Jane M. Hammarstrom[1], Dmitriy V. Alexeiev[2], Thomas P. Frost[1], Thomas D. Light[1], Gilpin R. Robinson, Jr.[1], Deborah A. Briggs[1], John Wallis[1], and Robert J. Miller[1], with contributions from Arthur A. Bookstrom[1], Andre Panteleyev[3], Andre Chitalin[4], Reimar Seltmann[5], Yan Guangsheng[6], Lian Changyun[6], Mao Jingwen[7], Li Jinyi[6], Xiao Keyan[6], Qiu Ruizhao[6], Shao Jianbao[6], Shai Gangyi[6], and Du Yuliang[6]

Abstract

The U.S. Geological Survey collaborated with international colleagues to assess undiscovered resources in porphyry copper deposits in the Central Asian Orogenic Belt and eastern Tethysides. These areas host 20 known porphyry copper deposits, including the world class Oyu Tolgoi deposit in Mongolia that was discovered in the late 1990s. The study area covers major parts of the world's largest orogenic systems. The Central Asian Orogenic Belt is a collage of amalgamated Precambrian through Mesozoic terranes that extends from the Ural Mountains in the west nearly to the Pacific Coast of Asia in the east and records the evolution and final closure of the Paleo-Asian Ocean in Permian time. The eastern Tethysides, the orogenic belt to the south of the Central Asian Orogenic Belt, records the evolution of another ancient ocean system, the Tethys Ocean. The evolution of these orogenic belts involved magmatism associated with a variety of geologic settings appropriate for formation of porphyry copper deposits, including subduction-related island arcs, continental arcs, and collisional and postconvergent settings. The original settings are difficult to trace because the arcs have been complexly deformed and dismembered by younger tectonic events.

Twelve mineral resource assessment tracts were delineated to be permissive for the occurrence of porphyry copper deposits based on mapped and inferred subsurface distributions of igneous rocks of specific age ranges and compositions. These include (1) nine Paleozoic tracts in the Central Asian Orogenic Belt, which range in area from about 60,000 to 800,000 square kilometers (km^2); (2) a complex area of about 400,000 km^2 on the northern margin of the Tethysides, the Qinling-Dabie tract, which spans central China and areas to the west, encompassing Paleozoic through Triassic igneous rocks that formed in diverse settings; and (3) assemblages of late Paleozoic and Mesozoic rocks that define two other tracts in the Tethysides, the 100,000 km^2 Jinsajiang tract and the 300,000 km^2 Tethyan-Gangdese tract.

Assessment participants evaluated applicable grade and tonnage models and estimated numbers of undiscovered deposits at different confidence levels for each permissive tract. The estimates were then combined with the selected grade and tonnage models using Monte Carlo simulations to generate probabilistic estimates of undiscovered resources. Additional resources in extensions of deposits with identified resources were not specifically evaluated.

Assessment results, presented in tables and graphs, show amounts of metal and rock in undiscovered deposits at selected quantile levels of probability (0.95, 0.9, 0.5, 0.1, and 0.05 confidence levels), as well as the arithmetic mean and associated standard deviations and variances for each tract. This assessment estimated a total of 97 undiscovered porphyry copper deposits within the assessed permissive tracts. This represents nearly five times the 20 known deposits. Predicted mean resources that could be associated with these undiscovered deposits are about 370,000,000 metric tons (t) of copper, 10,000 t of gold, 7,700,000 t of molybdenum, and 120,000 t of silver. The assessment area is estimated to contain about five times as much copper in undiscovered deposits as has been identified to date.

This report includes a summary of the data used in the assessment, a brief overview of the geologic framework of the area, descriptions of permissive tracts and known deposits, maps, and tables. A geographic information system database that accompanies this report includes the tract boundaries and known porphyry copper deposits, significant prospects, and prospects. Assessments of overlapping younger rocks and adjacent areas are included in separate reports available online at http://minerals.usgs.gov/global/.

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Introduction

The U.S. Geological Survey (USGS) conducted a probabilistic mineral resource assessment of undiscovered resources in porphyry copper deposits in parts of the Central Asian Orogenic Belt (CAOB) and eastern Tethysides as part of its global mineral resource assessment project (GMRAP). The purpose of the assessment was to (1) compile a database of known porphyry copper deposits and significant prospects, (2) delineate geology-based permissive areas (tracts) for undiscovered porphyry copper deposits at a scale of 1:1,000,000, (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 those undiscovered deposits.

This report describes an assessment of undiscovered resources in porphyry copper deposits for the CAOB and eastern Tethysides (figs. 1 and 2). The assessment describes permissive areas for porphyry copper deposits in Russia, Mongolia, and China, as well as small areas in Pakistan, Kazakhstan, Tajikistan, and India. In some cases, very small parts of tracts extend into Kyrgyzstan, Afghanistan, and Myanmar. The study was conducted in cooperation with the China Geological Survey (CGS), the Centre for Russian and Central EurAsian Mineral Studies (CERCAMS), and colleagues from the Russian Academy of Sciences and industry consultants.

The assessment was done using a three-part form of mineral-resource assessment based on established mineral deposit models (Singer, 1993, 2007a, b; Singer and Berger, 2007; Singer and Menzie, 2010). Geographic areas (permissive tracts) are delineated using geologic, mineral occurrence, geochemical, and geophysical data to identify areas with features typical of the type of deposit under consideration. The amount of metal in undiscovered deposits is estimated using grade and tonnage models derived from information about known deposits. Probabilistic estimates of numbers of undiscovered deposits are consistent with the known deposits that define grade and tonnage models (Singer, 2007a). Numbers of undiscovered deposits at various quantiles (degrees of certainty) are estimated by an assessment team of experts using a variety of strategies, such as counting the number and ranking the favorability of significant prospects and comparing the spatial density of known deposits and expected undiscovered deposits to that of known deposits in similar, well-explored regions (Singer, 2007b). Probable amounts of undiscovered resources are then estimated by combining estimates of numbers of undiscovered deposits with grade and tonnage models using a Monte Carlo simulation process (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012).

This report primarily addresses Paleozoic through Triassic porphyry copper deposits in central and eastern Asia. Readers are referred to separate porphyry copper assessment reports on adjacent and overlapping areas. These include reports on (1) the Mesozoic of East Asia in China, Vietnam, North Korea, Mongolia, and Russia (Ludington and others, 2012b) that describe Yanshanian events in the eastern part of the study area, (2) the Cenozoic of the Tibetan Plateau (Ludington and others, 2012a), (3) the Paleozoic of Kazakhstan (Berger and others, 2014), (4) the Late Triassic through Holocene Tethys region of western and southern Asia (Zürcher and others, in press), and (5) the Paleozoic through Holocene of northeast Asia in Far East Russia and northeasternmost China (Mihalasky and others, in press).

Terminology

The terminology used in this assessment 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), as well as mineral resource definitions used by the U.S. Bureau of Mines and U.S. Geological Survey (1980) and geologic definitions found in 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 (for example, see Committee for Mineral Reserves International Reporting Standards, 2004).

• **Mineral occurrence**—A locality where a useful mineral or material is found. A mineral concentration, usually (but not necessarily) considered in terms of some commodity (such as copper or gold) that is considered to be of value to someone, somewhere, or that is of scientific or technical interest. It can be said to have an anomalous concentration of one or more commodities. Enough information may be available to allow for classification as a specific deposit type or suite of deposit types.

• **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 kilometer or less below the surface of the ground, or an incompletely explored mineral occurrence that could have sufficient size and grade to be classified as a deposit.

• **Mineral prospect**—A mineral concentration that has been (or is being) examined to determine whether a mineral deposit exists.

• **Significant mineral prospect**—A mineral prospect that has been (or is being) actively investigated by means of exploration drilling, trenching, or other sampling methods and has recorded copper grades or partial ore tonnages or other indicators, such as detailed descriptions of mineralization, that suggest the prospect is of high interest.

• **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 as a particular type 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[8] reporting guidelines.

• **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, nonrigorous 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 extrusive equivalents (see Le Maitre, 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.

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

Report Format

This report begins with a discussion of porphyry copper deposit models, both descriptive and grade and tonnage models. This is followed by the definition of a permissive tract and a description of the nature and quality of the data used for the assessment, then by a brief description of the geologic framework and exploration history of the region. Next, the processes used to delineate permissive tracts are described. Subsequent sections provide descriptions of the permissive tracts. Permissive tracts are assigned unique coded identifiers based on the United Nations region (142 for Asia), a deposit type (pCu for porphyry copper), and a four-digit number (for example 8505) and names based on a prominent geographic or tectonic feature.

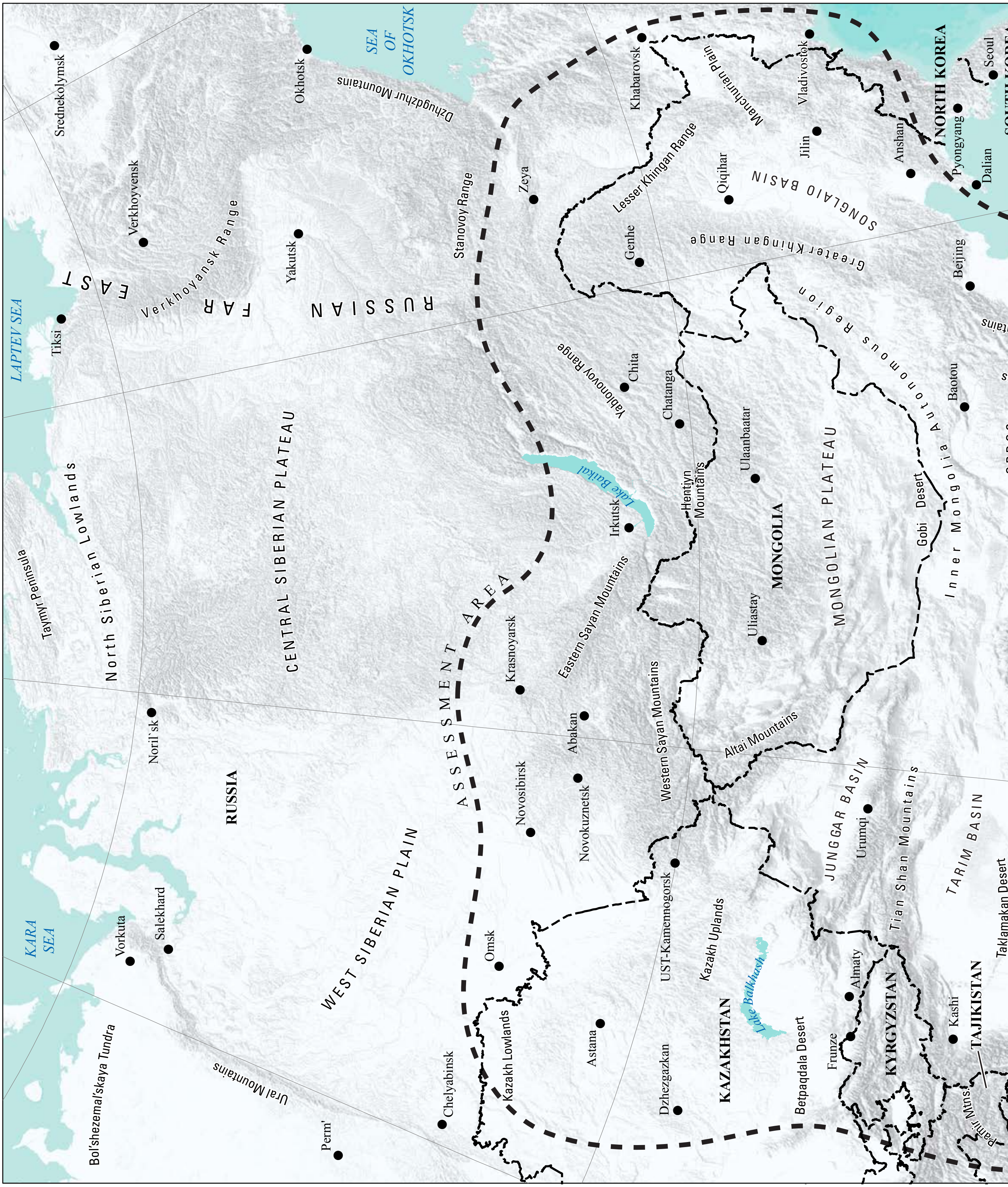
The last section of the report includes a discussion and a summary of results. Appendix A lists the principal sources of information used in the assessment. Appendix B is a table of porphyry copper deposits, significant prospects, and prospects. Permissive tract boundaries and point locations of deposits, significant prospects, and prospects are included in a geographic information system (GIS) database in appendix C, and appendix D identifies the participants in the assessment. Geologic time scales used on geologic maps for former Soviet Union countries, as well as for China and Mongolia, differ slightly from the International Stratigraphic Chart (International Commission on Stratigraphy, 2010) and from each other. Appendix E includes correlation tables to clarify geologic age terms and abbreviations used in this report.

Political Boundaries

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.

Considerations for Users of this Assessment

Ideally, assessments are done on a recurring basis, at a variety of scales, because available data change over time. This report is a synthesis of current, readily available information as of August 2013. The 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 the most reliable average grades available for each commodity of possible economic interest. The tonnages are based on the total of production, reserves, and resources at the


150° E
120° E
90° E
60° E
50° N
LAPTEV SEA
KARA SEA
SEA OF OKHOTSK
Srednekolymsk
Verkhoyvensk
Verkhoyansk Range
Tiksi
FAR EAST
RUSSIAN
Okhotsk
Dzhugdzhur Mountains
Yakutsk
Stanovoy Range
Zeya
Khabarovsk
Manchurian Plain
Vladivostok
NORTH KOREA
SOUTH KOREA
Seoul
Pyongyang
Anshan
Dalian
Jilin
Lesser Khingan Range
Qiqihar
SONGLIAO BASIN
Genhe
Greater Khingan Range
Beijing
Inner Mongolia Autonomous Region
Baotou
ORDOS
Yablonovoy Range
Chita
Chatanga
Ulaanbaatar
Hentiyn Mountains
Lake Baikal
Irkutsk
MONGOLIA
MONGOLIAN PLATEAU
Gobi Desert
Uliastay
Eastern Sayan Mountains
Krasnoyarsk
Abakan
Western Sayan Mountains
Altai Mountains
Taymyr Peninsula
North Siberian Lowlands
CENTRAL SIBERIAN PLATEAU
ASSESSMENT AREA
Noril'sk
RUSSIA
Novosibirsk
Novokuznetsk
WEST SIBERIAN PLAIN
JUNGGAR BASIN
Urumqi
Tian Shan Mountains
TARIM BASIN
Taklamakan Desert
UST-Kamennogorsk
Kazakh Uplands
Lake Balkhash
Almaty
KAZAKHSTAN
Omsk
Vorkuta
Salekhard
Kazakh Lowlands
Astana
Dzhezgazkan
Betpaqdala Desert
Frunze
KYRGYZSTAN
TAJIKISTAN
Kashi
Pamir Mtns.
Chelyabinsk
Ural Mountains
Perm'
Bol'shezemal'skaya Tundra

30° N

Basemap from U.S. Geological Survey, HYDRO1k Geographic Database (1998).
Oceans source: World Terrain Base, ESRI (2012).
Political boundaries from U.S. Department of State (2009).
Asia North Albers Equal Area Conic Projection.
Central meridian,100° E., latitude of origin, 30° N.

0 200 400 800 KILOMETERS
0 100 200 400 MILES

Figure 1. Map of the study area in central and eastern Asia, showing geographic features mentioned in this report.

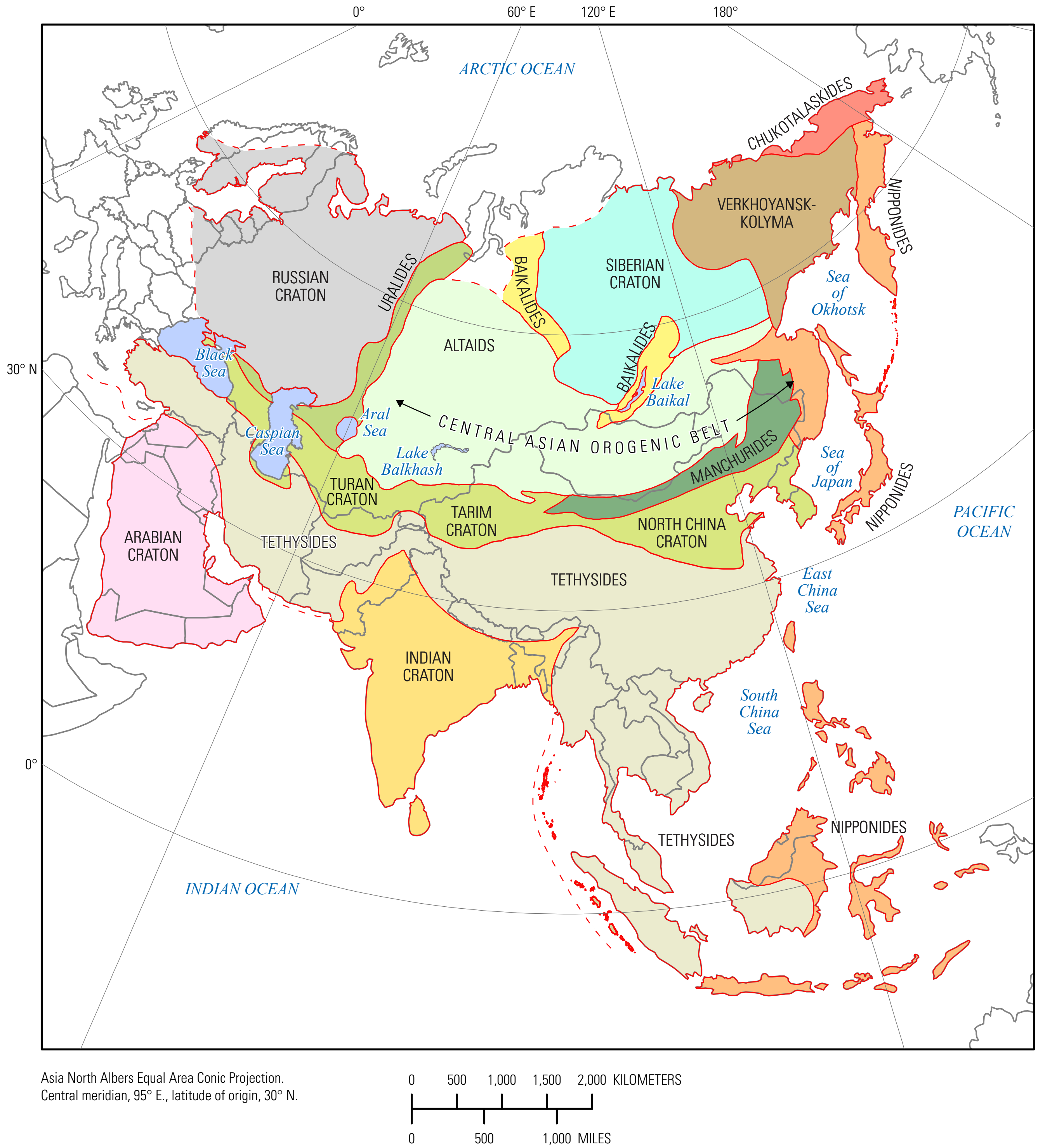


Figure 2. Map of the major orogenic systems of Asia showing the location of the Central Asian Orogenic Belt, the Tethysides, and major cratons, blocks, and belts. (Modified from Şengör and Natal'in, 1996a).

lowest cutoff grade for which data were available when the model was constructed.

The economic viability of any mineral deposit depends on a wide variety of factors, many of which vary with time. This caveat applies to the deposits used to construct the grade and tonnage models, as well as to undiscovered deposits, so care must be exercised when using the results of this assessment to answer economic questions. If discovered, deposits may not be developed immediately or ever. Furthermore, the estimates in this assessment 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 through further drilling and characterization. These probable deposits are treated here as undiscovered deposits, albeit ones with a high degree of certainty of existence.

This assessment considers the potential for both exposed deposits and concealed deposits within 1 kilometer (km) of the surface. Very high-grade deposits may be exploited at greater depths, but it is not common. Exploration for and possible exploitation of these deeper deposits may be so expensive that they may not be discovered in the near term. If they are discovered, the cost to mine a deeply buried porphyry deposit may easily prohibit its development into a mine 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. For additional information about proper usage of the tracts, see the completeness and accuracy statements in the metadata of the accompanying spatial datasets (appendix C).

Porphyry Copper Deposit Models

Porphyry copper deposits typically form in subduction-related, compressional tectonic settings, during active subduction of oceanic or continental crust (Sillitoe, 2010; John and others, 2010). These deposits are commonly associated with shallowly emplaced calc-alkaline plutons. The Andes range of South America is the classic province for continental-arc magmatism (Kay and others, 1999). Magma associated with porphyry copper deposits typically is hydrous, oxidized, and rich in sulfur and has likely undergone complex processes of differentiation and evolution at the crust-mantle boundary (Richards, 2003; John and others, 2010). Island arcs in the southwest Pacific Ocean are the archetypes of island-arc magmatism (Garwin and others, 2005). Magma associated with island-arc porphyry copper deposits is similar to that associated with continental arcs, but diorite, quartz diorite, and other more mafic rocks are comparatively more abundant (Kesler and others, 1975).

In recent years, evidence has accumulated for the existence of a family of porphyry copper deposits that formed in a significantly different tectonic setting—extensional, transtensional, or transpressional regimes that have evolved within relatively cratonized regions after active subduction had ceased. A number of the porphyry copper deposits in the study area represent examples of this family of porphyry copper deposits, which are referred to as “postconvergent” or “postcollisional” (Richards, 2009; Ludington and others, 2013). Their geology and mineralization style are broadly similar to subduction-related porphyry copper deposits; however, the magmas that are associated with them originated from as yet only partially understood mantle-involved processes (Richards, 2009; Richards and Kerrich, 2007; Hou and others, 2011).

Descriptive Models

Mineral deposit models used for this assessment include the descriptive porphyry copper models of Singer and others (2008), Cox (1986a, b, c), and John and others (2010). Cox (1986a, b, c) subdivides porphyry copper deposits into three subtypes on the basis of copper, gold, and molybdenum grades—(1) porphyry Cu, (2) porphyry Cu-Au, and (3) porphyry Cu-Mo. The recent review of salient features of porphyry copper deposits by Sillitoe (2010) is also pertinent.

Grade and Tonnage Models

Singer and others (2008) developed global grade and tonnage models for porphyry copper deposits from ore tonnages and average grades, based on the total production, reserves, and resources at the lowest possible cutoff grade. On the basis of available ore tonnages and grades of copper, gold, and molybdenum for 422 deposits worldwide, four global porphyry copper grade and tonnage models were defined—(1) porphyry Cu deposits (256 deposits), (2) porphyry Cu-Au (115 deposits), (3) porphyry Cu-Mo deposits (51 deposits), and (4) a “general model,” which includes all 422 deposits from the three subtype models

These global grade and tonnage models were tested for applicability for the assessment of undiscovered resources in porphyry copper deposits in the study area using statistical tests. For each permissive tract that contains known deposits, the grades and tonnages of any deposits in a tract were tested against global models with a Student’s *t*-test. In a *t*-test, the means and distributions of two sets of observations are compared to determine if they come from the same population or if they are representative of distinct populations. Analysis of variance (ANOVA) was used in cases of a single known deposit per tract. If the test results indicate no statistical differences between the tract deposits and the deposits of a given global model (that is, the data fit the model and are not distinguishable), the model was considered appropriate for estimating the undiscovered resources of a permissive tract. For tracts with no known deposits, the general model was selected as a default.

Permissive Tracts for Porphyry Copper Deposits

A permissive tract for porphyry copper deposits is delineated as a geographic area that includes intrusive and extrusive rocks of specified ranges of composition and age that are part of a magmatic arc or belt. These arcs have been traditionally related to convergent plate margins, but some magmatic belts have uncertain origins or formed after subduction ceased. A tract generally is bounded by the outline of the magmatic arc, as depicted at the scale of the maps available for tract delineation, and may include areas covered by younger or structurally overlying materials that are less than 1 km thick. For tracts in the study area, many of the igneous rocks most closely associated with porphyry copper formation are not depicted on available digital geologic maps. Instead, their locations come from the scientific literature.

Assessment Data

Our knowledge of the geology and mineral deposits of this part of the world can best be termed incomplete. Government geological agencies and institutions in some countries do not publicly distribute detailed earth science information. Critical geologic data are not always available from government and other earth science organizations through those institutions' Web sites (although in some cases datasets can be licensed or purchased).

Principal sources of information used by the assessment team for delineation of the tracts and compilation of deposits, significant prospects, and prospects are listed in appendix A.

Geologic Maps

Geologic maps at a variety of scales were used for tract delineation. For China, geologic maps of the Chinese provinces that were available as part of a collection of Geologic Memoirs that were produced by the Chinese Ministry of Geology and Mineral Resources from 1984 through 1993 were used. In addition, the digital geologic map of China, based on the 1:2,500,000-scale map by the China Geological Survey (2004a), was consulted. Although this map is at a smaller scale than those in the geologic memoirs, it incorporates significant new petrologic and radiometric age data gathered in the 1990s. For Mongolia, a digital version of the 1:1,000,000-scale geologic map of Mongolia compiled by Tomurtogoo and others (1999) was used (this is a compilation based on mapping at various scales). For Russia, a digital version of the 1:2,500,000 scale map of Russia and the Commonwealth of Independent States (CIS) countries published by the A.P. Karpinsky All-Russia Geological Research Institute (Petrov and Streinikov, 2008) was used. Similar to the 1:2,500,000 digital map of China, the Russia and CIS countries geologic map has incorporated newer data than the source maps from which it was compiled. The geology of Kazakhstan is covered in a digital GIS product authored by Seltmann and others (2012).

Mineral Occurrence Data

A global database of porphyry copper deposits and prospects published by Singer and others (2008) was supplemented with other global- and regional-scale mineral occurrence databases, including that of the Geological Survey of Canada (Natural Resources Canada, 2010; Kirkham and Dunne, 2000) and databases prepared by the Geological Survey of Japan (Kamitani and others, 2007). In addition, commercially available databases (InfoMine[9], Intierra[10], Metals Economic Group[11]), technical reports, company Web sites, and geologic literature were consulted. The GIS package for Central Asia by Seltmann and others (2012) includes detailed mineral occurrence data for Kazakhstan and adjacent areas. The U.S. Geological Survey Mineral Resources Data System (MRDS), an online searchable database, also includes information on mines, prospects, and mineral occurrences worldwide (U.S. Geological Survey, 2011). Promotional material from Web sites maintained by mineral exploration companies were very helpful in developing a deposit and prospect database, particularly in Mongolia.

Mineral occurrence sites were classified as deposits (grade and tonnage well delineated), significant prospects (incompletely characterized with respect to grade and tonnage), or prospects (some descriptive exploration information or assay data available) on the basis of recent published literature.

Information about porphyry copper deposits in this part of the world, and particularly China, has proven exceptionally difficult to compile. There is a certain amount of confusion about classification, as deposits are sometimes referred to as "porphyry-style" primarily because they are large and can be mined using open-pit methods, not because they have characteristics corresponding to existing deposit models.

Many of the locations reported should be treated with caution because, unless the mine is being exploited and its location can be verified by satellite imagery, the location often derives from an approximation based on a page-size location map, often without coordinates. Every attempt was made to update the locations of the deposits and prospects, with mixed success.

The deposit-type classification of some mineral sites is ambiguous because of insufficient information. Deposits, significant prospects, and prospects that could be classified with some certainty as porphyry copper or porphyry copper

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

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

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

related are included in an Excel spreadsheet file in appendix B and in the spatial database that accompanies this report (appendix C). Distributions of gold placers, copper- and copper-gold skarns, and epithermal precious-metal deposits, as well as unclassified copper and gold occurrences, were considered during the assessment, but those deposits are generally not included in the database. Some skarns were included if an associated porphyry system could plausibly be inferred.

Geophysical Data

Global magnetic anomaly data cover most of southern and eastern Asia (National Geophysical Data Center, 2009). The data are at 2 arc-minute resolution and display primarily broad, relatively deep magnetic features; however, because they do not correlate well with mapped outcrops of permissive rocks, they were of limited use. These data were used for delineating regional-scale structural and tectonomagmatic features, such as suture zones, and in some instances, for identifying possible permissive plutonic complexes under Cenozoic cover along and within shallow basins. The 1:5,000,000-scale aeromagnetic map of China (China Geological Survey, 2004b) and the magnetic anomaly map of the former Union of Soviet Socialist Republics (USSR) (A.P. Karpinsky Russian Geological Research Institute (VSEGEI), 1978; Racey and others, 1996) were similarly of limited use.

Regional Geodynamics and Metallogeny

The first modern, comprehensive English-language syntheses of the tectonics of Eurasia and the Tethysides became available in the 1980s and 1990s in publications by Şengör and his colleagues (Şengör, 1984; Şengör and others, 1988; Şengör and others, 1993; Şengör and Natal'in, 1996a, b). Badarch and others (2002) established a terrane synthesis for Mongolia based on 60 years of studies of that part of the CAOB, and Windley and others (2007), Xiao and others (2010), and Wilhem and others (2012) reviewed models for the Neoproterozoic through Permian accretion of the CAOB. These and other geodynamic studies established a framework that continues to be challenged, refined, and reinterpreted. Nevertheless, the understanding of the complex geodynamic framework, magmatism, and metallogeny of eastern Asia is rapidly evolving owing to abundant new data on the age, geochemistry, and isotopic signatures of igneous rocks, much of which is becoming available in English. A May 2013 issue of Gondwana Research on the tectonics of China, for example, which was published after this assessment was largely completed, addressed the nature and age of many of the magmatic systems that may host porphyry copper deposits in China.

Results from an international project that examined the mineral resources, metallogenesis, and tectonics of Northeast Asia that covers parts of the study area were published by Nokleberg and others (1999). Readers also are directed to selected papers published since the early 2000s that provide discussions of the settings for porphyry copper deposits in eastern Asia. Specifically, Seltmann and Porter (2005) summarized the tectonic setting and described porphyry copper-gold-molybdenum deposits of central Eurasia. A number of papers deal with the settings for porphyry copper deposits in the Altaids (Yakubchuk, 2002, 2004, 2008, 2009), including a 2008 issue of the Journal of Asian Earth Sciences focused on the geodynamics and metallogeny of the Altaids orogen (Xiao and others, 2008). Seltmann and others (2010) summarized the metallogeny of Siberia, including a discussion of porphyry and skarn deposits along the southern margins of the craton within the study area. Pirajno and others (2011) reviewed mineral systems and associated tectonic settings of northern Xinjiang, China. Pirajno's (2013) book on the geology and tectonic setting of China's mineral deposits (and references therein) provides a comprehensive synthesis of the state of knowledge for China and adjacent areas, as well as a cogent discussion of time scales and terminology used in the geologic literature of eastern Asia.

Geologic Framework

The study area encompasses parts of several major lithotectonic domains—(1) the Central Asia Orogenic Belt (Altaids) on the southern margin of the Siberian Craton in southern Russia, northern Kazakhstan, Mongolia, and northeastern China, (2) the North China (also referred to as the Sino-Korean) and Tarim Craton blocks that span central China, and (3) eastern parts of the Tethysides (Alpine-Himalayan orogenic belt) (fig. 2). Paleozoic through Triassic porphyry copper deposits mainly are concentrated in magmatic belts along major sutures, regional-scale transcurrent structural features, and fold belts that bound these lithotectonic domains. These orogenic belts are complex collages that include continental margin and oceanic magmatic arcs and belts that formed in convergent and postconvergent settings (see Ludington and others, 2013). These major lithotectonic domains evolved to their present configuration through major orogenies that mark ocean basin closures, multiple collisions, and terrane reconfigurations—the early Paleozoic Caledonian orogeny (~540–400 million years before present/mega-annum, Ma), the late Paleozoic Variscan orogeny (~400–280 Ma), the Mesozoic Indosinian (~280–200 Ma) and Yanshanian (~200–65 Ma) orogenies, and the ongoing Cenozoic Himalayan orogeny. In many parts of the study area, vestiges of all of these orogenies are preserved and younger events overprint and obscure older events.

Twelve permissive tracts for porphyry copper deposits were delineated within the study area (table 1). From oldest to youngest, the tracts include four early Paleozoic and five late Paleozoic tracts within the Central Asia Orogenic Belt, and three Paleozoic to Mesozoic tracts that belong to the eastern part of the Tethysides (fig. 3). Within the Central Asia Orogenic Belt, the early and late Paleozoic tracts are intimately mixed and some younger tracts overlap older tracts (fig. 4). The age ranges for each tract are shown schematically in figure 3, along with the names of the orogenies that are applied to events in the literature. The use of the names of orogenies as time terms is inappropriate, but because they are so commonly used, especially in the Chinese literature, to denote "magmatic stages," the same terminology is used here. In the discussion that follows, the term "Caledonian time" is used to mean about 540 to 400 Ma, "Variscan time" to mean about 400 to 280 Ma, "Indosinian time" to mean about 280 to 200 Ma, and "Yanshanian time" to mean about 200 to 65 Ma (also see the time-scale correlation chart in appendix E).

The permissive tracts represent examples of a variety of geologic settings, including island arcs, continental arcs, postconvergent magmatic belts, and composite settings that represent arcs accreted to former continental margins as ancient oceans closed. All of the tracts are elongated in a general east-west direction, perpendicular to the modem Asian Pacific Ocean continental margin, and some reflect the deformation of permissive units into regional-scale oroclines (such as parts of tracts 142pCu8504, Mongol-Sayan, and 142pCu8507, Molgol-Altai). Porphyry copper assessments for adjacent areas are shown in gray on figure 4. These include assessments of western Central Asia (Berger and others, 2014), the Tibetan Plateau (Ludington, and others, 2012a), the Mesozoic of East Asia (Ludington and others, 2012b), and the Tethys region of western and southern Asia (Zürcher and others, in press).

A brief and simplified summary of the broad-scale geologic framework for porphyry copper deposits in the study area is presented here. More specific details are described for individual permissive tracts later in this report. Readers are cautioned that geodynamic models for this part of the world are controversial, often contradictory, and repeatedly change as new data become available. Identification of permissive settings for porphyry copper deposits in the future will undoubtedly benefit from more studies integrating new age determinations, igneous geochemistry, and large-scale geodynamic-metallogenic studies.

Central Asian Orogenic Belt

The Central Asian Orogenic Belt (CAOB) is a collage of amalgamated Precambrian through Mesozoic terranes that extends from the Ural Mountains in the west, nearly to the Pacific Coast of Asia in the east (fig. 2). It includes all the terranes between the Eurasian Continent (Siberian Craton) and the combination of the North China Craton and the Tarim Craton. The CAOB, which is one of the world's largest orogenic systems, formed along the southern margin of the Eurasian Continent in a complex and much-debated manner. It includes microcontinental fragments, island arcs, continental arcs, back-arc basins, accretionary wedges, and oceanic plateaus, as well as numerous suture zones that bound all these terranes.

Two key features characterize all the various models for the evolution of the CAOB—(1) Many island arcs and continental arcs developed through subduction of the Paleo-Asian and Paleotethys Oceans, and (2) a number of continental fragments, mainly of Precambrian crust, periodically rifted off both Gondwanaland and Eurasia and became incorporated with the arcs into the resulting collage. The subduction-related island arcs and continental arcs, as well as some postconvergent magmatic belts, have produced porphyry copper deposits in a variety of places and times. Although development of the CAOB began before 1,000 Ma (Kröner and others, 2007), and there are several named arcs of Vendian (late Precambrian) age along the southern margin of Siberia (Yenesei, Kan, Baikal-Muya), there are no significant Precambrian porphyry copper deposits or prospects (see appendix E for geologic-age terms). This assessment deals only with the Paleozoic and early Mesozoic parts of the orogen. To review the competing theories of continental evolution, see Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013.

Caledonian Magmatism

At least two major magmatic arcs and three other areas of volcanic rocks in the CAOB that involved subduction of oceanic crust of the Paleo-Asian Ocean were active from at least Vendian time through approximately the end of the Silurian.

Caledonian-age rocks that occur in unnamed island arcs in the southern part of the CAOB are assessed by the Solonker (142pCu8501) and the Gobi-Amur (142pCu8503) tracts (fig. 5). The few Caledonian rocks in the Solonker tract (which is delineated mostly on the basis of Variscan and Indosinian rocks) are scattered across northern China, from eastern Xinjiang Autonomous Region in China eastward nearly to the Pacific Ocean in Heilongjiang and Liaoning Provinces in eastern China. There are no known porphyry copper deposits of Caledonian age. The Chehugou deposit (table 2, fig. 5) is within the area of the Solonker tract, but it is late Permian to Early Triassic in age. Younger volcanic rocks largely cover the second unnamed Caledonian arc, which corresponds to the Gobi-Amur tract. It extends from southwestern Mongolia eastward through southern Mongolia to Heilongjiang Province in China near the boundary with Russia and hosts the Duobaoshan porphyry copper deposit at the eastern end (see fig. 5).

Table 1. Permissive tracts for porphyry copper deposits in the Central Asian Orogenic Belt and eastern Tethysides.

[km^2, square kilometers]

Tract	Tract name	Countries	Area (km^2)	Geologic feature assessed	Duration of igneous activity (million years)
			Central Asia Orogenic Belt—early Paleozoic (Caledonian time)		
142pCu8501	Solonker	China	250,100	Paleozoic through Triassic igneous rocks (early Paleozoic Bainaimiao island arc, a late Paleozoic continental arc formed by south-directed subduction of the Paleo-Asian Ocean beneath the North China craton) and Permo-Triassic rocks formed by collision of the North China and Tarim cratons (Manchurides) with Eurasia (Altaids).	297
142pCu8502	Kazakh-Tianshan	Kazakhstan and China	89,610	A varied assemblage of Cambrian through Silurian igneous rocks (Kipchak and Stepnyak-North Tienshan island arcs) in the western part of the Central Asian Orogenic Belt. Partly covered by the Late Paleozoic Balkash-Yili Arc.	126
142pCu8503	Gobi-Amur	Mongolia, China, and Russia	56,090	An assemblage of Cambrian through Early Devonian igneous rocks that consist mostly of continental-margin arc rocks with some island-arc rocks at the eastern end; mostly covered by the Late Paleozoic Kazakh-Mongol Arc.	144
142pCu8504	Mongol-Sayan	Mongolia, China, and Russia	575,100	An assemblage of Cambrian through Silurian igneous rocks primarily in central and northern Mongolia and bordering parts of Russia, including the Tuva-Mongol island arc and a variety of other calc-alkaline rocks.	126
			Central Asia Orogenic Belt—late Paleozoic (Variscan and Indosinian time)		
142pCu8505	Kazakh-Tarim	Kazakhstan and China	344,290	A varied assemblage of Devonian through Early Triassic igneous rocks that include the Balkash-Yili continental-margin arc, as well as younger rocks related to the Indosinian orogeny (collision of China with Asia).	170
142pCu8506	Oyu Tolgoi	Mongolia and China	329,850	A varied assemblage of Devonian through Triassic igneous rocks primarily in Mongolia and China that include the Devonian Kazakh-Mongol continental-margin arc, as well as younger rocks related to the Indosinian orogeny (collision of China with Asia).	216
142pCu8507	Mongol-Altai	Russia, Mongolia, China, and Kazakhstan	785,570	A varied assemblage of Devonian through early Permian igneous rocks in Mongolia and Russia that include primarily calc-alkaline continental-margin arc rocks.	145
142pCu8508a	Erdenet Southwest	Mongolia	61,430	An assemblage of middle Permian through Triassic igneous rocks in Mongolia that formed during and after closure of the Mongol-Okhotsk Ocean, apparently in a postsubduction environment.	70
142pCu8508b	Erdenet Northeast	Russia	103,790	An assemblage of middle Permian through Triassic igneous rocks in Russia that formed during and after closure of the Mongol-Okhotsk Ocean, apparently in a postsubduction environment.	70

Table 1.—Continued

Tract	Tract name	Countries	Area (km^2)	Geologic feature assessed	Duration of igneous activity (million years)
			Tethyside region—early Paleozoic		
142pCu8701	Qinling-Dabie	China and Tajikistan	403,220	An assemblage of Paleozoic through Triassic igneous rocks in central China that includes a Cambro-Ordovician island arc, a Devonian continental-margin arc related to north-directed subduction of the Paleotethys Ocean beneath the North China, Qaidam, and Tarim Cratons, and Permian-Triassic rocks formed as a result of the collision of the North China and Tarim cratons (Manchurides) with the Eurasian continent (Altaids).	340
			Tethyside region—late Paleozoic and Mesozoic		
142pCu8702	Jinsajiang	China	111,690	An assemblage of Carboniferous, Permian, and Triassic igneous rocks in southwestern China that formed both as island arcs and continental-margin arcs during subduction of the Paleotethys Ocean below the Qiangtang, and South China terranes	157
142pCu8706	Tethyan-Gangdese	China, India, and Pakistan	289,650	An assemblage of Late Triassic, Yanshanian (Jurassic and Cretaceous), and early Tertiary igneous rocks in southwestern China that were formed during subduction of the Tethys Ocean below the southern margin of Asia.	185

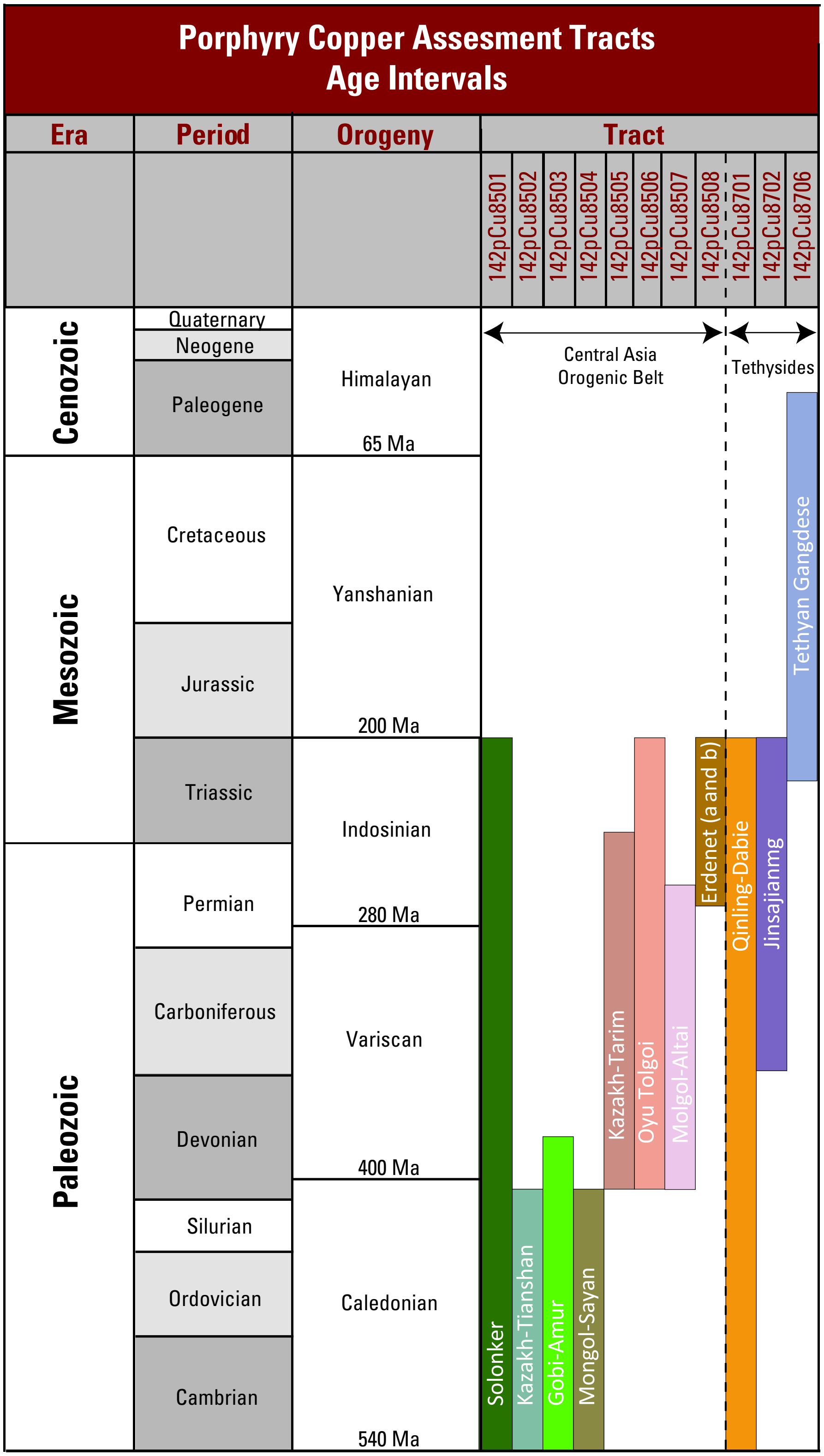
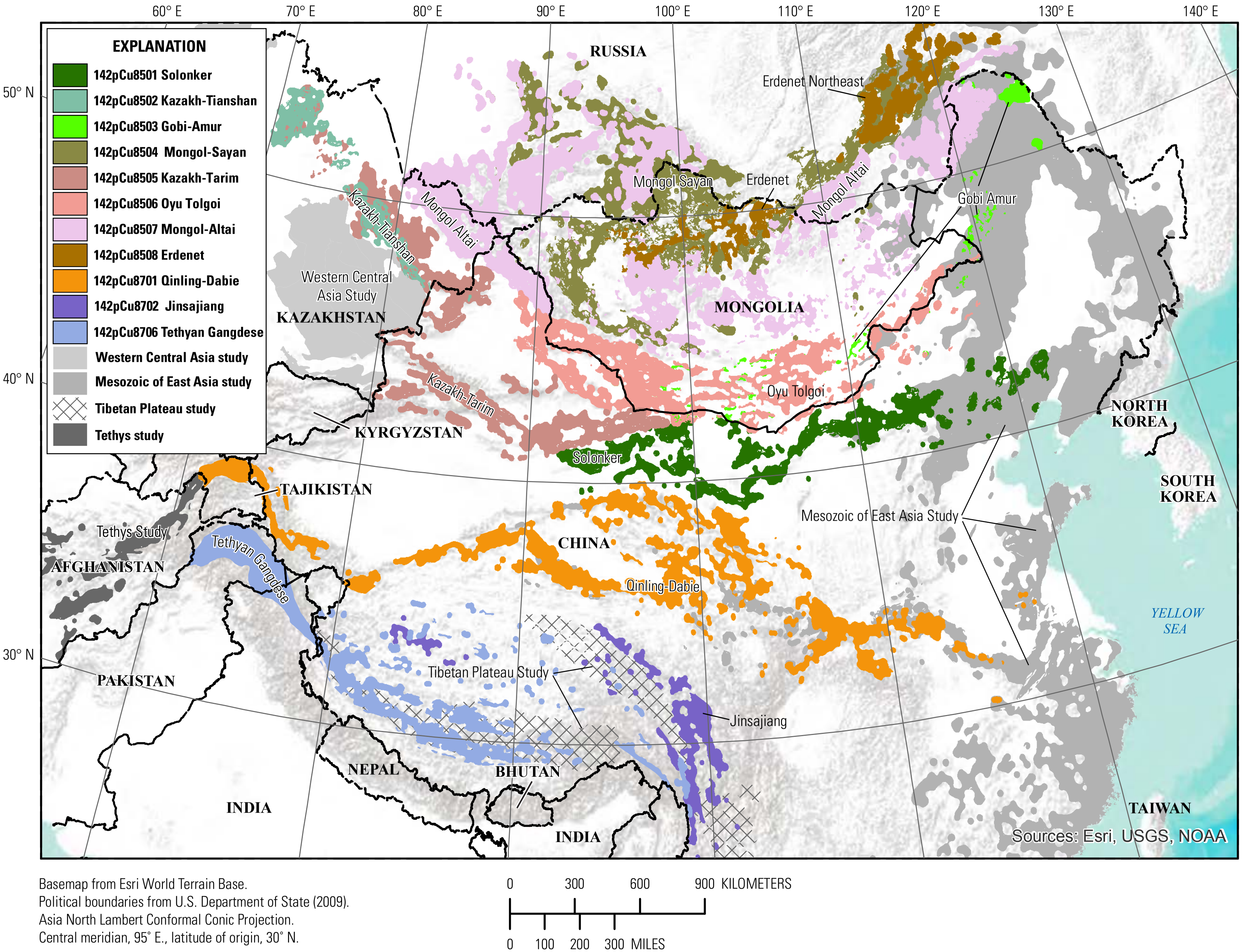


Figure 3. Chart showing the distribution of the permissive tracts for porphyry copper deposits in the Central Asia Orogenic Belt and eastern Tethysides regions in terms of geologic time span and orogenic events. Note that tract 142pCu8508 (Erdenet), consisting of two sub-tracts ("a" and "b"), is represented as a single time-interval bar on the chart. Ma, mega-annum/millions of years before present.



Basemap from Esri World Terrain Base.
Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.

Figure 4. Map showing the distribution of permissive tracts for porphyry copper deposits in the Central Asia Orogenic Belt and eastern Tethysides and adjacent study areas. The tracts shown in gray and cross-hatch patterns were assessed in other studies by Berger and others (2014), Ludington and others (2012a), Ludington (2012b), and Zürcher and others (in press).

In northeast Kazakhstan, rocks of the Caledonian Kipchak mixed island arcs and continental arcs host the Bozshakol, Nurkazgan, and Kyzyltu porphyry copper deposits and define the Kazakh-Tianshan tract (142pCu8502).

Different parts of the Kipchak Arc are sometimes referred to as the Baidulet-Akbastau, Bozshakol-Chingiz, Selety, and Stepnyak-North Tien Shan Arcs (see fig. 5) (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013). Not all of these arcs are in the Kazakh-Tianshan tract. Most of the southwestern part of the Kipchak Arc is described and assessed in Berger and others (2014).

In Russia, west of Lake Baikal, probable Vendian and Caledonian continental-arc rocks of the Uimen-Lebed and Gorny Altai assemblages form the northern part of the Mongol-Sayan tract (142pCu8504) and host the Agaskyr, Kiyalykh-Uzen, and Sora porphyry copper deposits (fig. 5, table 2) (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013). Closest to the Siberian Craton is the Tuva-Mongol island arc, which corresponds generally to the southern part of the Mongol-Sayan tract. This is a long arc that has been oroclinally folded and covers a large area in central and northern Mongolia and eastern Russia. The Tuva-Mongol arc hosts the Aksug porphyry copper deposit, as well as several prospects in western Mongolia (table 2, fig. 5).

Variscan Magmatism

In Devonian time, reorganization of the tectonic plates in the area resulted in the initiation of new arcs, including the Kazakh-Mongol, an island arc primarily in the southern part of present-day Mongolia, and the Balkash-Ili, primarily a continental arc located in present-day Kazakhstan (fig. 6). Both these arcs were active from approximately Devonian time until the collision of the North China and Tarim Cratons with the southern margin of the CAOB in Permian time (initiation of the Indosinian orogeny) (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013).

The Carboniferous and Permian Kazakh-Mongol island arc is included in parts of two assessment tracts, the Kazakh-Tarim (142pCu8505), in western China, and the Oyu Tolgoi (142pCu8506), mostly in southern Mongolia. The westernmost parts of the arc, in China, are also known as the Dulate-Baytag and Yemaquan Arcs (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013). The most important porphyry copper deposit in the Kazakh-Mongol Arc is the giant Oyu Tolgoi deposit in southern Mongolia (table 2, fig. 6).

In Kazakhstan and northwestern China, the Balkash-Ili island arc (sometimes considered to be part of the Kazakh-Mongol Arc) corresponds to a major part of the Kazakh-Tarim tract and contains the Koktasdzhal and Kyzylkain deposits in Kazakhstan, the Baogutu deposit in China, and the large Tuwu-Yandong-Yanxi deposit in Xinjiang province of China (table 2, fig. 6) (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013). The part of the arc near Tuwu-Yandong-Yanxi is also known as the Dananhou-Tousuquan Arc. The part of the arc in northeast Kazakhstan is also called the Zharma-Saur Arc. The parts of the Balkash-Ili Arc that are in southeast Kazakhstan are described and assessed by Berger and others (2014).

The Selenga-Gobi-Khanka Arc refers to a belt of primarily Middle Carboniferous to Early Triassic intrusive rocks in eastern Russia that make up part of the Mongol-Altai tract (142pCu8507). The origin of these intrusions involved a considerable amount of crustal melting. There are no known porphyry copper deposits in this assemblage of rocks. Parts of the Mongol-Altai tract are also defined by parts of the Permian-Triassic Sayan-Transbaikal continental arc (see fig. 6) (Windley and others, 2007; Xiao and others, 2010; Wilhem and others, 2012; and Pirajno, 2013).

Indosinian Magmatism

The Indosinian orogeny is recognized throughout East Asia and took place in Permian and Triassic time. It refers to the deformation related to the final amalgamation of the North and South China Cratons (also referred to as the Yangtze Terrane) and the Indochina Block with South China and appears to have triggered widespread postconvergent magmatism throughout much of eastern Asia. The Selenga-Gobi-Khanka continental arc (fig. 7) of Permian-Triassic age is the result of the youngest magmatism in the CAOB, formed during Indosinian time, and probably contains both subduction-related and postconvergent rocks. The postconvergent rocks are usually referred to as being related to the Mongolian-Transbaikalian rift belt (Jahn and others, 2009; Reichow and others, 2010). This area corresponds to the Erdenet tract (142pCu8508) and contains the important Erdenet porphyry copper deposit (table 2, fig. 7).

Tethysides

The Tethysides (Alpine-Himalayan belt) represent a superorogenic collage that lies to the south of the Central Asia Orogenic Belt (see fig. 2). The Tethysides record the evolution and final closure of the Paleotethys and Neotethys Oceans and the ongoing tectonics related to the collision of India with southern Eurasia.

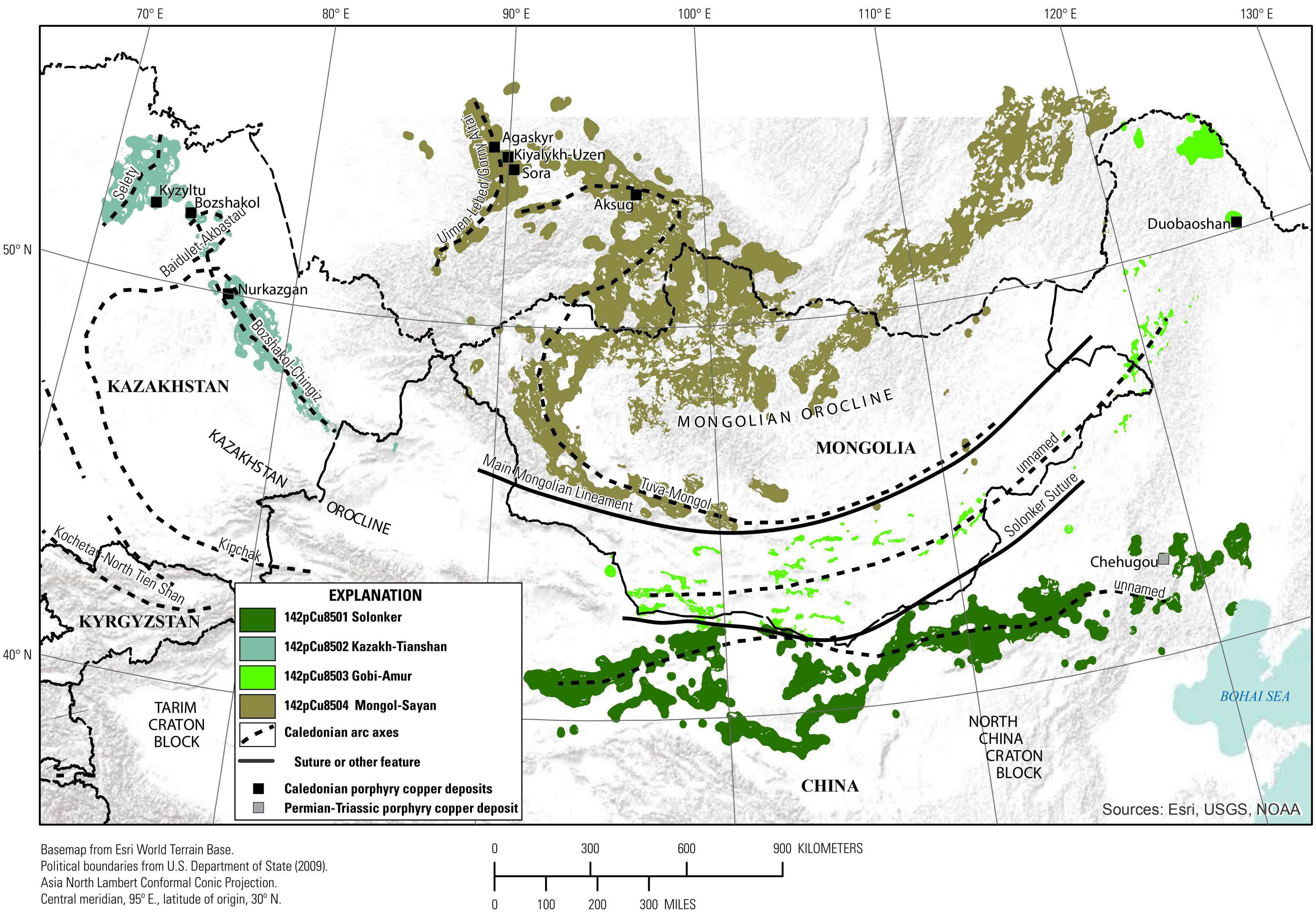
Caledonian Through Indosinian Magmatism

South of the CAOB, the Qinling-Dabie orogen marks the suture between the North China and Tarim Cratons with the South China (Yangtze) Craton to the south. The Ordovician Erlangping island arc (fig. 7) produced the oldest rocks in the orogeny. In Devonian time, an unnamed continental arc overprinted the area, and further magmatism related to the final amalgamation of North and South China in Indosinian time also punctuated the area. The composite Qinling-Dabie orogen and some igneous rocks further west in China and Tajikistan define the Qinling-Dabie tract (142pCu8701). Saishitang, a moderate-sized skarn-related porphyry copper deposit is in the central part of the orogen (table 2, fig. 7).

Table 2. Summary of identified resources in porphyry copper deposits of the Central Asian Orogenic Belt and eastern Tethysides.

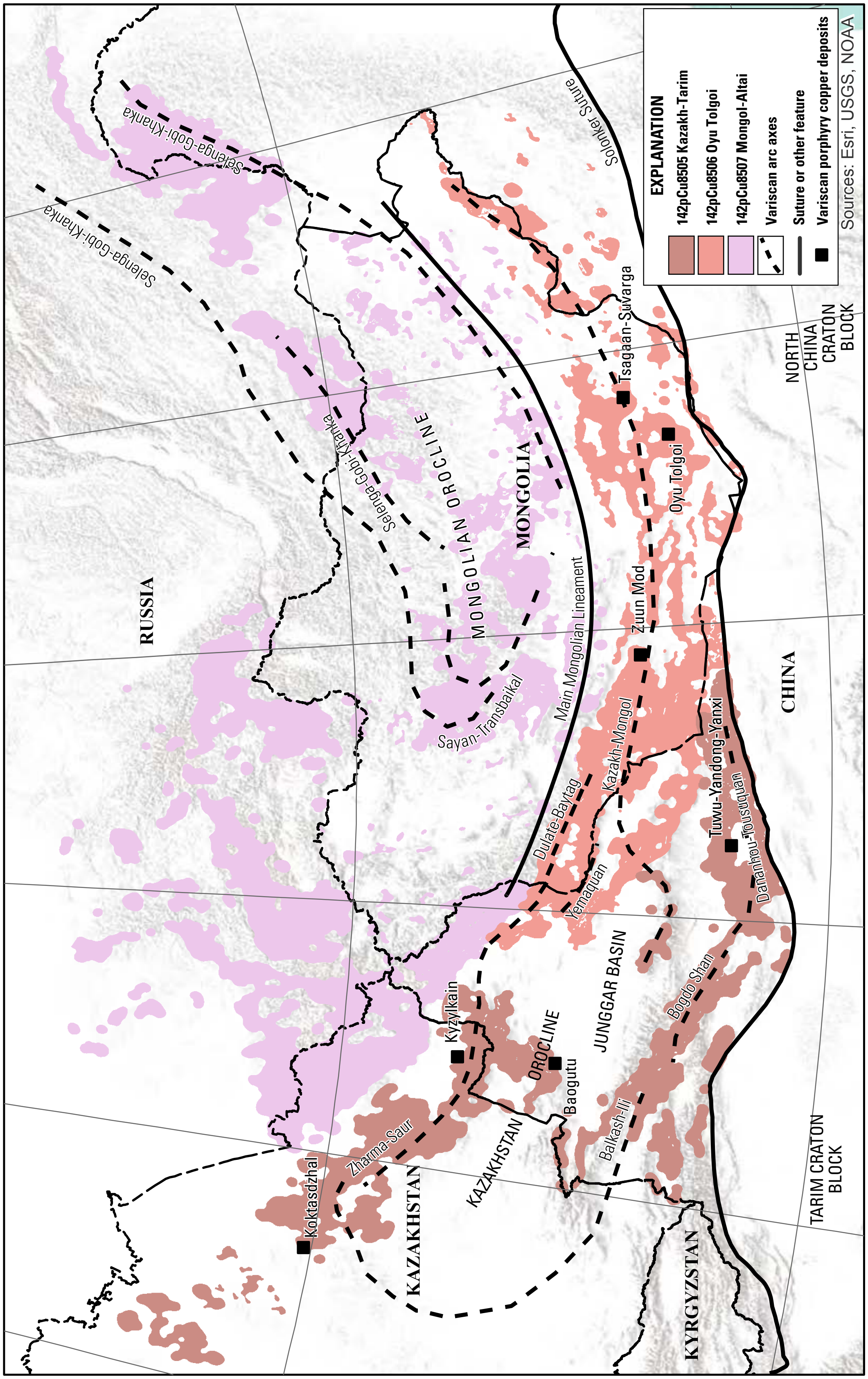
[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton, n.d., no data. *, Solonker tract includes rocks as young as Indosinian. See appendix B for sources of resource data]

Tract	Tract Name	Name	Country	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)
Central Asia Orogenic Belt—early Paleozoic (Caledonian time)										
142pCu8501	Solonker	Chehugou*	China	257.5	178.6	0.14	0.07	n.d.	n.d.	250,000
142pCu8502	Kazakh-Tianshan	Bozshakol	Kazakhstan	481	1,000	0.67	0.023	0.049	1.61	6,700,000
142pCu8502	Kazakh-Tianshan	Kyzyltu	Kazakhstan	445	65.8	0.48	0.015	0.2	6.56	320,000
142pCu8502	Kazakh-Tianshan	Nurkazgan	Kazakhstan	410	213	0.81	0.01	0.26	2.5	1,725,300
142pCu8503	Gobi-Amur	Duobaoshan	China	485	644	0.52	0.02	0.255	6.1	3,300,000
142pCu8504	Mongol-Sayan	Aksug	Russia	516	805.2	0.52	0.014	0.156	0.99	4,200,000
142pCu8504	Mongol-Sayan	Sora	Russia	396.5	323.5	0.17	0.058	0.017	2.3	550,000
142pCu8504	Mongol-Sayan	Agaskyr	Russia	n.d.	310.5	0.032	0.05	n.d.	1.64	99,400
142pCu8504	Mongol-Sayan	Kiyalykh-Uzen	Russia	470	30	1.0	0.05	n.d.	n.d.	300,000
Central Asia Orogenic Belt—late Paleozoic (Variscan and Indosinian time)										
142pCu8505	Kazakh-Tarim	Tuwu-Yandong-Yanxi	China	328	674.3	0.61	0.01	0.1	1.28	4,100,000
142pCu8505	Kazakh-Tarim	Kyzylkain	Kazakhstan	325	542	0.3	0.005	n.d.	n.d.	1,626,000
142pCu8505	Kazakh-Tarim	Baogutu	China	311	225	0.28	0.011	0.1	1.8	630,000
142pCu8505	Kazakh-Tarim	Koktasdzhal	Kazakhstan	292	57	0.62	n.d.	0.72	3.8	353,400
142pCu8506	Oyu Tolgoi	Oyu Tolgoi	Mongolia	372	3,754.6	0.98	0.01	0.38	n.d.	37,000,000
142pCu8506	Oyu Tolgoi	Zuun Mod	Mongolia	n.d.	650	0.063	0.046	n.d.	n.d.	409,500
142pCu8506	Oyu Tolgoi	Tsagaan-Suvarga	Mongolia	370	240	0.53	0.018	0.084	2.6	1,272,000
142pCu8508a	Erdenet Southwest	Erdenet	Mongolia	240.7	2,370	0.38	0.013	n.d.	n.d.	9,006,000
Tethyside region—early Paleozoic through Indosinian										
142pCu8701	Qinling-Dabie	Saishitang	China	226	128	1.13	n.d.	0.48	n.d.	1,400,000
Tethyside region—late Paleozoic and Mesozoic										
142pCu8702	Jinsajiang	Pulang	China	213	1,229	0.34	0.01	0.18	1.27	4,200,000
142pCu8702	Jinsajiang	Xuejiping	China	225	60	0.5	n.d.	0.06	1.4	300,000



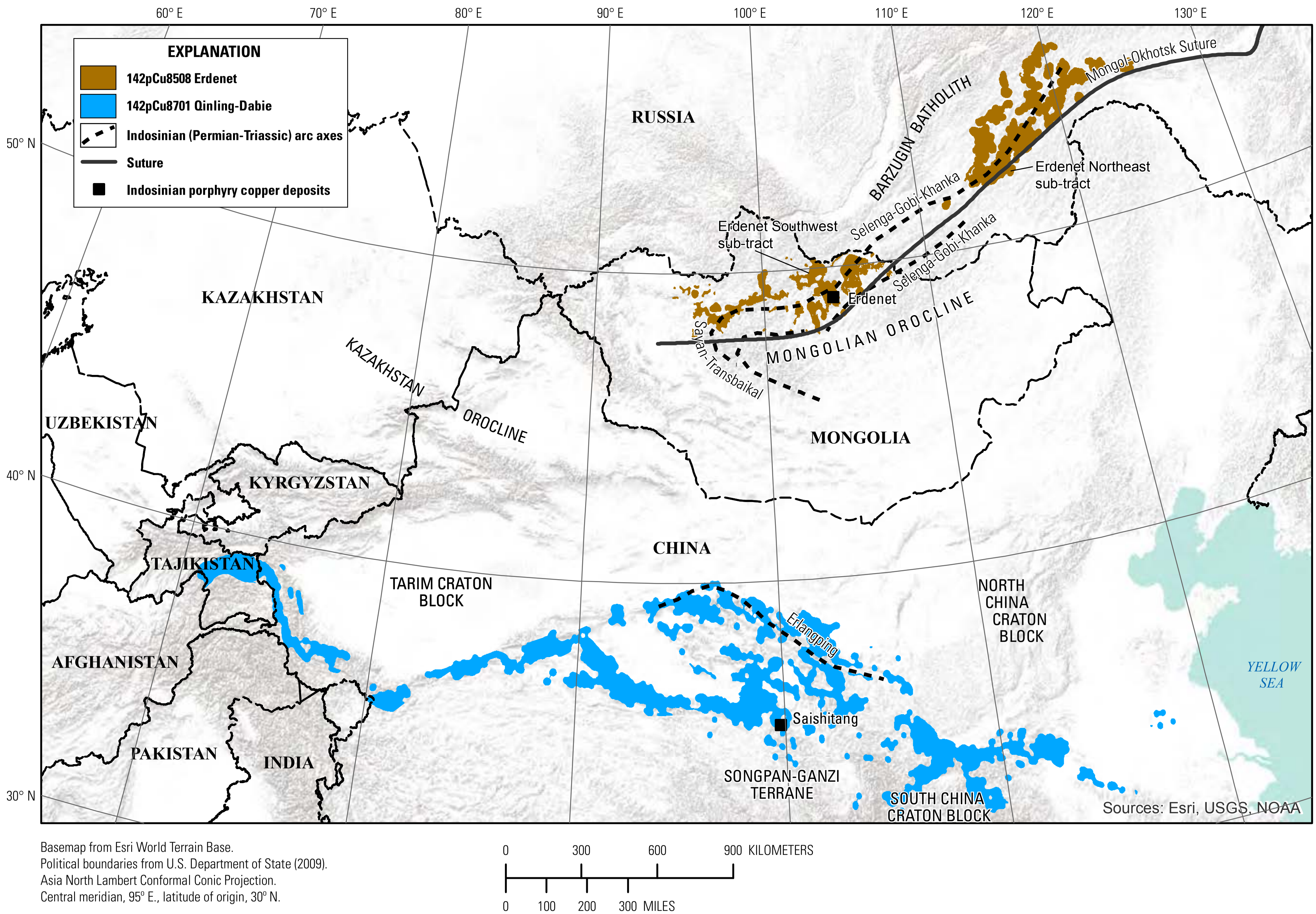
Basemap from Esri World Terrain Base.
Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.

Figure 5. Map of the Central Asia Orogenic Belt showing Caledonian age (540 to 400 million years ago) arcs, porphyry copper deposits, and assessment tracts.



Basemap from Esri World Terrain Base.
Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.

Figure 6. Map of the Central Asia Orogenic Belt showing Variscan age (400 to 280 million years ago) arcs, porphyry copper deposits, and assessment tracts.



Basemap from Esri World Terrain Base.
Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.

Figure 7. Map of the Indosinian (280 to 200 million years ago) Erdenet permissive tract of the Central Asia Orogenic Belt and the Caledonian (540 to 400 million years ago) through Indosinian Qinling-Dabie orogen of the Tethysides region showing porphyry copper deposits.

Indosinian Through Early Tertiary Magmatism

Further south, along the northeastern margin of the Tibetan Plateau, several Permian and Triassic continental arcs and island arcs are incorporated into the Jinsa Suture that separates the Qiangtang Terrane to the southwest and the Songpan-Ganze and Yangtze (South China) Terranes to the north and east (fig. 8). This suture marks the closure of the Paleotethys Ocean at the end of Indosinian time, in the Late Triassic. The Jiangda-Weixi and Zugong-Jinghong (fig. 8) are both continental arcs of Permian age that contain no known porphyry copper deposits. The Yidun (or Zhongdian) island arc is a somewhat younger (Triassic) feature that contains two known porphyry copper deposits, Pulang and Xuejiping, and a number of poorly explored prospects (table 2, fig. 8) (Hou and others, 2007). The Permian and Triassic igneous rocks accreted to the Yangtze and Songpan-Ganze Terranes define the Jinsajiang tract (142pCu8702).

After the docking of the Qiangtang Terrane, at the end of the Triassic, arc volcanism continued in response to subduction within and at the northern margin of the Tethys Ocean until the Paleocene docking of the Indian continental block with Asia. One set of plutonic rocks characterizes the Bangong-Nujiang Suture (fig. 8), which marks the middle Jurassic accretion of the Lhasa microcontinental terrane to the Qiangtang Terrane. These rocks, emplaced into largely continental crust, range in age from Jurassic through middle Cretaceous. There are no fully explored deposits in this region, but the 118 Ma Duolong prospect, discovered in about 2000, is actively undergoing development and contains at least 4 million metric tons (Mt) of copper, likely more (Rui and others, 2005; Tse, 2008; Li and others, 2011a). In the southern part of the Lhasa Terrane, the continental-margin Gangdese batholith and associated volcanic rocks range in age from middle Cretaceous to Paleocene. There are no known porphyry copper deposits. Together, all these Mesozoic and earliest Tertiary arc rocks define the Tethyan Gangdese tract (142pCu8706). Post-Paleocene igneous activity and porphyry copper deposits are described in a porphyry copper assessment of the Tibetan Plateau by Ludington and others (2012a).

Exploration History

In many parts of the world, porphyry copper exploration activity has been cyclic in response to changing global economic trends and the evolution of local infrastructure development. Exploration methods for porphyry copper deposits based on porphyry copper deposit models were not well known in China until the 1960s, when scientific and industrial activity was renewed after a long period of warfare and internal turmoil. Access to the region was also difficult due to limited infrastructure. Subsequently, basic geologic mapping and detailed geochemical and geophysical surveys have been completed, resulting in the discovery of numerous porphyry copper deposits and prospects. Remote-sensing techniques are increasingly being used in rarely visited areas to map alteration and identify targets for follow-up field investigations (Liu and others, 2013). A few international companies based outside of China have operated in the region since about 1990, but most of the exploration activity has been conducted by Chinese companies and is not well documented in the English language literature.

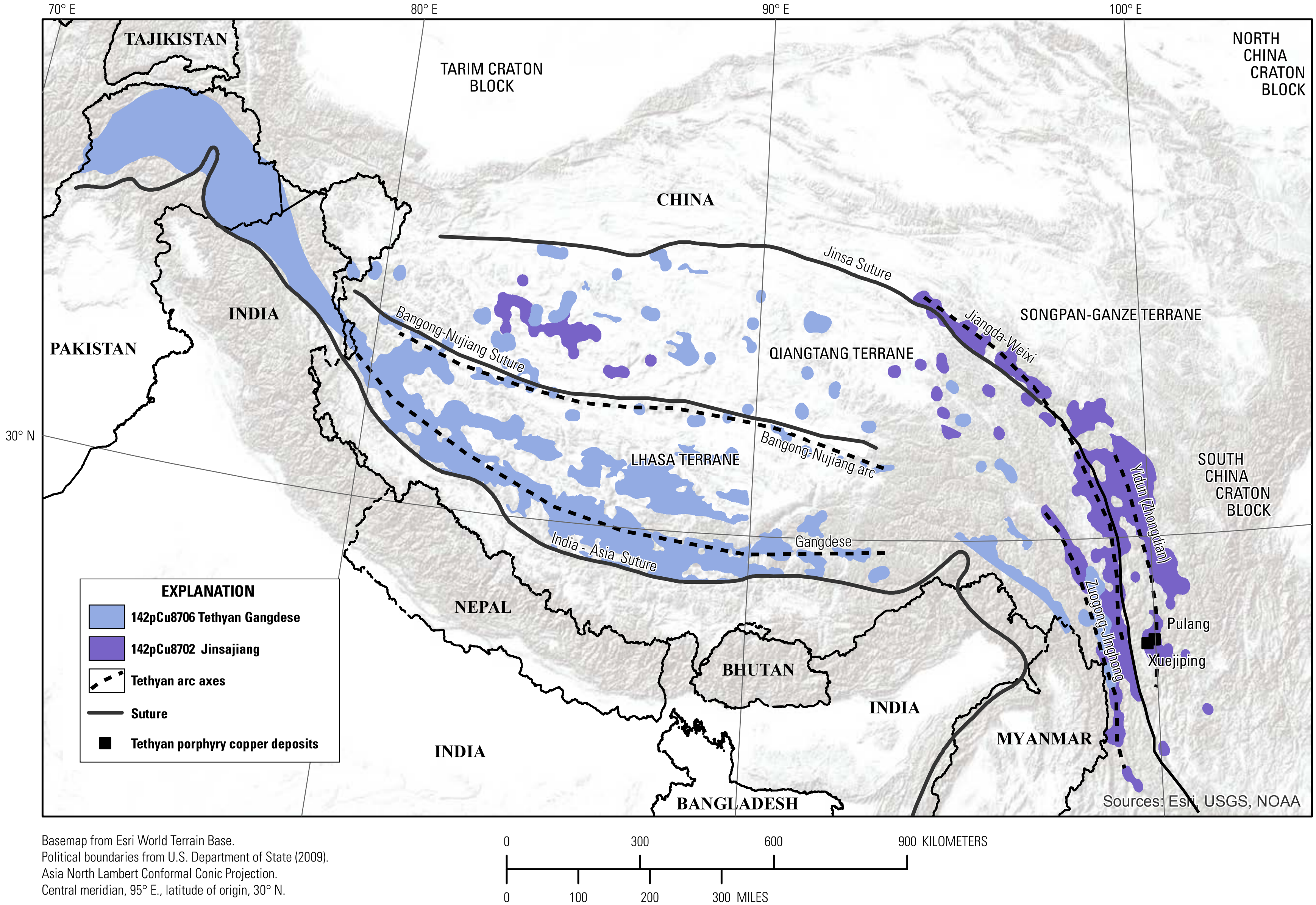
More than 99 percent of Mongolia has been mapped at a scale of 1:200,000, and about 25 percent of the country has been mapped and explored at a scale of 1:50,000. Aerial multispectral surveys at scales of 1:50,000 and 1:25,000 cover about 30 percent of the country (Javkhlanbold, 2006). Many of the prominent exposed mineralized systems were first discovered before 1991 and the information produced before that time is difficult to access. Recent private sector exploration using modern methods is expected to result in new discoveries, as exemplified by the discovery in the late 1990s of the giant Oyu Tolgoi porphyry copper deposit (Perelló and others, 2001). In July 2014, the Mongolian parliament ended a 4-year moratorium on issuing new mineral exploration licenses and extended exploration periods from 9 to 12 years (Kohn, 2014).

Before its breakup, exploration in the former Soviet Union was state sponsored. Geochemical exploration data (for example, stream sediment) and commodity occurrences are recorded on 1:200,000 scale maps produced mainly in the 1960s and 1970s, but detailed reports are not in the public domain. In recent years, strict mining laws limit amounts of foreign investment and exploration in Russia. Much of the recent exploration activity in the parts of eastern Kazakhstan covered in this report is focused on massive sulfide deposits and orogenic gold. In April 2013, Kazakhstan lifted a 4-year ban on the issuance of new mineral exploration licenses.

Tract Delineation

The geology-based strategy for permissive tract delineation used in this assessment is described below. Digital geologic data were processed in a GIS using Esri ArcMap software as follows:

- Regional-scale maps and geologic literature were used to identify the fundamental units for tract delineation (magmatic arcs or belts of igneous rocks of a given age range and petrologic association).
- Digital geologic maps were then used to select map units to define preliminary tracts permissive for porphyry copper deposits. Igneous map units were subdivided by age groups and classified as permissive or nonpermissive based on lithology. Permissive rocks include calc-alkaline and alkaline plutonic and volcanic rocks. Nonpermissive rocks include, for example, basaltic and ultramafic assemblages, ophiolitic assemblages, highly evolved granites, and peraluminous granites.
- Typically, a 10-km buffer was then applied to plutonic rock polygons or a 2-km buffer was applied to volcanic rock polygons. This generally expanded the area of



Basemap from Esri World Terrain Base.
Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.

Figure 8. Map of the Tethysides region showing Permian, Mesozoic, and Paleocene magmatic arcs, porphyry copper deposits, and assessment tracts.

the tract to include all porphyry copper deposits and significant associated prospects.

- After buffering, available data on mineral occurrences, locations of dated igneous rock samples, and geophysical and geochemical information were examined to identify previously unrecognized evidence of unmapped permissive rocks or hydrothermal systems. Scanned and rectified page-size illustrations from the literature were incorporated in the GIS database to check locations and permissive rock boundaries. In a few instances,10-km-wide buffers were also placed at known locations of porphyry copper deposits, significant prospects, and prospects if intrusive rocks were reported from the literature and depicted in deposit-scale maps but not shown at the regional scale of the available digital map base.
- An aggregation and smoothing routine was applied to the resulting polygons, and the tracts were further edited by hand to insure that all units were contained within the delineated permissive area. In many cases, more detailed geologic maps were used to resolve tract boundary issues. Tract boundaries were also edited to honor major tectonic boundaries.
- Areas where postmineral volcanic centers, depositional basins, and other forms of cover were judged to exceed 1 km in thickness were excluded from the tracts. Intrusions younger than the designated tract age were also excluded. Volcanic rocks younger than the designated tract age, but inferred to be less than 1 km thick, were included within permissive areas.

The different mapping scales and mapping styles available for the assessment posed challenges in identifying permissive versus nonpermissive rocks. Some map units considered permissive unavoidably contain rock types that would normally be excluded. Similar issues exist with respect to the generalized stratigraphic ages assigned to some map units. More detailed geologic maps would likely result in a smaller, more restrictive tracts.

Estimating Numbers of Undiscovered Deposits

The assessment team evaluated the available data and made individual, subjective, initially blind estimates of the numbers of undiscovered porphyry copper deposits using expert judgment. Estimates are expressed in terms of different levels of certainty. Estimators were asked for the least number of deposits of a given type that they believe could be present at 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 one, a 50-percent chance of at least three, and a 10-percent chance of at least five undiscovered deposits in a permissive tract. The individual blind estimates were then shared and discussed as a group, and a consensus estimate was agreed upon by the team for each tract.

The estimates were converted to a mean number of undiscovered deposits and associated standard deviation based on the algorithm developed by Singer and Menzie (2005). The algorithm can be described by the following general equations to calculate a mean number of undiscovered deposits (λ) and a standard deviation (s_x) based on estimates predicted at different quantile levels[12] (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 spreadsheet to allow the team to quickly evaluate their estimates. The difference between the number of undiscovered deposits associated with the 90th percentile and the 10th percentile or 1st percentile is a measure of uncertainty; large differences suggest great uncertainty. Estimates of number of deposits explicitly represent the probability (or degree of belief) that some fixed but unknown number of undiscovered deposits exist in the delineated tracts (Singer, 2007a). 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 ($100 \times C_v$). Thus, the final team estimates reflect both the uncertainty in what may exist and the favorability of the tract (Singer, 2007a).

The estimates were combined with appropriate grade and tonnage models in a Monte Carlo simulation using the EMINERS computer program (Bawiec and Spanski, 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 were applied, so results must be viewed with the understanding that deposits, even if discovered, may not be feasible.

The rationales for individual tract estimates are discussed in the tract descriptions below. In some cases, the density of known significant porphyry copper prospects within a tract was also used as part of the basis for estimates at the 90th and 50th quantiles. Particular weight was given

[12]To use the equation in cases where three nonzero 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}.

to significant 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 published literature, company Web sites, and technical reports for exploration projects were examined 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.

In addition, the distribution of reported copper and gold occurrences of unknown type and placer gold workings are relevant. The level of exploration was also a factor in making estimates. In less well-explored areas, and in areas with poor documentation of mineral occurrences, such methods could not be used effectively. The spread in estimates, and their relatively high coefficients of variation, reflect higher degrees of uncertainty. In a few cases, team members provided information about prospects based on personal observations from site visits.

Assessment of Tracts in the Central Asian Orogenic Belt and Eastern Tethysides

The assessment for each permissive tract in the Central Asian Orogenic Belt and eastern Tethysides is described below in a standardized format that begins with a reference to the descriptive and the grade and tonnage model used and a brief statement describing the fundamental geologic feature that formed the basis for delineation of the tract. This is followed by descriptions of the tract location, tectonic setting, geologic criteria for tract delineation, and a discussion of important deposits, significant prospects, and prospects. For each tract, map figures show (1) the permissive tract with porphyry copper deposits and significant prospects within it and (2) the distribution of permissive intrusive and extrusive rocks that formed the basis for tract delineation, along with any significant geologic features mentioned in the tract description.

The criteria used to select the grade and tonnage model for the probabilistic assessment of undiscovered resources are summarized in table 3 and discussed in the text. Estimates of numbers of undiscovered deposits and results of the Monte Carlo simulation are also presented in tables and as cumulative frequency plots. The tables list estimates at the different levels of certainty, the probabilistic amounts of undiscovered resources and associated statistical parameters, and the deposit densities for each tract. Because tract delineation is a subjective process, it could be misleading to place great credence in calculated deposit densities, especially for large tracts based on small-scale geologic map units. In most cases, the assessment team's subjective estimate is consistent with worldwide deposit density estimates (Singer and Menzie, 2010; Singer, 2008, 2010; Singer and others, 2005).

Results of the Monte Carlo simulations for each tract are shown graphically as cumulative frequency plots. These graphs show the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean for each commodity and for total mineralized rock.

Early Paleozoic Tracts in the Central Asia Orogenic Belt

Four permissive tracts in the CAOB include rocks as old as the early Paleozoic (Caledonian). The Caledonian tracts (fig. 5) are described here from south to north.

Solonker Tract (142pCu8501)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Paleozoic through Triassic igneous rocks, primarily in northern China, that includes the early Paleozoic Bainaimiao island arc, a late Paleozoic continental arc formed by south-directed subduction of the Paleo-Asian Ocean beneath the North China Craton, and Permian-Triassic rocks formed as a result of the collision of the North China and Tarim Cratons (Manchurides) with the Eurasian Continent (Altaids)

Location

The Solonker tract is a 2,400-km-long by as much as 300-km-wide belt that extends from easternmost Xinjiang eastwards through the southern Gobi Desert (fig. 1) to the lowlands north of Beijing, in northeastern China (fig. 9). Except for a very small part in Mongolia, the tract lies within China.

Tectonic Setting

The Solonker tract is named for the Solonker Suture (fig. 5), an east-west zone that marks the final closure of the Paleo-Asian Ocean during the convergence of the North China and the Siberian Cratons in Permian time. This tract consists of an assemblage of Caledonian and Variscan igneous rocks that belong to island arcs and continental arcs that formed along the northern margin of the North China and Tarim Cratons before the closure, along with a few Permian-Triassic igneous rocks that formed during and immediately after closure. Thus, three different magmatic systems are superimposed here—(1) a Cambrian-Ordovician island arc that formed in the Paleo-Asian Ocean, (2) a Carboniferous and Permian continental arc formed by south-directed subduction of the Paleo-Asian Ocean beneath the North China and Tarim Cratons, and (3) collisional and postcollisional rocks that formed in the Permian and Triassic (Indosinian).

Table 3. Statistical test results for grade and tonnage model selection, porphyry copper assessment of the Central Asian Orogenic Belt and eastern Tethysides.

[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 global models of Singer and others (2008) at the 1-percent level; *, fails *t*-test; Cu, copper; Mo, molybdenum; Ag, silver; Au, gold; t, metric tons; n.d., no data]

Tract	Tract name	N_{known}	Model tested	*p* values						Model selected	Rationale
				t	Cu	Mo	Ag	Au	Contained Cu		
142pCu8501	Solonker	1	Cu-Au-Mo	0.85	0.015	0.08	n.d.	n.d.	0.39	Cu-Au-Mo	*t*-test results; Au and Mo associated with significant prospects
142pCu8502	Kazakh-Tianshan	3	Cu-Au-Mo	0.98	0.14	0.7	0.43	0.87	0.79	Cu-Au-Mo	*t*-test results
142pCu8503	Gobi-Amur	1	Cu-Au-Mo	0.5	0.69	0.62	0.2	0.71	0.46	Cu-Au-Mo	*t*-test results
142pCu8504	Mongol-Sayan	4	Cu-Au-Mo	0.93	0.83	0.02	0.59	0.24	0.89	Cu-Mo subtype	*t*-test results; Mo-rich known deposits and prospects
			Cu-Mo subtype	0.44	0.85	0.39	0.91	0.17	0.44		
142pCu8505	Kazakh-Tarim	4	Cu-Au-Mo	0.89	0.92	0.5	0.96	0.55	0.92	Cu-Au-Mo	*t*-test results
142pCu8506	Oyu Tolgoi	3	Cu-Au-Mo	0.15	0.27	0.38	0.77	0.88	0.3	Cu-Au-Mo	*t*-test results
142pCu8508a	Erdenet Southwest	1	Cu-Au-Mo	0.12	0.78	0.94	n.d.	n.d.	0.18	Cu-Au-Mo	*t*-test results
142pCu8701	Qinling-Dabie	1	Cu-Au-Mo	0.68	0.04	n.d.	n.d.	0.39	0.83	Cu-Au-Mo	*t*-test results
142pCu8702	Jinsajiang	2	Cu-Au-Mo	0.9	0.88	0.85	0.5	0.66	0.94	Cu-Au subtype	Deposits in the tract are Au-rich; the geology of the tract is a continuation of the Au-rich Sukhotai tract to the south (Hammarstrom and others, 2013).
			Cu-Au subtype	0.77	0.85	0.27	0.34	*0.001	0.83		

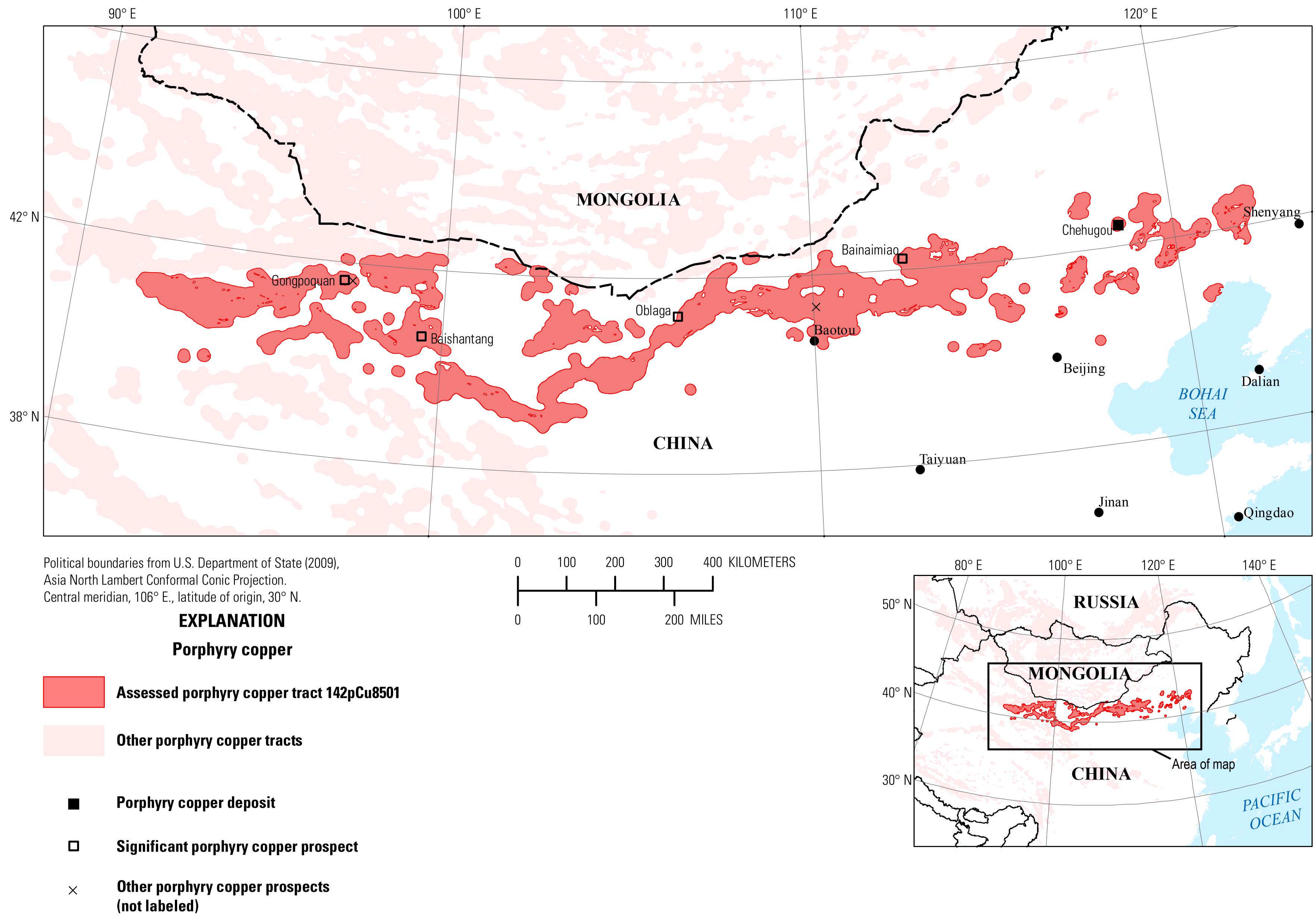


Figure 9. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8501, Solonker—China.

Geologic Criteria

The Solonker tract was defined using calc-alkaline, intermediate-composition igneous map units with map unit ages of Caledonian, Cambrian, Ordovician, Silurian, Variscan, Hercynian, Devonian, Carboniferous, and Permian (fig. 10). Intrusive map units include granite, diorite, monzonite, and syenite. Extrusive units include primarily rhyolite and andesite closely associated with permissive intrusive units, with lesser amounts of dacite.

The Solonker tract is bound on the north by the Variscan Solonker Suture. The tract pinches out to the west against the eastern margin of the Tarim Craton. To the south, the western half of the tract is bound by various Caledonian and Variscan sutures and faults associated with the northern Qinling-Dabie orogen, and the eastern half of the tract is bound by the northern margin of the Sino-Korean (or North China) Craton. The eastern end of the tract is limited by the eastern margin of the CAOB, beyond which the magmatic history is related to Mesozoic Pacific-margin subduction. The extent of the tract was primarily delineated by the selection of appropriate map units and the distribution of mineral deposits.

Known Porphyry Deposits

Chehugou

Chehugou, the only porphyry copper deposit in the tract, is an example of a group of deposits that seem to be common in eastern Asia that have subequal copper and molybdenum grades. Although vein deposits had been known since 1956, the porphyry deposit was recognized only in 2007 (Zeng and others, 2011). The deposit is relatively small, with a copper resource reported as about 178,000,000 t with a copper grade of 0.14 percent. The molybdenum grade is reported to be 0.1 percent.

The deposit is related to a Permian syenogranite porphyry stock with a zircon SHRIMP (sensitive high resolution ion microprobe) age of about 245 Ma (Zeng and others, 2011). Molybdenite from the deposit has a rhenium-osmium (Re-Os) date of about 258 Ma (Liu and others, 2010). Hydrothermal alteration is primarily phyllic (Zeng and others, 2011).

Prospects, Mineral Occurrences, and Related Deposit Types

Information was available for six porphyry copper prospects in the tract, four of which are judged to be particularly significant (fig. 9, appendix B). The Bainaimiao prospect has been known since 1959. Its classification and age are both controversial. Jian and others (2007) interpret two distinct mineralization episodes, a Caledonian age volcanogenic massive sulfide overprinted by Permian-Triassic porphyry-style mineralization. Other workers discount the massive sulfide interpretation but disagree about the age, which has been determined variously as about 466 Ma, 429 Ma, and 396 Ma. The latter is an argon (Ar^{40}-Ar^{39}) age determination on hydrothermal biotite (Li and others, 2008b), which likely represents the mineralization age. Li and others (2008b) interpreted the deposit as an orogenic deposit rather than a porphyry or sedimentary exhalative deposit on the basis of fluid inclusions and an age that correlates with peak metamorphism of the host rocks.

There is a partial resource of more than 500,000 t of copper with a mean grade of 0.91 percent copper (Jian and others, 2007). The prospect is still being explored. Baishantang, Gongpoquan, and Oblaga all appear to be small vein and (or) skarn deposits associated with porphyry-style mineralization (appendix B). Exploration at Oblaga by Ivanhoe Mines, Ltd., in 2003 described high-grade copper-gold skarns and porphyry-related quartz-chalcopyrite-molybdenite-bornite-pyrite veinlets (Ivanhoe Mines, Ltd., 2004). Oblaga had been mined on a small-scale by local Chinese operators as a porphyry-related copper-gold mine.

Grade and Tonnage Model Selection

There is only one known porphyry copper deposit in the tract, Chehugou (table 2). ANOVA tests of the tonnage and grade data for Chehugou at the 1-percent confidence level using log-transformed values for ore tonnage, as well as copper and molybdenum grades, indicate that Chehugou is not distinguishable from the general global porphyry copper model of Singer and others (2008). Also, both gold and molybdenum are reportedly associated with significant copper prospects in the tract.

Estimates of Undiscovered Deposits and Rationale

One deposit, Chehugou, and four significant prospects are known across the ~250,000 km^2 Solonker tract. Small-scale mining of Cu-Au skarn ore at the Oblaga prospect (1987) might be related to a deep-seated porphyry system. Bainaimiao has an estimated reserve in excess of 500,000 t copper, defined by drilling and trenching, and could achieve deposit status if ongoing exploration reveals additional resources. Baishantang has a reported resource of 179,000 t copper. In addition, there are at least two other prospects that have been identified in the Chinese-language scientific literature (see appendix B).

The assessment team noted that some of the prospects in this tract were not unequivocally porphyry copper types and that available data for these occurrences indicates a Variscan age. This tract represents a combination of mainly Caledonian and Variscan rocks, and the team suspected that most of the undiscovered deposits within this tract would likely be associated with Variscan permissive rocks, rather than Caledonian rocks.

The level of mineral exploration was considered to be moderate to high. However, exploration in this region has

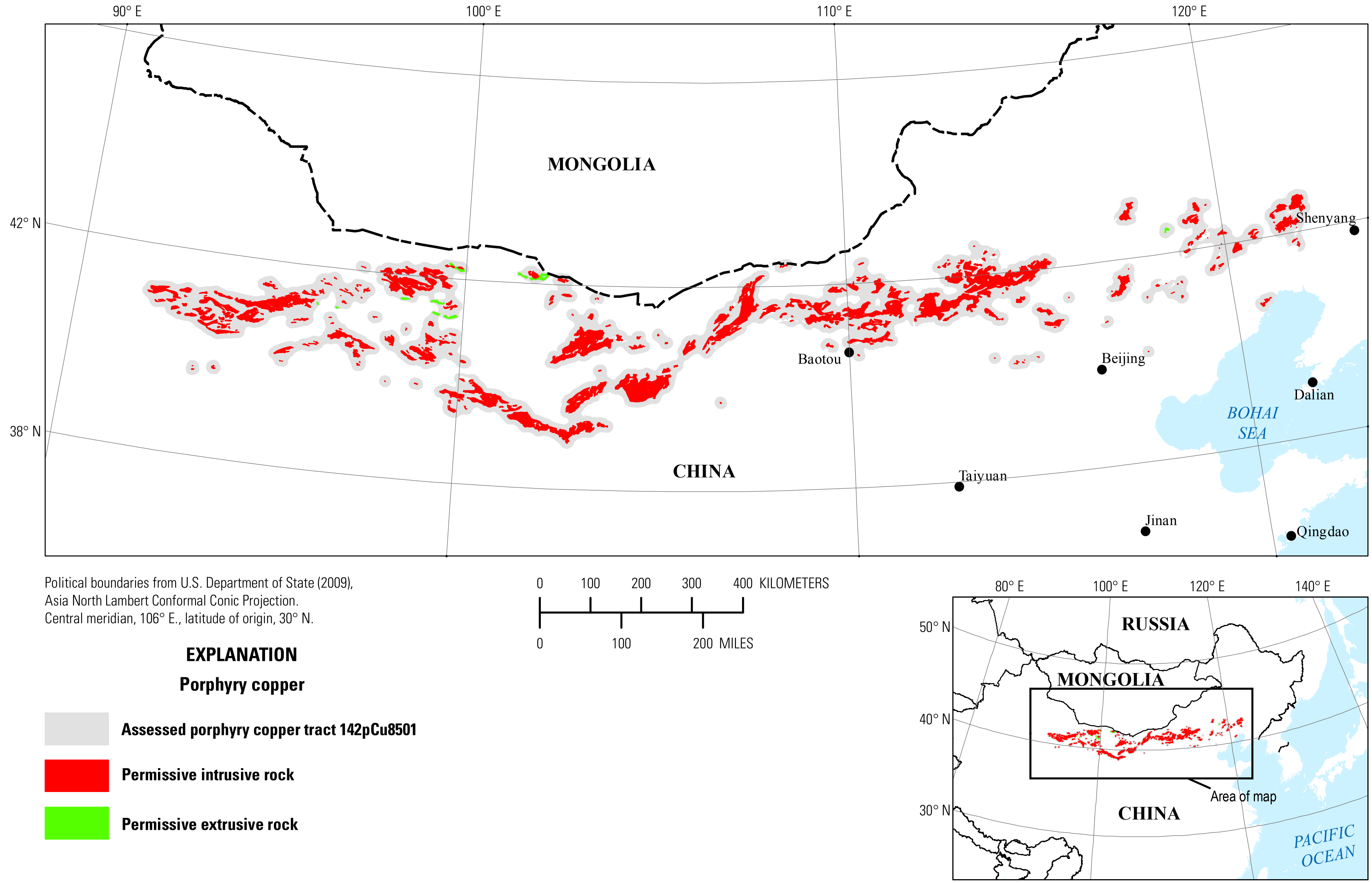


Figure 10. Map showing the distribution of permissive rocks used to delineate tract 142pCu8501, Solonker—China.

focused primarily on small high-grade, vein-type orogenic gold and rare-earth element (REE) deposits (for example, the Bayan Obo REE-Fe-Nb deposit) rather than large, low-grade porphyry deposits. Although only a few exploration and detailed mineral investigations have taken place, mainly in the eastern and central part of the tract (see maps available at China Geological Survey, 2005), the entire area has been covered by geochemical surveys and has been evaluated for mineral resources at a reconnaissance level. Maps showing the degree of mineral resource exploration and geologic research (China Geological Survey, 2012) indicate that high levels of activity have taken place mostly in the eastern part of the tract.

The team estimated a 90-percent chance for 1 or more undiscovered deposits in the tract, a 50-percent chance of 2 or more deposits, and a 10-percent chance of 15 or more deposits, for a mean of 5.5 expected undiscovered deposits (table 4*A*).

In a previous assessment (Yan and others, 2007), four upper and lower Paleozoic age assessment tracts (X-2, X-3, IX-6, and III-1) are largely coincident with all but the easternmost part of the Solonker tract. Their estimate for these areas totaled 5.8 undiscovered deposits, which is similar to the estimate of 5.5 made here.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources was 22 Mt of copper (table 4*B*), far in excess of the 250,000 t of copper identified at Chehugou. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 4*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 11).

Kazakh-Tianshan Tract (142pCu8502)

Descriptive models: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: A varied assemblage of Cambrian through Silurian igneous rocks in northeastern Kazakhstan and northwestern China

Location

The Kazakh-Tianshan tract is a northwest-trending belt about 1,200 km long and as much as 200 km wide in northeast Kazakhstan and far northwestern China (Xinjiang Autonomous Area) (fig. 12). Berger and others (2014) provided a detailed discussion of the early Paleozoic tectonics and porphyry copper potential for eastern Kazakhstan, but did not assess this area.

Tectonic Setting

This area was largely formed by the early Silurian in the eastern part of the Gondwana supercontinent by accretion and collision of ribbon microcontinents and island-arc terranes (Wilhem and others, 2012) but did not arrive at its present location, relative to Eurasia, until the Triassic. The tract outlines segments of these Caledonian-age island arcs in eastern Kazakhstan and western China that formed before the Variscan-age deformation that resulted in the formation of the Kazakhstan Orocline. The arcs include Kipchak Arc segments known as the Selety, Baidulet-Akbastau, and Bozshakol-Chingiz Arcs (fig. 5) along the eastern margins of the orocline (Windley and others, 2007; Wilhem and others, 2012). The tract includes tectonically juxtaposed Early and Middle Cambrian and Late Cambrian-Early Ordovician island arcs preserved in fragments in volcanic belts (Degtyarev, 2011). These early Paleozoic arcs in the western part of the CAOB are extensively fragmented and deformed by Late Devonian and younger events. During the Triassic, large northwest- and east-west-trending strike-slip faults further segmented the arcs.

Geologic Criteria

The Kazakh-Tianshan tract was defined using calc-alkaline, intermediate-composition igneous map units with map unit ages of Cambrian, Ordovician, and Silurian as shown on a digital geologic map of Central Asia (Seltmann and others, 2012). Plutonic units are mainly granodiorite, tonalite, quartz diorite, and diorite. Volcanic units are mainly andesite and dacite. The permissive rocks include the Late Ordovician Qryqquduk Complex in the Selety Arc (fig. 5), where large volumes of granitoids were emplaced along faults and fault intersections and cut by later faults. Intrusive bodies have the form of lopoliths or intrusive sheets as much as 8 km thick with flat bottoms, as indicated by geophysical data (Degtuyarev, 2011).

The tract includes four main segments (fig. 13). The southeastern segment of the tract outlines an area in the Xiemisitai Mountains in the northern West Junggar area of China (fig. 13), where Late Silurian to Early Devonian (423–411 Ma) extrusive rocks and subvolcanic, caldera-related intrusions associated with porphyry copper occurrences are described (Shen and others, 2010a; Shen and others, 2012). The tract here is based on the extent of a copper geochemical anomaly and mapping of Late Silurian extrusive rocks (andesite, tuff, and rhyolite) and subvolcanic felsite and granite porphyry (fig. 3 in Shen and others, 2012). These rocks likely represent an extension of the Bozshakol-Chingiz Arc (fig. 13) and metallogenic belt of eastern Kazakhstan (Shen and others, 2012).

The tract is bounded on the west by the core of the Kazakhstan Orocline and younger permissive tracts assessed by Berger and others (2014). The tract extends to the eastern extent of known permissive rocks of Caledonian age in western China.

Known Porphyry Deposits

There are three known porphyry copper deposits in the tract, Kyzltu, Bozshakol, and Nurkazgan, all in Kazakhstan (table 2, fig. 12). They are all Ordovician or Silurian in age, with radiometric ages ranging from 481 Ma to 410 Ma. Bozshakol is the largest. These deposits are also described by Berger and others (2014).

Table 4. Probabilistic assessment results for tract 142pCu8501, Solonker—China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	2	15	15	15	5.5	5.4	97	1	6.5	250,100	3

B. Results of Monte Carlo simulations of undiscovered resources.

[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	190,000	7,600,000	60,000,000	90,000,000	22,000,000	0.32	0.07
Mo	0	0	140,000	1,600,000	2,800,000	600,000	0.26	0.21
Au	0	0	180	1,500	2,300	540	0.32	0.19
Ag	0	0	1,400	20,000	33,000	7,500	0.25	0.29
Rock	0	49	1,700	12,000	18,000	4,500	0.33	0.07

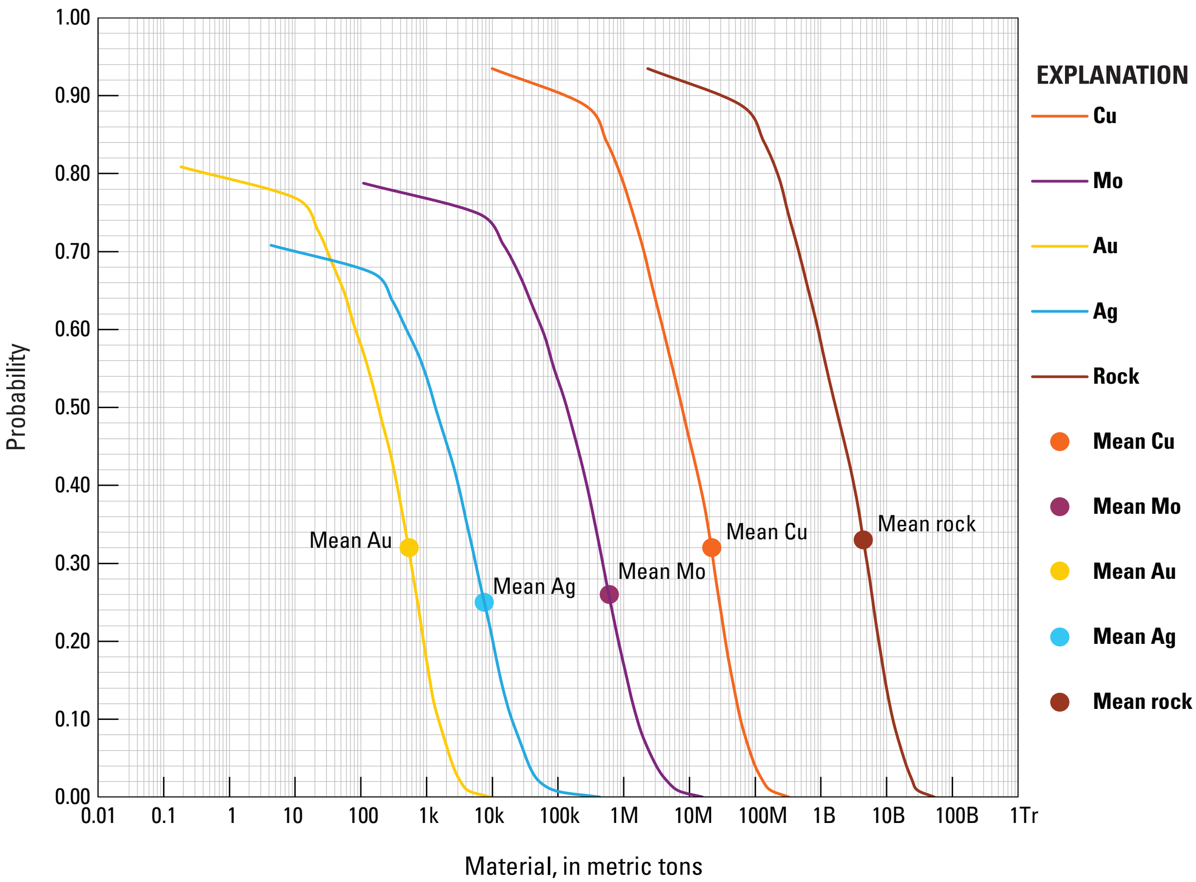


Figure 11. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8501, Solonker—China. k=thousands, M=millions, B=billions, Tr=trillions.

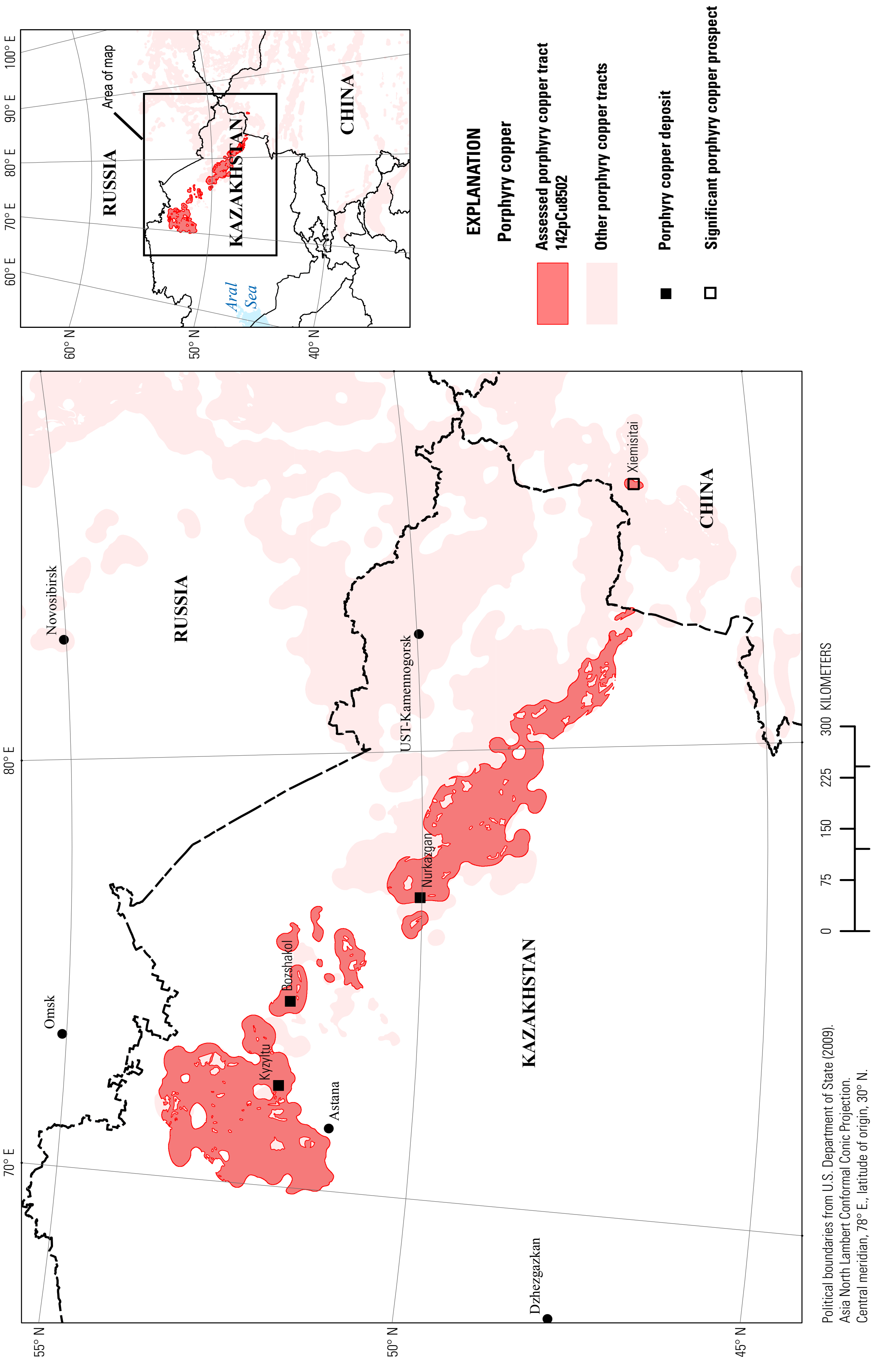


Figure 12. Map showing the location, known deposits, and significant prospects for permissive tract 142pCu8502, Kazakh-Tianshan—Kazakhstan and China.

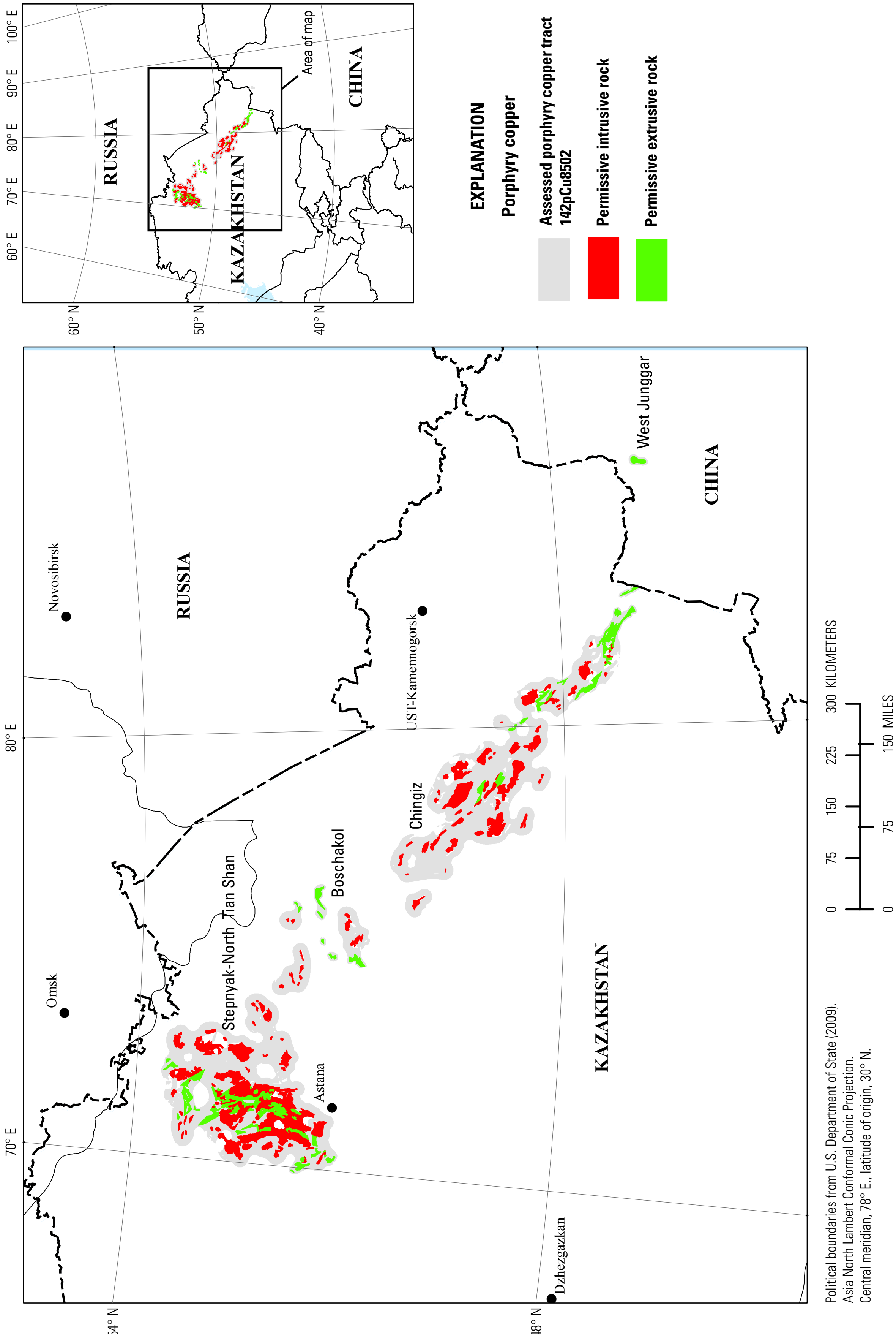


Figure 13. Map showing the distribution of permissive rocks used to delineate tract 142pCu8502, Kazakh-Tianshan—Kazakhstan and China.

At Bozshakol, in the northern part of Kazakhstan, a feasibility study has been completed, the mine is under construction, and mining is expected to commence by 2015 (Kazakhmys PLC, 2011). It is a large deposit, containing more than 4,000,000 t of copper. The main ore-related intrusion is a porphyritic tonalite that is the final intrusion of a suite of dioritic, quartz dioritic, and tonalitic rocks (Porter Geoconsultancy, 2004). Seltmann and Porter (2005) report an age for the deposit of 481 Ma.

Prospects, Mineral Occurrences, and Related Deposit Types

Information was available about only one porphyry copper prospect, the newly discovered Xiemistai, in Xinjiang, which has a uranium-lead (U-Pb) date of 423 Ma (Shen and others, 2010a). The area hosts the younger (311 Ma) Baogutu porphyry copper-gold deposit included in the late Paleozoic Kazakh-Tarim tract. Remote sensing is in use to map alteration and small intrusions in the area (Liu and others, 2013), which when combined with field investigations and more radiometric dating may lead to further porphyry discoveries in the area.

Probabilistic Assessment

Grade and Tonnage Model Selection

The use of *t*-tests to compare the three porphyry copper deposits in the tract with the general global porphyry copper model of Singer and others (2008) shows that the log-transformed values for ore tonnage and copper, molybdenum, gold, and silver grades of the three deposits fit the model at the 1-percent confidence level (table 3).

Estimates of Undiscovered Deposits and Rationale

There are three known deposits in the tract, including one (Bozshakol) that contains more than 4 Mt of copper. The newly discovered prospect at Xiemistai lends credence to the idea that Caledonian-age rocks in this part of China may contain porphyry copper deposits.

The proportion of volcanic to plutonic rocks of all ages indicates that the level of erosion is appropriate for the exposure and preservation of porphyry copper deposits. The level of mineral exploration was considered to be moderate to high in the northern parts of the tracts. The tract area in China is just starting to be studied in detail, and new age determinations indicate that rocks in China that were dated as Middle Devonian by fossils are older (Shen and others, 2012). Although only a few detailed mineral investigations are reported, much of the area has been covered by geochemical surveys and has been evaluated for mineral resources at the reconnaissance level.

The team estimated a 90-percent chance for 1 or more undiscovered deposits in the tract, a 50-percent chance of 2 or more deposits, and a 10-percent chance of 8 or more deposits, for a mean of 3.4 expected undiscovered deposits (table 5*A*).

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources was 14 Mt of copper (table 5*B*), compared to the 6.15 Mt of copper identified at the three known deposits in the tract. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 5*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 14).

Gobi-Amur Tract (142pCu8503)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Cambrian through Early Devonian igneous rocks primarily in southern Mongolia that consist mostly of continental-arc rocks with some island-arc rocks at the northeastern end

Location

The Gobi-Amur tract is an arcuate, fragmented belt about 3,200 km long and as much as 200 km wide that extends through southern Mongolia in the northern Gobi Desert and stretches northeastward through Heilongjiang Province in China (fig. 15).

Tectonic Setting

This tract consists of a poorly exposed assemblage of Caledonian igneous rocks that belong to unnamed island arcs and continental arcs that formed in and on the northern margin of the Paleo-Asian Ocean to the north of the arc that defines the Solonker tract (142pCu8501). These arc rocks may have had a much larger original extent because they are largely covered by the younger Devonian rocks of the Kazakh-Mongol Arc. Rocks of the tract were accreted to the Asian Continent no later than the Permian.

Geologic Criteria

The Gobi-Amur tract was defined using calc-alkaline, intermediate-composition igneous map units with Ordovician, Silurian, and earliest Devonian map-unit ages, as well as a few units designated as lower Paleozoic (fig. 16). Plutonic rock types include granite, granodiorite, tonalite, and plagiogranite. Volcanic rock types include mainly andesite with minor amounts of welded tuff and, where deemed appropriate, mixed volcano-sedimentary assemblages containing permissive rock types.

The Gobi-Amur tract is bounded by the Solonker Suture to the south, and by the Main Mongolian Lineament to the north (fig. 5). The eastern margin of the tract is the eastern limit of the CAOB, beyond which the magmatic history is related to Mesozoic Pacific margin subduction. The western end of the tract is bound by Paleozoic rocks and structures of the Kazakhstan Orocline to the west. The extent of the tract was primarily delineated by the selection of appropriate map units and the distribution of mineral deposits.

Table 5. Probabilistic assessment results for tract 142pCu8502, Kazakh-Tianshan—Kazakhstan and China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
1	2	8	8	8	3.4	2.7	80	3	6.4	89,610	7

B. Results of Monte Carlo simulations of undiscovered resources.

[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	210,000	5,500,000	34,000,000	52,000,000	14,000,000	0.28	0.06
Mo	0	0	78,000	940,000	1,700,000	370,000	0.23	0.24
Au	0	0	120	850	1,300	330	0.29	0.19
Ag	0	0	750	10,000	19,000	4,300	0.23	0.32
Rock	0	51	1,200	6,900	11,000	2,700	0.30	0.06

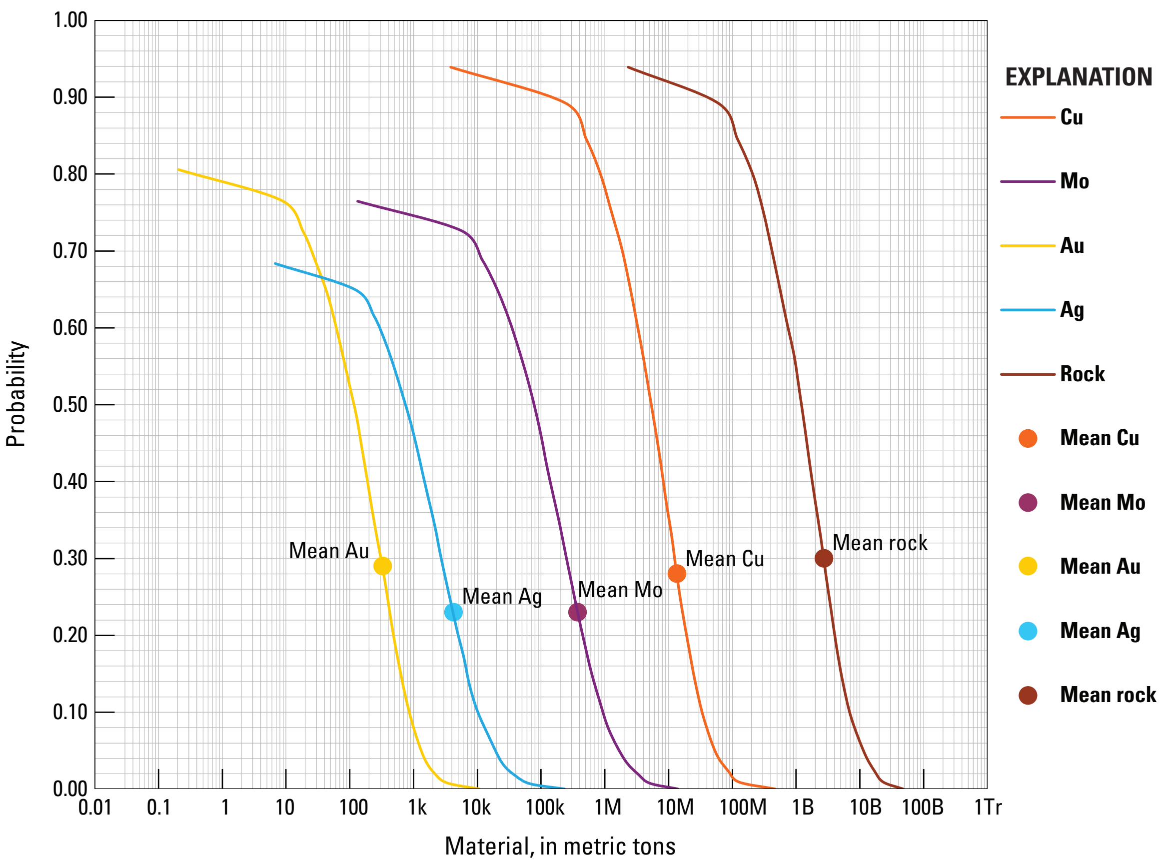


Figure 14. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8502, Kazakh-Tianshan—Kazakhstan and China. k=thousands, M=millions, B=billions, Tr=trillions.

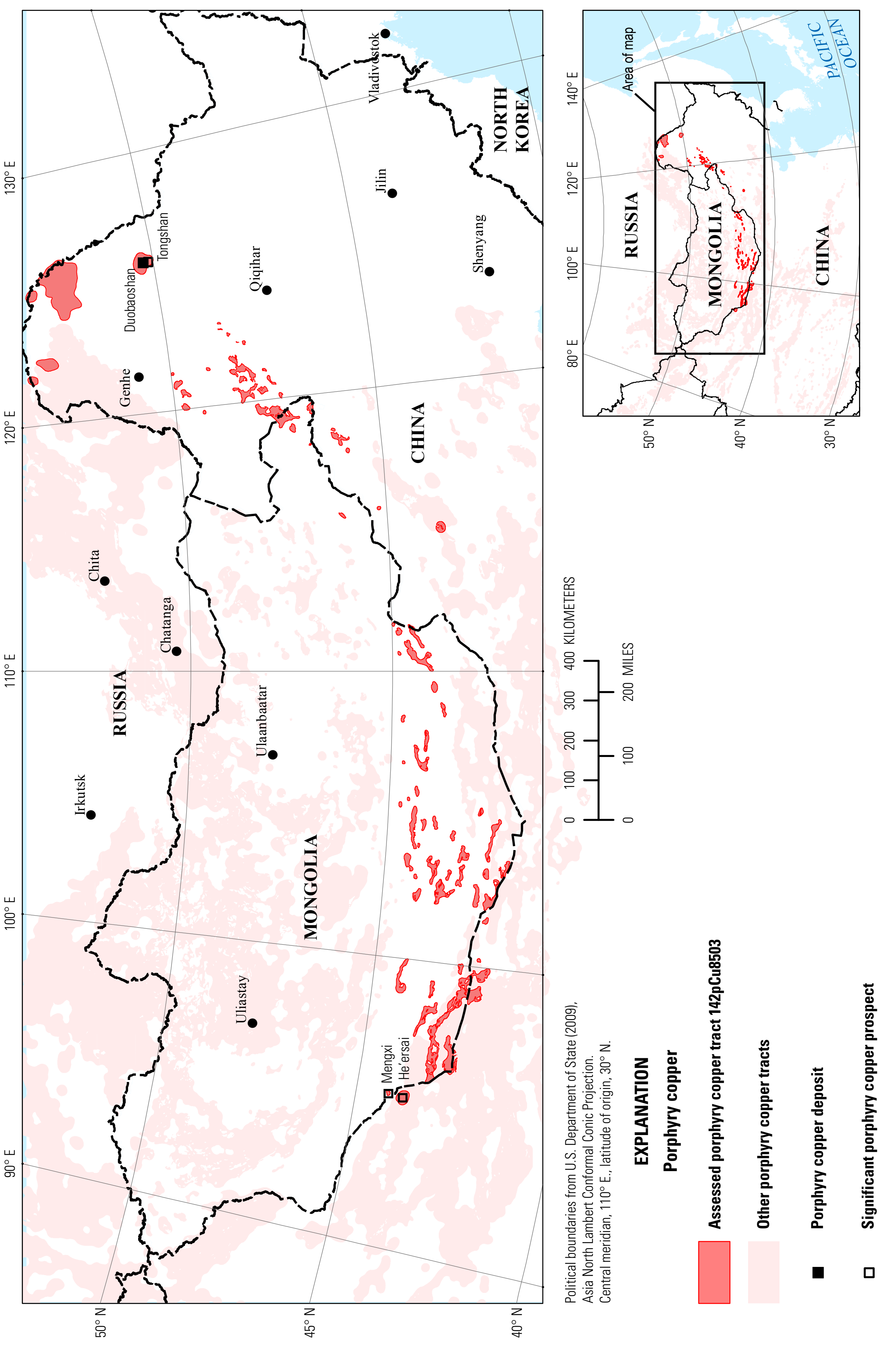


Figure 15. Map showing the location, known deposits, and significant prospects for permissive tract 142pCu8503, Gobi-Amur—Mongolia, China, and Russia.

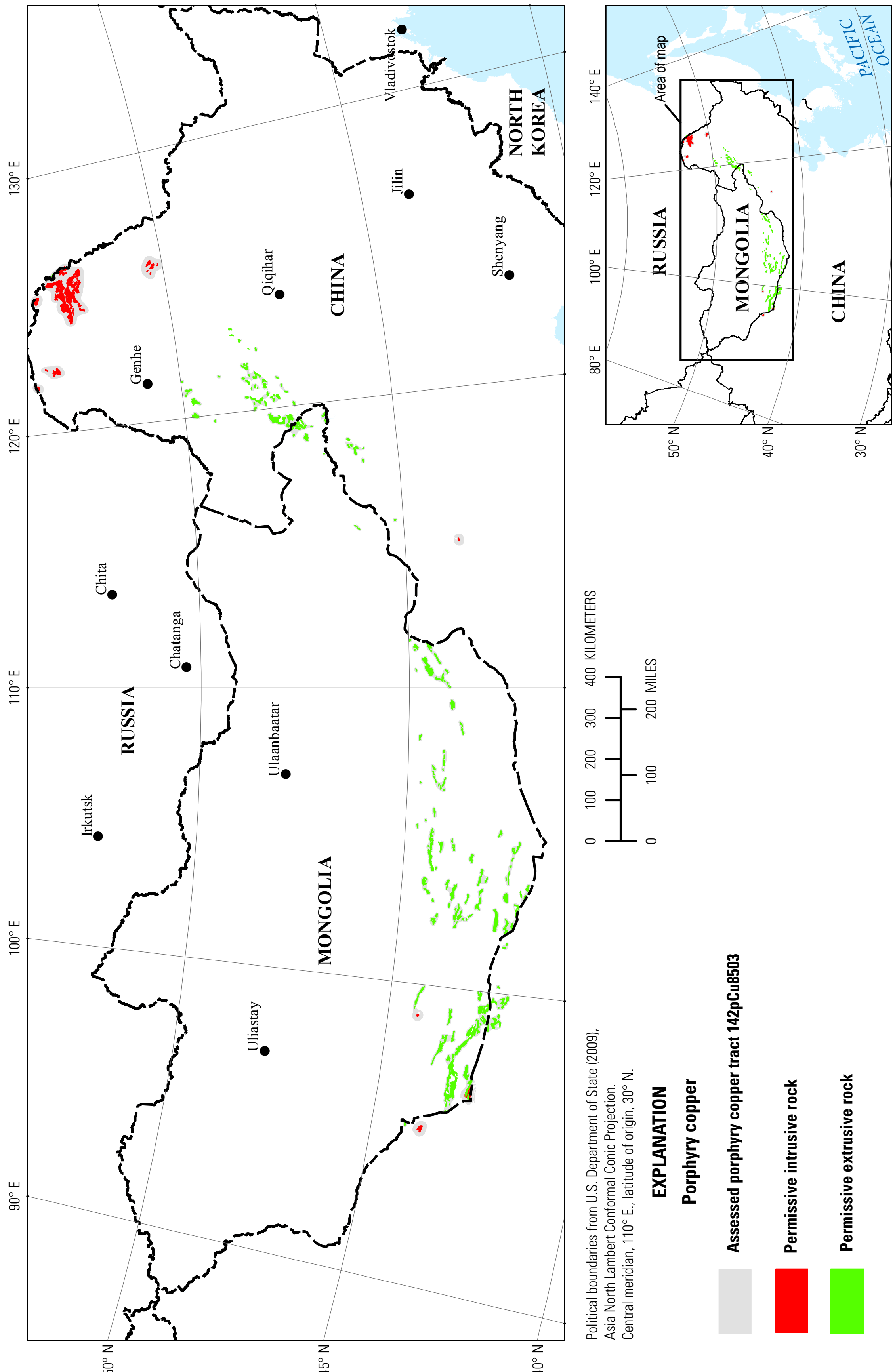


Figure 16. Map showing the distribution of permissive rocks used to delineate tract 142pCu8503, Gobi-Amur—Mongolia, China, and Russia.

Known Porphyry Deposits

Duobaoshan

Duobaoshan, in northern China, is the only known porphyry copper deposit in the tract (fig. 15). Duobaoshan has been dated as Early Ordovician (about 485 Ma) by Ge and others (2007) using U-Pb methods, but a Re-Os age on molybdenite from the deposit is Late Cambrian (about 506 Ma; Zhao and others, 1997). Duobaoshan is a large deposit that is currently being mined that contains more than 3,000,000 t of copper (Singer and others, 2008).

Prospects, Mineral Occurrences, and Related Deposit Types

Information was available for three porphyry copper prospects in the tract (fig. 15). Tongshan, judged to be particularly significant, is located about 10 km south of Duobaoshan and is also being mined. No information was available about the resource there, and so, for the purposes of this assessment, it is considered as a prospect with a very high probability of being a deposit.

Mengxi and He'ersai are newly identified prospects nearly 2,500 km to the west; each has Devonian U-Pb and Re-Os ages (Wang and others, 2009b, 2010; Cheng and others, 2010; appendix B).

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used. The available grade and tonnage data for the single known deposit, Duobaoshan, suggest that the general model is appropriate. The results of an ANOVA test, applied at the 1-percent confidence level using log-transformed values for ore tonnage, as well as copper and molybdenum grades, indicate that Duobaoshan is not distinguishable from deposits in the global general porphyry copper model.

Estimates of Undiscovered Deposits and Rationale

The Gobi-Amur tract is the smallest of the Central Asian tracts. One deposit, Duobaoshan, and one significant prospect are known in the northeastern part of the tract. Only two additional prospects are known, identified in Chinese-language academic publications, and these are located at the opposite, western side of the tract.

Despite the presence of one large deposit, the assessment team noted the lack of other prospects throughout most of the tract, as well as some uncertainty about the age of some of the rocks that define the tract. It is possible that some of the undated prospects in the Oyu Tolgoi tract, which overlies the Gobi-Amur, could be Caledonian in age, but the Variscan rocks appear to be more prospective in this area.

The permissive units in this tract are mainly volcanic and mixed volcanogenic-sedimentary rocks, chiefly andesite, with relatively few plutons. This distribution of rock types would suggest that the level of erosion may be relatively shallow throughout much of the tract.

The level of mineral exploration was considered to be variable, ranging from well explored in Mongolia, especially in the southeast, to moderately and poorly explored in the northeastern part of the tract in China. The Mongolian part of the tract has received much interest since 1991 and most surface outcrops have likely been examined. Nearly all of Mongolia has been mapped at 1:200,000 scale, about 25 percent mapped and explored at 1:50,000 scale, and about 32 percent covered by aerial multispectral surveys at 1:50,000 and 1:25,000 map scales (Javkhlanbold, 2006). Mineral-exploration and mining-lease maps of Mongolia (Mineral Resources Authority of Mongolia (MRAM), 2003; Javkhlanbold, 2006) show nearly complete coverage of the tract region (with the exception of several large environmentally sensitive protected areas), indicating that much of the area has undergone scrutiny. However, much of the eastern part of the tract in China is remote and heavily forested. The eastern and western parts of the tract in China have been evaluated for mineral resources at the reconnaissance level, and select areas, particularly in the eastern part of the tract, have been the site of mineral-resource surveys and exploration at map scales between 1:10,000,000 and 1:2,500,000. A few detailed investigations, also mainly in the east, have been carried out (see maps available at China Geological Survey, 2005). For example, a high level of activity has taken place around the Duobaoshan deposit and nearby Tongshan prospect (China Geological Survey, 2012).

The team estimated a 50-percent chance of 1 or more deposits, a 10-percent chance of 3 or more deposits, and a 5-percent chance of 6 or more deposits for a mean of about 1.5 expected undiscovered deposits (table 6*A*).

In a previous assessment (Yan and others, 2007), two tracts (VIII-4 and IX-2) are largely coincident with the western and central parts of the Gobi-Amur tract. Their estimate for these areas was about 2.3 mean undiscovered deposits.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 5.9 Mt copper is about twice the identified copper resource (3 Mt copper) at Duobaoshan. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 6*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 17).

Table 6. Probabilistic assessment results for tract 142pCu8503, Gobi-Amur—Mongolia, China, and Russia.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 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	115	1	2.5	56,090	4

B. Results of Monte Carlo simulations of undiscovered resources.

[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	1,100,000	14,000,000	26,000,000	5,900,000	0.22	0.30
Mo	0	0	1,400	360,000	790,000	170,000	0.17	0.49
Au	0	0	8	400	720	150	0.22	0.47
Ag	0	0	0	4,200	8,700	2,000	0.17	0.57
Rock	0	0	260	3,000	5,500	1,200	0.24	0.30

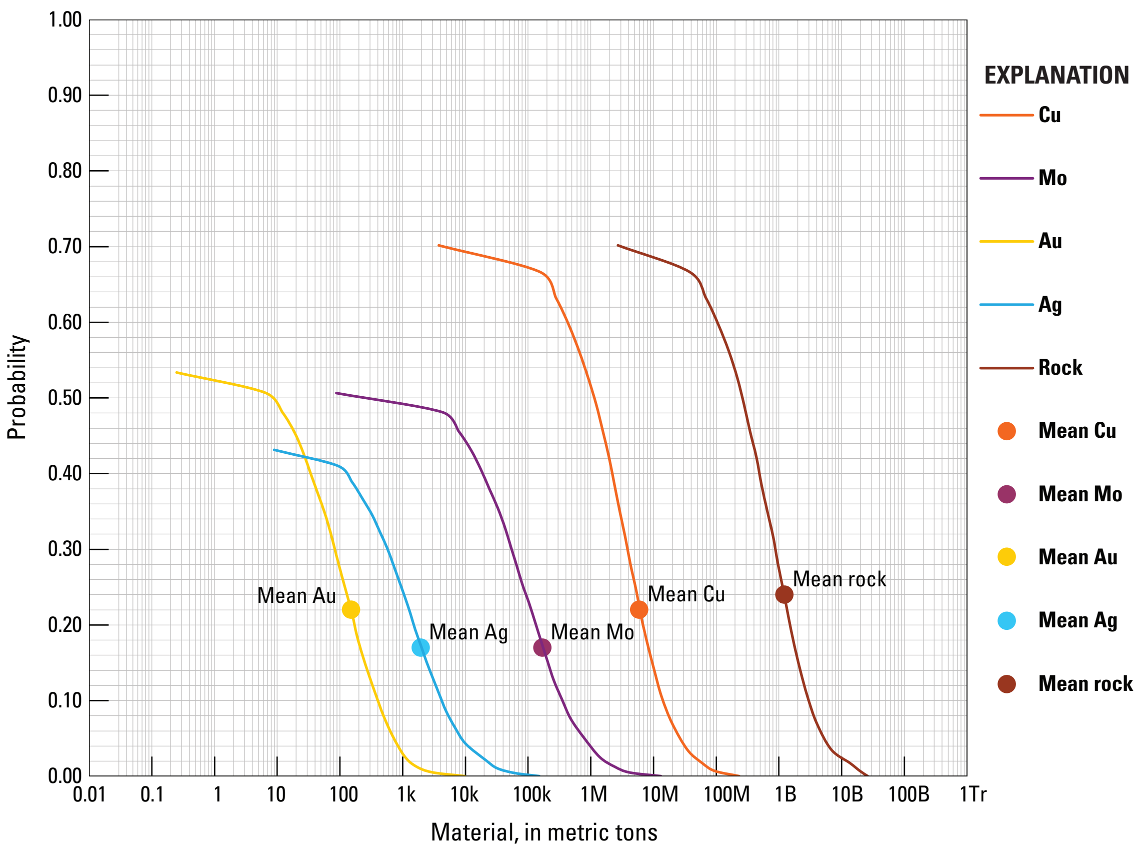


Figure 17. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8503, Gobi-Amur—Mongolia, China, and Russia. k=thousands, M=millions, B=billions, Tr=trillions.

Mongol-Sayan Tract (142pCu8504)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global porphyry copper, Cu-Mo subtype model (Singer and others, 2008)
Geologic Feature Assessed: A widespread and varied assemblage of Cambrian through Silurian igneous rocks in central and northern Mongolia and bordering parts of Russia, including the Tuva-Mongol island arc and a variety of other calc-alkaline rocks

Location

The Mongol-Sayan tract, in central and northern Mongolia and adjacent parts of Russia, consists of curvilinear belts of rock that have been deformed on a large scale (fig. 18). The tract includes a very small area in China along the border with Russia. The axis of the tract measures about 2,500 km in length and 900 km at its widest.

Tectonic Setting

The southern part of the tract consists of the very large Caledonian Tuva-Mongol island arc (also known as the Lake-Kamshara Terrane), that has been tectonically deformed into a backwards S-shape (fig. 5) due to mid-Paleozoic rotation of the Siberian continental block (Seltmann and others, 2014). In the western part of the tract, the Uimen-Lebed is an accreted island arc, whereas the Gorny Altai region includes continental-arc rocks that formed on the margin of Siberia (Wilhem and others, 2012). The Caledonian rocks in the Transbaikal region that form the eastern part of the tract are poorly known and may have large crustal components in their source.

Geologic Criteria

The Mongol-Sayan tract was defined using calc-alkaline, intermediate-composition igneous map units with Cambrian, Ordovician, and Silurian map-unit ages, as well as a few units designated lower Paleozoic (fig. 19). Plutonic rock types include granodiorite, granite, quartz diorite, diorite, plagiogranite, and granosyenite, gabbrodiorite, with lesser amounts of monzogabbro, monzonite, and alkaline granitoids. Volcanic rocks include primarily andesite, with lesser amounts of dacite and rhyolite.

The Mongol-Sayan tract is bound by the Main Mongolian Lineament on the south (fig. 5) and by the margin of the Siberian Continent on the north. The eastern margin of the tract is the eastern limit of the CAOB, beyond which the magmatic history is related to Mesozoic Pacific margin subduction. The western boundary of the tract is the same as the boundary between the Mongolian Orocline and the Kazakhstan Orocline. The extent of the tract was primarily delineated by the selection of appropriate map units and the distribution of mineral deposits.

Known Porphyry Deposits

There are four known porphyry copper deposits in the tract, all in the Altai-Sayan area of southern Siberia in Russia (table 2, fig. 18). Aksug is a large porphyry copper deposit of apparent Cambrian age. Kiyalykh-Uzen, Sora, and Agaskyr are smaller, molybdenum-rich porphyry deposits. The small (30 Mt) 470-Ma Kiyalykh-Uzen deposit was classified as a porphyry copper deposit by Singer and others (2008), whereas Distanov and others (2006) list the deposit as a copper skarn associated with an early Paleozoic collisional gabbro-granitoid plutonic belt.

Aksug

Aksug (table 2, fig. 18) was discovered in 1952, and is currently in development (Berzina and Berzina, 2008). It is a large deposit, with more than 4 Mt of copper, containing about 805 Mt of ore at a copper grade of 0.52 percent, a molybdenum grade of 0.014 percent, a gold grade of 0.16 grams per metric ton (g/t), and a silver grade of 0.99 g/t (Porter Geoconsultancy, 2005; Singer and others, 2008). The deposit appears to be related to quartz diorite, tonalite, and granodiorite porphyries that have ^{40}Ar-^{39}Ar ages ranging from about 405 Ma to about 368 Ma, whereas a Re-Os date on molybdenite from the deposit yielded an age of about 511 Ma (Berzina and Berzina, 2008). These porphyries are interpreted to be postconvergent, with primarily mantle sources. Ore is associated with phyllic hydrothermal alteration and potassic alteration is rare. Molybdenite from the ore contains relatively high contents of rhenium (about 460 parts per million, ppm), and associated rocks contain 9–31 parts per billion (ppb) palladium and 17–34 ppb platinum (Sotnikov and others, 2001; Berzina and others, 2005a,b).

Sora

The molybdenum-rich, copper-poor Sora (also known as Sorsk or Sorskoe) porphyry copper deposit in southwestern Siberia is associated with a multiphase Cambrian-Ordovician to Devonian granitoid complex. The complex includes a number of suites ranging from early mafic (gabbro, monzogabbro, and monzonite) through intermediate (diorite, granodiorite, monzonite, syenite) to late-stage granite porphyries (Berzina and others, 2010, 2011a, b; Sotnikov and others, 2001; Seltmann and others, 2010). The age of the deposit is complex and reported ages range from 481 to 356 Ma, probably reflecting overprinting by younger events. Several porphyry bodies intruded after the main copper-molybdenum mineralization (388–389 Ma). Molybdenum- and copper-bearing stockworks are associated with quartz-biotite–potassium-feldspar alteration; high-grade molybdenum (0.5 to 1 percent) is associated with breccias. Late-stage mineralization formed quartz-fluorite-galena-sphalerite veins and late quartz-fluorite-pyrite and quartz-molybdenite veinlets.

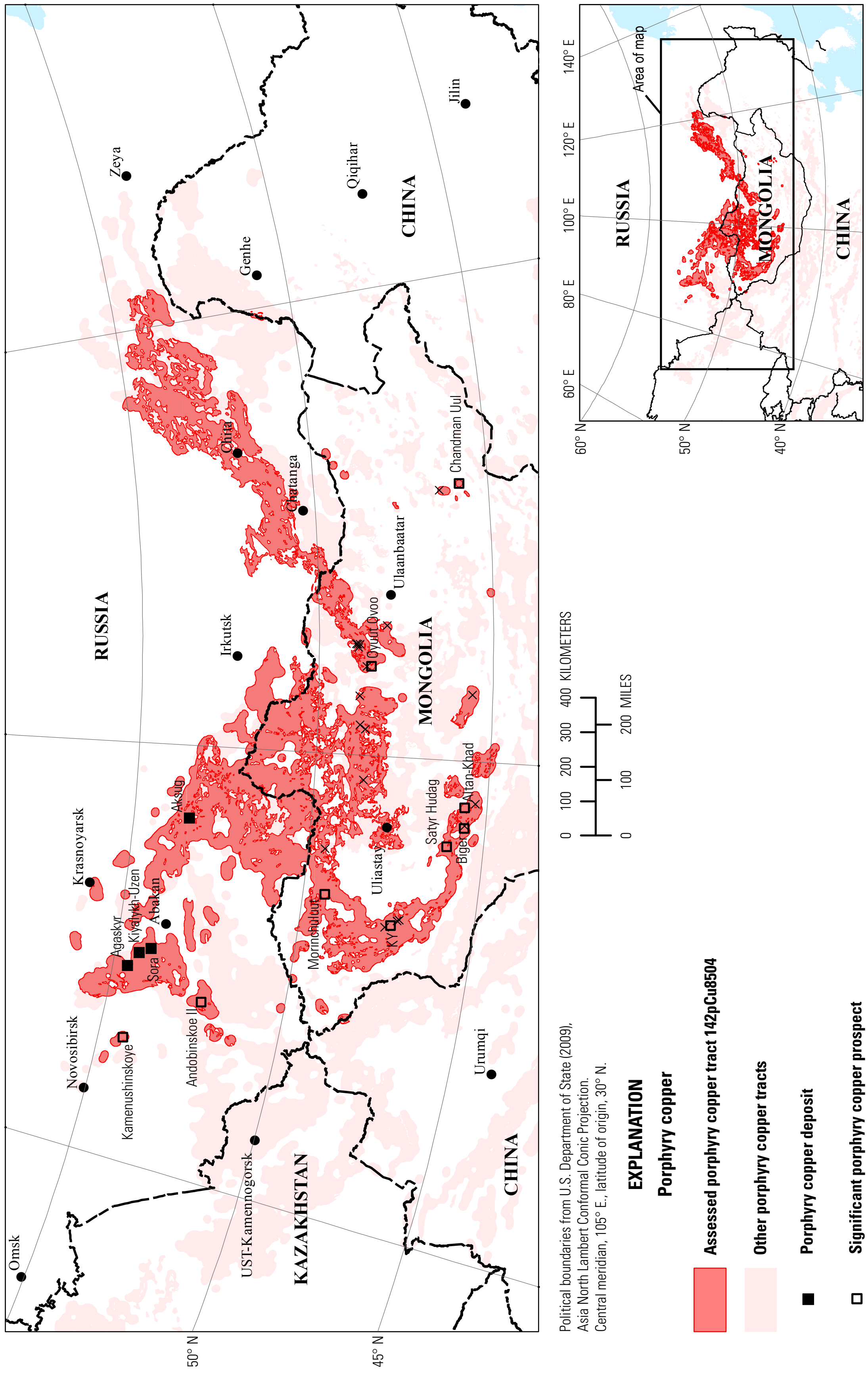


Figure 18. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8504, Mongol-Sayan—Mongolia, Russia, and China.

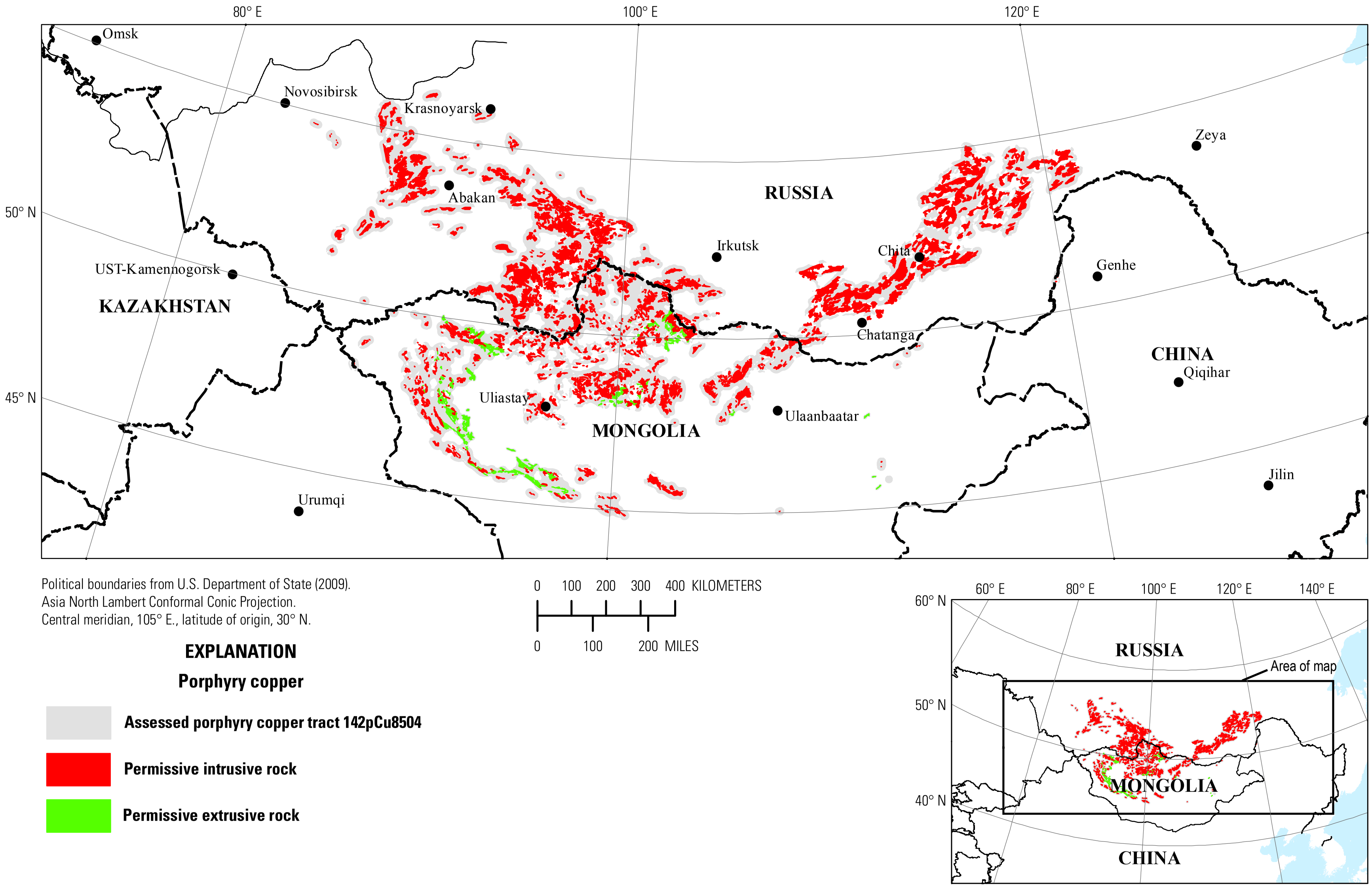


Figure 19. Map showing the distribution of permissive rocks used to delineate tract 142pCu8504, Mongol-Sayan—Mongolia, Russia, and China.

The deposit was discovered in 1937, and open-pit mining started in 1950 (Strikeforce Mining and Resource, Ltd., 2013). Remaining ore averages 0.058 percent molybdenum, 0.055 percent copper, 2.3 g/t silver, and some gold. Rocks associated with the Sora deposit contain less than 10 ppb platinum and 9–18 ppb palladium (Sotnikov and others, 2001).

Agaskyr

The Agaskyr deposit, reported to be Russia's third largest molybdenum deposit, was discovered in 1953. Reserves are reported (Russian standards) as 310 Mt of category B+C1 copper-molybdenum ore containing 155.3 thousand metric tons (kt) of molybdenum, 98.7 kt of copper, 509.1 t silver, and 5.9 t rhenium. A feasibility study was scheduled for 2013 (Russia and CIS Business and Financial Newswire, 2013).

Prospects, Mineral Occurrences, and Related Deposit Types

The assessment team acquired information for about 27 porphyry copper prospects in the tract. Nine of them are considered significant, but three in Mongolia, Oyuut Ovoo, KY, and Biger, are judged to be particularly significant (fig. 18, appendix B). Oyuut Ovoo, in the central part of the tract, about 200 km west of Ulaan Baatar, the Mongolian capital, is little explored, but has yielded samples with copper grades as high as 0.6 percent (Dejidmaa and others, 2002).

KY and Biger are in the southwestern part of the tract in far western Mongolia. Exploration drilling at Biger has yielded an intersection of 0.5 percent copper over 24 meters (m) that also contained 0.1 g/t gold and palladium; exploration is ongoing (Erdene Resource Development Corp., 2007).

KY is a large area of altered Cambrian granitoid rocks that range in composition from quartz diorite to granodiorite (Lyndhurst Enterprises Pty, Ltd., 2011). U-Pb dates on these rocks range from about 500 Ma to 475 Ma, and a Re-Os date on molybdenite from the prospect is about 510 Ma. Reconnaissance drilling has intercepted subeconomic copper and gold mineralization (Altan Rio, 2012).

Probabilistic Assessment

Grade and Tonnage Model Selection

Statistical tests of the grades and tonnages of the four known deposits listed in table 3 show that the general model could be used because the tonnage and commodity grades all meet the 1-percent probability level recommended for testing models (Singer and Menzie, 2010). However, three of the four known deposits are classified as Cu-Mo subtype on the basis of average molybdenum grades (greater than 0.03 percent), and the molybdenum grade is better-described by the Cu-Mo subtype model (p value of 0.39 versus p value of 0.02 for the general model). In addition, most of the prospects in Mongolia as well as in Russia list molybdenum (appendix B). The tonnages for the four deposits bracket the median Cu-Mo subtype model tonnage of 280 Mt (Singer and others, 2008). The Cu-Mo subtype grade and tonnage model of Singer and others (2008) was used, although either model could apply.

Estimates of Undiscovered Deposits and Rationale

The Mongol-Sayan tract is one of the largest of the Central Asia tracts, making up a little more than 11 percent of the total area of all the tracts combined (table 1). Four deposits are known in the northwestern part of the tract, and 27 prospects, nine of them significant, are scattered throughout the tract.

Despite the large tract area, the assessment team noted that many of the prospects have inadequate descriptions, and it is not certain that all are porphyry copper prospects—some may be polymetallic vein, skarn, or massive sulfide-related (appendix B). Age information is also uncertain. The Aksug deposit, for example, has conflicting information indicating that it could be Caledonian (Berzina and Berzina, 2008), transitional between Caledonian and Variscan (Sotnikov and others, 2003), or Variscan (Sotnikov and others, 2003). Thus, some of the undated prospects also could be Variscan in age. The assessment team also observed that prospects are noticeably scarce in the Russian part of the tract. Given the uncertainty in deposit type and age, the prospectivity for undiscovered porphyry copper deposits of Caledonian age in this region may not be as favorable as it appears.

The proportion of extrusive to intrusive rock types is noticeably different between the Mongolian and Russian geologic maps. The permissive units on the Russian geologic map show mainly plutonic types, with very few volcanic rocks. The permissive units on the Mongolian geologic map show a more balanced mix between plutonic and volcanic types (fig. 19). The Mongolian map has a wide variety of volcanic unit compositions, whereas the Russian map has only one volcanic rock type, rhyolite. Because of these inconsistencies between the geologic maps, it is difficult to make a general determination about the level of erosion.

The level of mineral exploration was considered to be variable, ranging from well-explored in Mongolia, to moderately and poorly explored in the northern parts of the tract, which are rugged and remote. Most of the 1:200,000 geologic research and mapping in the Russia region of the tract was done before 1979 (Tikhomirova, S.R., written commun., 2011). The south-central (Mongolian) part of the tract has been well mapped and investigated. The Mongolian part of the tract has received a lot of interest since 1991, and most surface outcrops have likely been examined. Nearly all of Mongolia has been mapped at 1:200,000 scale, about 25 percent mapped and explored at 1:50,000 scale. Mineral-exploration and mining-lease maps of Mongolia (MRAM, 2003; Javkhlanbold, 2006) show that most of the tract has received targeted study, with the exception of some protected areas in central and western Mongolia.

The team estimated a 90-percent chance for 1 or more undiscovered deposits in the tract, a 50-percent chance of 6 or more deposits, and a 10-percent chance of 24 or more deposits, for a mean of about 10 expected undiscovered deposits (table 7*A*).

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 100 Mt copper on the basis of the Cu-Mo subtype model greatly exceeds the 6 Mt of identified copper resources. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 7*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 20). To show the effects of model selection on assessment results for the tract, the undiscovered resources also were estimated using the general porphyry copper model (table 7*C*). The general model predicts a much smaller mean amount of copper (38 Mt) and 2.8 Mt of molybdenum in contrast to the 12 Mt of molybdenum using the Cu-Mo subtype model.

Late Paleozoic Tracts in the Central Asia Orogenic Belt

The three tracts that include primarily late Paleozoic rocks are shown on figure 6. The tracts are described from south to north.

Table 7. Probabilistic assessment results for tract 142pCu8504, Mongol-Sayan—Mongolia, Russia, and China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	6	24	24	24	9.8	8.4	86	4	14	575,100	5

B. Results of Monte Carlo simulations of undiscovered resources using the Cu-Mo subtype model.

[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	960,000	55,000,000	270,000,000	340,000,000	100,000,000	0.37	0.06
Mo	0	73,000	2,600,000	12,000,000	15,000,000	4,600,000	0.37	0.06
Au	0	0	130	670	910	250	0.35	0.1
Ag	0	0	19,000	130,000	180,000	45,000	0.33	0.11
Rock	0	250	11,000	48,000	58,000	18,000	0.39	0.06

C. Results of Monte Carlo simulations of undiscovered resources using the general model.

[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	580,000	21,000,000	97,000,000	130,000,000	38,000,000	0.35	0.07
Mo	0	0	430,000	2,800,000	4,200,000	1,100,000	0.30	0.13
Au	0	0	500	2,400	3,400	950	0.34	0.11
Ag	0	0	4,700	32,000	50,000	13,000	0.28	0.17
Rock	0	140	4,500	20,000	27,000	7,700	0.37	0.07

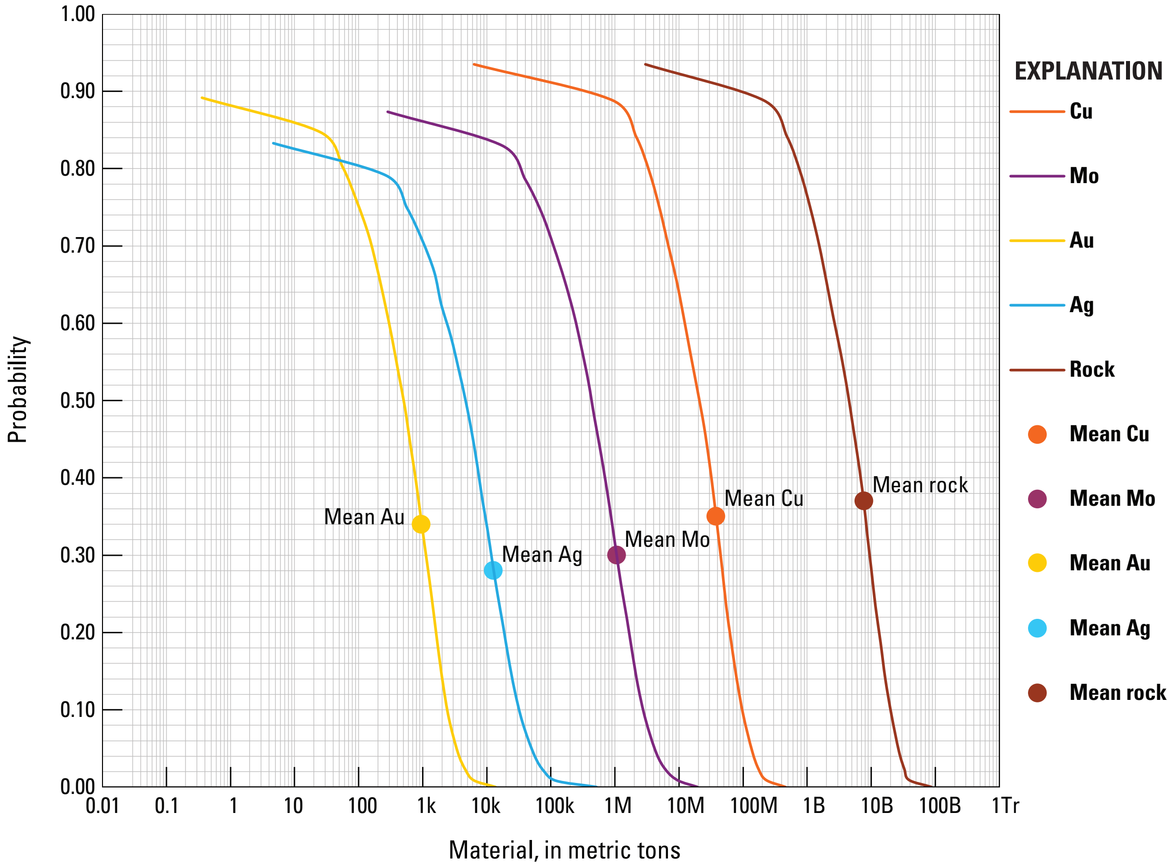


Figure 20. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8504, Mongol-Sayan—Mongolia, Russia, and China. k=thousands, M=millions, B=billions, Tr=trillions.

Kazakh-Tarim Tract (142pCu8505)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Devonian through Early Triassic igneous rocks in Kazakhstan and China that include parts of the Balkash-Ili continental arc and a few younger rocks related to the Indosinian orogeny

Location

The Kazakh-Tarim tract consists of two arcuate belts (fig. 21). The northerly belt (about 1,200 by 200 km) trends southeast through northeastern Kazakhstan into the Junggar region of Xinjiang Autonomous Region in China. The southerly belt (about 1,400 by 200 km) extends eastward from the Kazakh border through the Tien Shan Mountains (fig. 1) eastward to the northern tip of Gansu Province and the Nei Mongol Autonomous Region in China.

Tectonic Setting

This tract is the result of the assembly of several separate island-arc and continental-arc systems by a complex series of events in late Paleozoic time about which there is little consensus regarding timing, position, and orientation of the disparate parts during assembly into modern Central Asia. The Zharma-Saur island arc (fig. 6) that is host to two of the porphyry copper deposits in the tract was apparently accreted on to Asia sometime after the Carboniferous (Wilhem and others, 2012). The Dananhu-Tousuquan and Bogdo Shan are also apparently small island-arc fragments that were incorporated between the Tarim and Junggar Basin Craton blocks during the late Paleozoic continental assembly of Asia (Xiao and others, 2004; Wilhem and others, 2012). The Dananhu-Tusuquan Arc hosts the Tuwu-Yandong-Yanxi porphyry copper deposit (Han and others, 2006a, b). See Xiao and others (2010) for details about the myriad and contrasting possibilities for the paleotectonic history of this region.

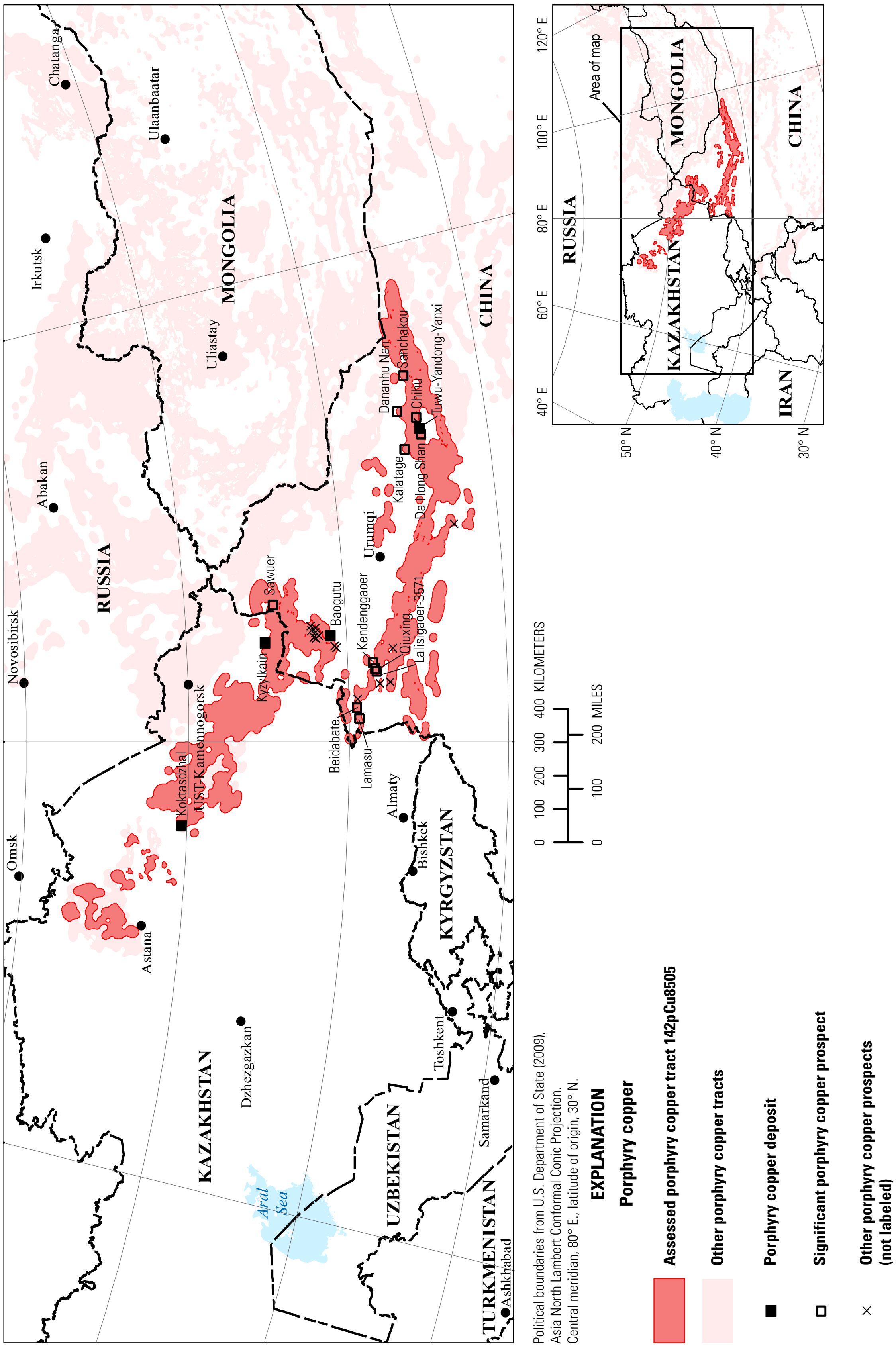


Figure 21. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8505, Kazakh-Tarim—Kazakhstan and China.

Geologic Criteria

Calc-alkaline, intermediate-composition igneous map units with Devonian, Carboniferous, and Permian map-unit ages define the Kazakh-Tarim tract (fig. 22). A few Early Triassic igneous rocks (probably collision related) were also included. Plutonic rock types include granite and granite porphyry, granodiorite, diorite and quartz diorite, plagiogranite, granosyenite and syenite, and monzonite, with lesser amounts of gabbro-diorite, alkaline granitoids, and monzodiorite. Volcanic rock types include primarily rhyolite and rhyolite-dacite, andesite, and dacite, with lesser amounts of trachyrhyolite and, a few tuffaceous units and mixed units of volcano-sedimentary assemblages.

The Kazakh-Tarim tract is bounded on the northeast by the Altai Mountains (fig. 1), whose rocks define the Mongol-Altai tract (142pCu8507). The western margin is the cluster of assessment tracts that include the majority of the rocks of the Balkash-Ili Arc that were assessed by Berger and others (2014). The southern boundary of the tract is the Tarim Craton and continental block. Most of the tract is surrounded by fault-bounded basins filled with thick (1 to 2 km or more) sequences of Mesozoic and Cenozoic sedimentary rocks.

Known Porphyry Deposits

There are four known porphyry copper deposits in the Kazakh-Tarim tract (fig. 21). Two are in Kazakhstan—Koktasdzhal and Kyzlkain. Two deposits with Carboniferous ages are in China—Baogutu and Tuwu-Yandong-Yanxi.

Koktasdzhal

Koktasdzhal is a small porphyry copper deposit in the core of an anticline. The deposit is hosted in granitoids of the Koktaszhalsky igneous complex composed of early peripheral gabbro-diorite, a core of quartz diorites, tonalite and granodiorite, and late plagiogranite and granodiorite porphyries and dikes. Faults have broken the deposits into several blocks, and ore bodies dip steeply. Ore (chalcopyrite and bornite) is present in lenses on the order of 10 to 100 m thick. A 20–50-m oxide zone (malachite, azurite, chrysacolla, native copper, goethite) is present, but no well-developed supergene enrichment zone is observed. The deposit has been known since the 1800s and was explored by drilling that encountered ore to depths of 440–560 m. Copper, gold, and silver reserves were determined by the State Committee for Reserves but the deposit was categorized as a subeconomic property (Zhukov and others, 1998). Molybdenum is reported, but grades are not available.

Kyzlkain

The Kyzylkain porphyry deposit in eastern Kazakhstan is hosted in middle Carboniferous basic and intermediate porphyries, diorite, quartz diorite, granodiorite, granite, and granosyenite of the Saur igneous complex that intruded a 1 km-thick Carboniferous volcano-sedimentary sequence (tuffaceous sandstones, tuffs). The deposit occupies the central uplifted part of a circular depression that has a diameter of 2–3 km. Rocks within the depression are highly altered (albite, chlorite, sericite, carbonates, pyrite). Copper ore in the form of quartz stockworks with chalcopyrite, molybdenite, chalcocite, and covellite is localized in zones along faults. A third of the deposit area is covered by alluvium. The deposit was drilled, but overall low metal grades (average 0.3 percent at a cutoff grade of 0.2 percent) halted continued development of the property (Zhukov and others, 1998; Singer and others, 2008; D.P. Cox, USGS, written commun., 2001; Shevchenko, 1973; Pavlova, 1978).

Baogutu

Baogutu was discovered during regional exploration in 1985–1990. Drilling during 2002–2008 delineated the deposit, which contains 225 Mt of ore with a copper grade of 0.28 percent, molybdenum grade of 0.011 percent, gold grade of 0.1 g/t, and silver grade of 1.8 g/t (Shen and others, 2009, 2010b). Mineralized rock is exposed at the surface in an area of about 1,100 by 800 m and persists to a depth of more than 700 m. The highest grades are in deeper parts of the deposit. The deposit remains undeveloped pending development of infrastructure and water availability for open pit mining (Shen and others, 2009).

The intrusive rocks related to the deposit are predominantly diorites and quartz diorites, both equigranular and porphyritic. Zircon U-Pb ages from these rocks range from about 349 to 292 Ma (Shen and others, 2010b), whereas a Re-Os date on molybdenite is about 310 Ma (Song and others, 2007). Mineralized rock is predominantly found within the pluton and occurs both as disseminated minerals and stockwork veinlets. Alteration assemblages include potassic (biotite dominated), phyllic, and propylitic.

Tuwu-Yandong-Yanxi

Tuwu-Yandong-Yanxi, discovered in 1997, is one of the largest copper deposits in China. The Tuwu and Yandong deposits are about 6 km apart, but drilling between them has encountered additional mineralization. Yanxi is immediately adjacent to the Yandong deposit. Thus, the three of them were treated as a single deposit that exhibits mineralization over a strike length of nearly 14 km. The magnitude of the resource at the deposit is problematic, as only Yanxi has a published resource that conforms to National Instrument 43-101.[13] Singer and others (2008) give figures for Tuwu of 280 Mt at 0.75 percent copper and for Yandong of 372 Mt at 0.58 percent copper. The resource at Yanxi is 22.3 Mt at 0.74 percent copper (Roscoe Postle Associates, Inc., 2011). Combining these data, for the purposes of this assessment, the resource at Tuwu-Yandong-Yanxi was taken to be 674.3 Mt of ore at a copper grade of 0.61 percent, a gold grade of 0.1 g/t and a silver grade of 1.3 g/t. Molybdenum content of the ore appears to be generally less than 0.01 percent (Roscoe Postle Associates, Inc., 2011). This estimate yields a combined

[13]A national instrument for Standards of Disclosure for Mineral Projects within Canada. These standards define criteria for reserve and resource categories.

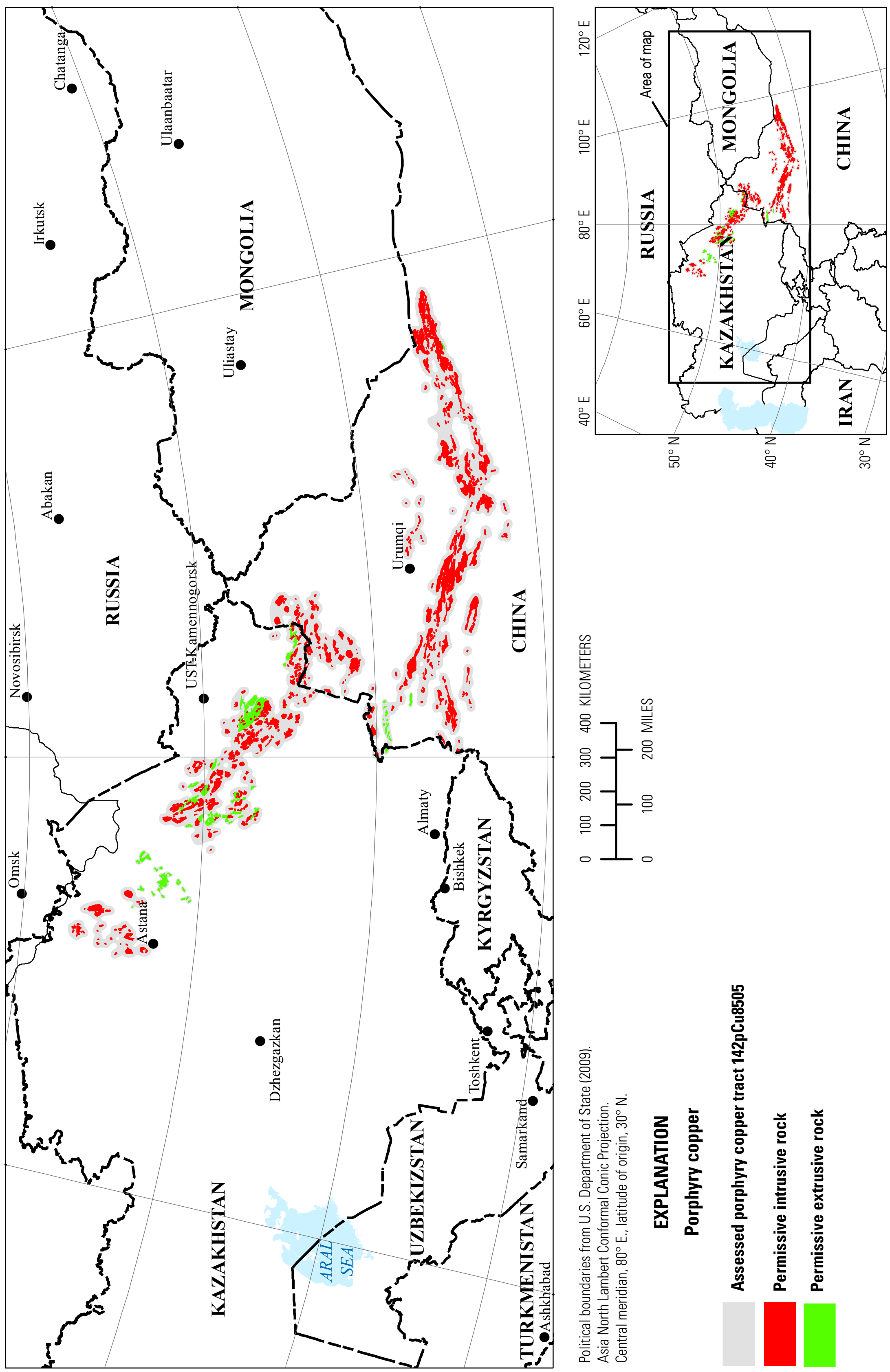


Figure 22. Map showing the distribution of permissive intrusive and extrusive rocks used to delineate tract 142pCu8505, Kazakh-Tarim—Kazakhstan and China.

copper content of 4.4 Mt. Both Mao and others (2006) and Han and others (2006a) state that the resource is 4.7 Mt at a grade of 0.67 percent copper, but neither gives the source of their estimate nor indicate exactly which deposits it includes. The Tuwu deposit is being mined; Yandong and Yanxi are being developed. The deposits have been explored to depths of more than 500 m and are still open at depth.

The deposits are hosted in Carboniferous age granodiorite and plagiogranite porphyry that has been dated at Tuwu to be about 333 Ma by U-Pb methods. A Re-Os age on molybdenite is about 323 Ma (Han and others, 2006b). Most of the ore is in phyllically altered rock, which is surrounded by a propylitic alteration zone; potassic alteration is not prominent in the deposit (Han and others, 2006b).

Prospects, Mineral Occurrences, and Related Deposit Types

There are 26 porphyry copper prospects in the tract, and 11 of them are judged to be particularly significant because they have some measured amounts of mineralized rock. Sanchakou, Chihu, Da Hong Shan, Dananhu Nan, and Kalatage are significant prospects (fig. 21, appendix B) that, along with the large Tuwu-Yandong-Yanxi deposit, define the East Tienshan metallogenic belt in the Dananhu-Tusuquan Arc (fig. 6) in the eastern part of the tract. To the west, near the Kazakhstan border, Lamasu, Beidabate, Lalisigaoer-3571, Qiuxing, and Kendengaoer are also in the East Tienshan belt but are in the Balkash-Ili Arc (fig. 6). To the north, the Sawuer prospect (includes Hanzheganeng, Taketakuolasi, and Xiyakesitao) is in the eastern part of the Zharma-Saur Arc where it extends into China (fig. 21, appendix B). See appendix B and the spatial database for names, locations, and characteristics of the less significant prospects.

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used. Statistical tests comparing the log-transformed tonnage and grade data for the four deposits show that the general porphyry copper model is appropriate for assessing undiscovered resources within the tract (table 3).

Estimates of Undiscovered Deposits and Rationale

The Kazakh-Tarim tract covers more than 300,000 km^2. The discoveries to date confirm that this tract is prospective for porphyry copper deposits. In recent years, the level of geologic understanding of the area has increased dramatically, and modern exploration methods have resulted in the discovery of numerous porphyry copper prospects, especially in the Chinese part of the tract. However, the multiple, mostly fault bounded, tectonic entities that make up the area continue to prevent precise understanding of the tectonic and metallogenic history. The fragmented and discontinuous nature of the exposures has also made it challenging to decide if the level of erosion is appropriate for preservation of porphyry copper deposits, but the proportion of volcanic to plutonic rocks in many parts of the tract does seem appropriate.

The known Variscan-age deposits in adjacent parts of Kazakhstan, where exploration has been more thorough (see Berger and others, 2014), is a favorable indicator. The level of mineral exploration was considered to be thorough in the parts of the tract in Kazakhstan and moderate in China.

The geology of Kazakhstan was not studied in depth before World War II, but since then, it has been well mapped. All the parts of the country that are characterized by magmatic activity have been mapped at 1:200,000 scale, and large parts of the country are covered by 1:50,000-scale mapping, particularly the mineralized areas. The parts of the tract in China are all covered at 1:200,000 scale, but 1:50,000-scale mapping is a more recent phenomenon. Although only a few exploration and detailed mineral investigations have taken place (see maps available at China Geological Survey, 2005), the entire area has been covered by geochemical surveys and has been evaluated for mineral resources at the reconnaissance level. Maps showing the degree of mineral-resource exploration and geologic research (China Geological Survey, 2012) indicate that high levels of activity have taken place recently in a few parts of the tract.

The team estimated a 90-percent chance for 3 or more undiscovered deposits in the tract, a 50-percent chance of 5 or more deposits, and a 10-percent chance of 25 or more deposits, for a mean of about 10 undiscovered deposits (table 8A).

Three upper Paleozoic assessment tracts (VIII-1, VIII-3, and IX-1) and four upper and lower Paleozoic tracts (IX-2, IX-3, IX-4, and IX-5) from Yan and others (2007) correlate well in space and time with the parts of the Kazakh-Tarim tract that extend into China. For those tracts, Yan and others (2007) estimated a mean number of undiscovered porphyry copper deposits of about 10.3, which corresponds very well to the estimate of about 10 made here.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 39 Mt copper is about six times the identified copper resources (6.7 Mt copper). Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 8*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 23).

Table 8. Probabilistic assessment results for tract 142pCu8505, Kazakh-Tarim—Kazakhstan and China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
3	5	25	25	25	10.0	8.4	83	4	14	344,290	4

B. Results of Monte Carlo simulations of undiscovered resources.

[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	600,000	2,200,000	21,000,000	99,000,000	140,000,000	39,000,000	0.34	0.03
Mo	0	7,800	420,000	2,800,000	4,100,000	1,100,000	0.30	0.08
Au	0	23	520	2,500	3,400	980	0.34	0.06
Ag	0	0	4,800	34,000	50,000	13,000	0.29	0.12
Rock	140	530	4,400	21,000	27,000	7,900	0.35	0.03

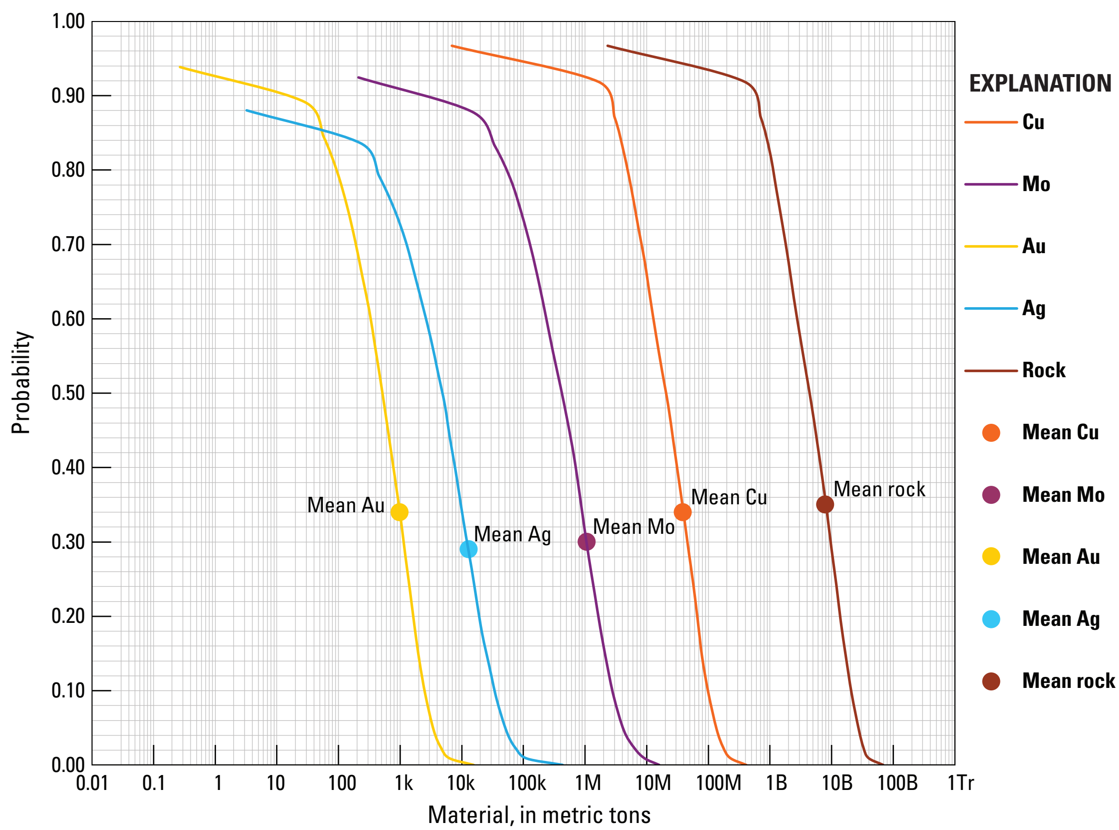


Figure 23. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8505, Kazakh-Tarim—Kazakhstan and China. k=thousands, M=millions, B=billions, Tr=trillions.

Oyu Tolgoi Tract (142pCu8506)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Devonian through Triassic igneous rocks primarily in Mongolia and China that includes the Devonian Kazakh-Mongol island arc, as well as younger rocks related to the Indosinian orogeny (collision of China with Asia)

Location

The Oyu Tolgoi tract consists of an arcuate belt that measures about 2,500 km in length and 200–300 km wide (fig. 24). The tract extends from northeastern Xinjiang Autonomous Region in China, near the Mongolian border, eastward across the length of southern Mongolia, terminating just across the Chinese border in Nei Mongol Autonomous Region.

Tectonic Setting

The Oyu Tolgoi tract is named for one of the largest and richest porphyry copper deposits in the world, the Late Devonian Oyu Tolgoi deposit in the eastern part of the tract (fig. 24, table 2). The major part of the tract is defined by the Devonian through Permian igneous rocks of the Kazakh-Mongol island arc (Seltmann and others, 2010). In the westernmost part of the tract, a few of the rocks are known locally in China as the Yemaquan island arc and the Dulate-Baytag continental arc (Han and others, 2010). In the eastern part of the tract, there are a few Triassic (probably collision related) plutons that are contiguous with the arc, and which are included in the tract.

Geologic Criteria

The tract is defined by calc-alkaline, intermediate composition igneous map units of Devonian, Carboniferous, and Permian age. In addition, a few early Mesozoic plutons, some possibly as young as Jurassic, are included. Plutonic rock types include granite, granite-leucogranite, diorite, granodiorite, plagiogranite, and granosyenite, with lesser amounts of syenite, monzonite, gabbrodiorite, and alkaline granitoids. Volcanic rock types include andesite, dacite, and rhyolite, with lesser amounts of trachyte, trachydacite, and trachyandesite.

The Oyu Tolgoi tract is bounded on the south by the Solonker Suture and on the north by the Main Mongolian Lineament (fig. 5). The eastern end of the tract is limited by the eastern margin of the CAOB, beyond which the magmatic history is related to Mesozoic Pacific-margin subduction. The western end of the tract is defined by the Junggar Basin, where no igneous rocks are found (fig. 25).

Known Porphyry Deposits

There are three known porphyry copper deposits in the tract, all of them in Mongolia (fig. 24, table 2). They are, from west to east, Zuun Mod, Oyu Tolgoi, and Tsagaan-Suvarga.

Zuun Mod

Zuun Mod was discovered in 2002. It has subequal grades of copper and molybdenum and is a classic example of a deposit that is difficult to classify—the copper grade is higher, but the molybdenum is more valuable, because of the price differential. At a cut-off grade of 0.03 percent molybdenum, the resource at Zuun Mod is 650 Mt with a copper grade of 0.063 percent and a molybdenum grade of 0.046 percent. This translates into about 406 kt of copper and 302 kt of molybdenum (Clark and Baudry, 2011).

Oyu Tolgoi

Oyu Tolgoi (Mongolian for "Turquoise Hill") is a 22-km-long district that contains at least 8 Late Devonian porphyry copper-gold centers (fig. 26) in the Gobi Desert of southern Mongolia (Perelló and others, 2001; Khasgerel and others, 2009). Oyu Tolgoi is the largest known porphyry copper deposit in the study area. It is one of the largest porphyry copper deposits in the world and contains more than 36 Mt of copper. The Oyu Tolgoi deposits are all related to high-potassium calc-alkaline quartz monzodiorite intrusions hosted by augite basalt lavas described as primitive basaltic island-arc rocks (Khashgerel and others, 2009). The region preserves a record of the Paleozoic accretion of continental arcs and island arcs to the southern margin of Mongolia. Postmineral Carboniferous alkaline rocks intruded the area during a time when the Oyu Tolgoi deposits were buried. Regional uplift in the Cretaceous brought the deposits near to the surface.

The main mineralization was initially described within a 2.5- by 1.5-km area as three zones known as North (renamed Hugo Dummett in 2003), Central, and South Oyu (Perelló and others, 2001). Subsequent exploration identified additional pipelike and elongate ore bodies along the same north to northeast trend (fig. 26). The deposits have similar ages (four deposits in the central part of the district have U/Pb zircon ages of 372 ± 3 Ma) and are all distributed along a thrust fault and bounded by steeper faults. Individual ore bodies vary in geometry, dominant hypogene ore mineralogy (chalcopyrite or bornite), dominant host rock (quartz monzodiorite, breccia, basalt), and alteration (Khasgerel and others, 2009). Some ore bodies are partly exposed at the surface; others are concealed beneath poorly consolidated Cretaceous sedimentary rocks and alluvium. Regional synmineral Silurian-Devonian uplift contributed to telescoping of epithermal alteration over deeper, higher temperature porphyry copper alteration. Advanced argillic alteration characterizes ore bodies in the Hugo Dummett and Central areas but is absent (or not preserved) in the southern ore bodies, where high-sulfidation epithermal parts of the system are eroded exposing deeper levels of porphyry. The Central ore body preserves a 25- to 50-m leached cap over

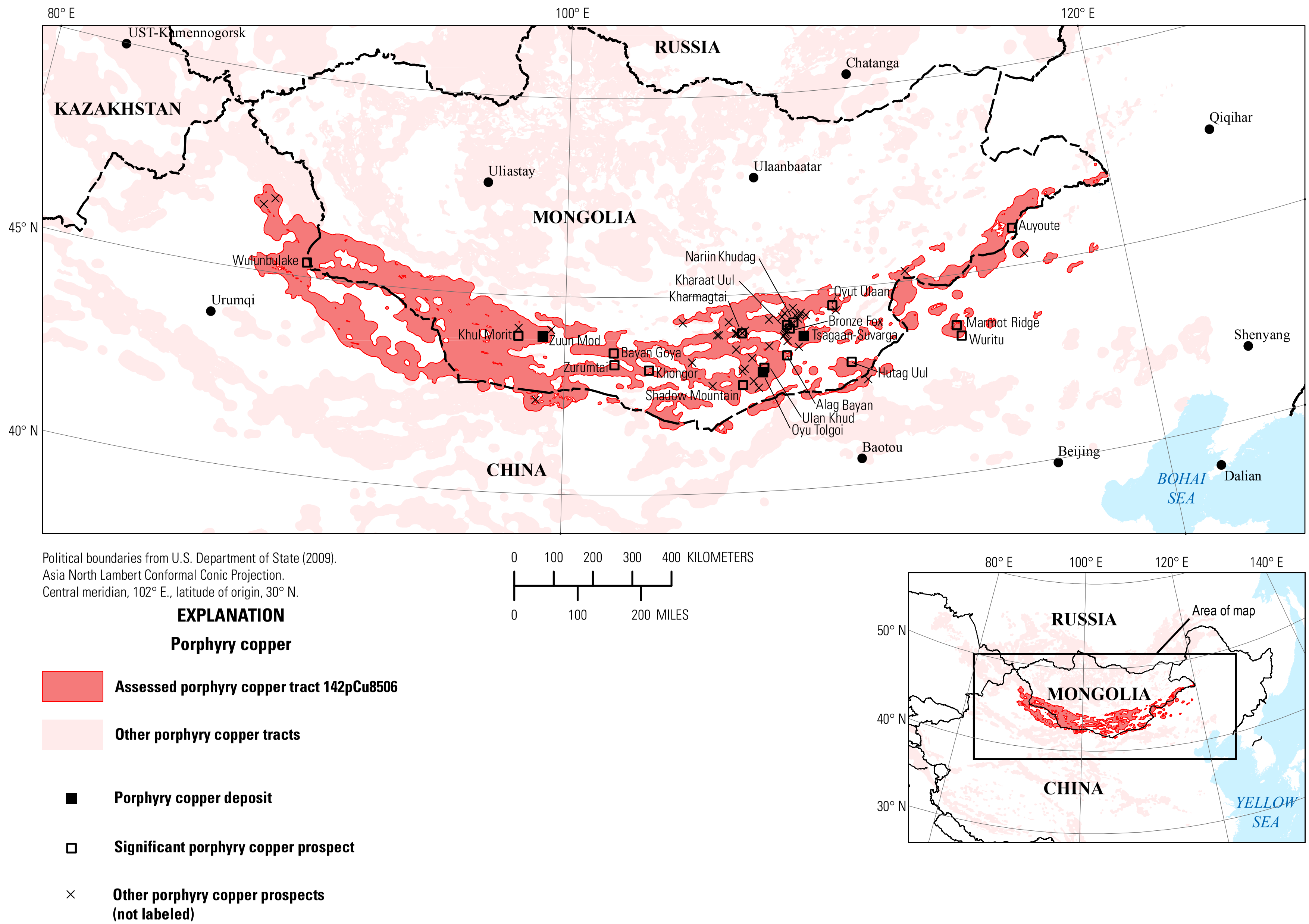


Figure 24. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8506, Oyu Tolgoi—Mongolia and China.

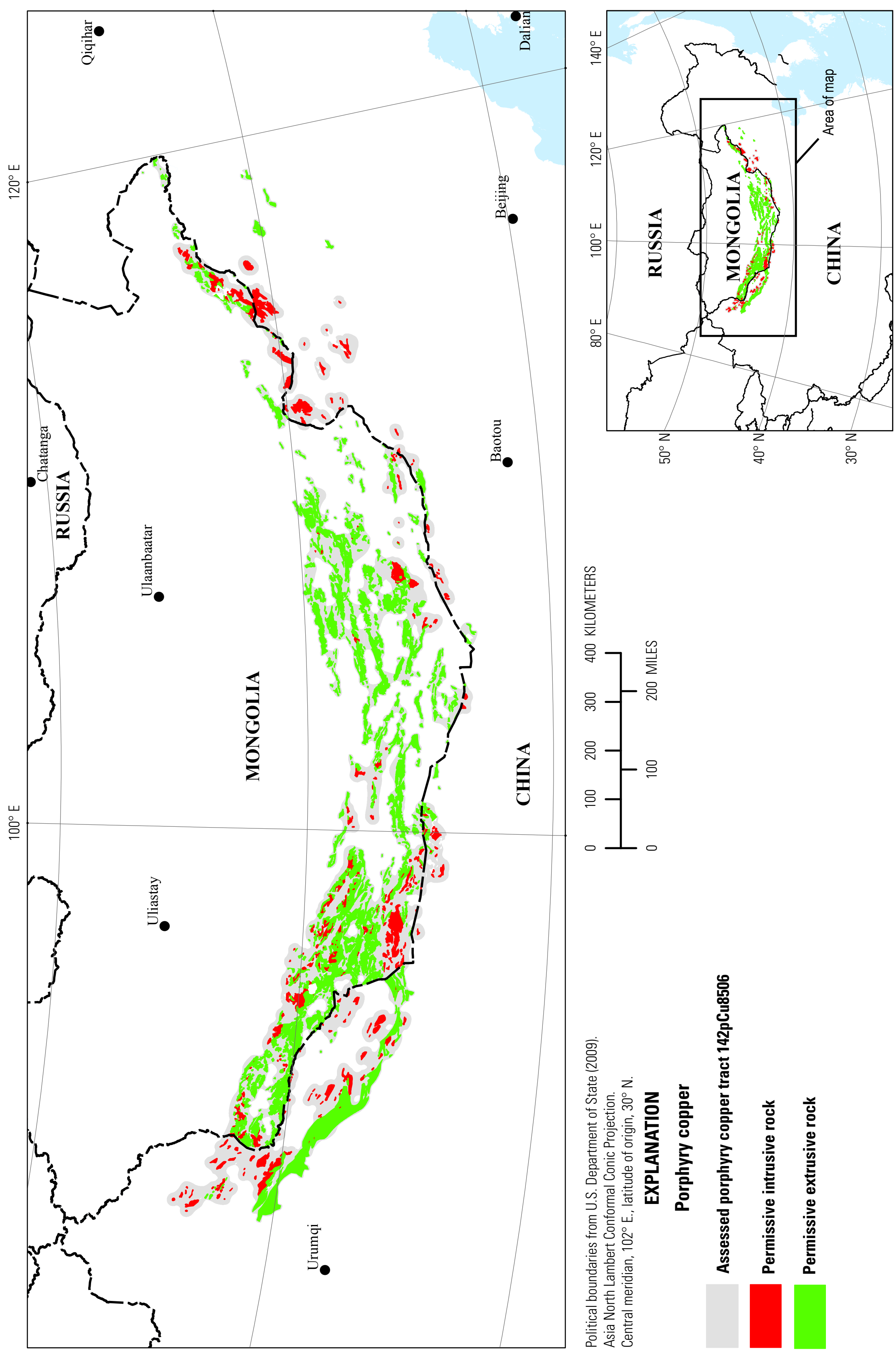


Figure 25. Map showing the distribution of permissive intrusive and extrusive rocks used to delineate tract 142pCu8506, Oyu Tolgoi—Mongolia and China.

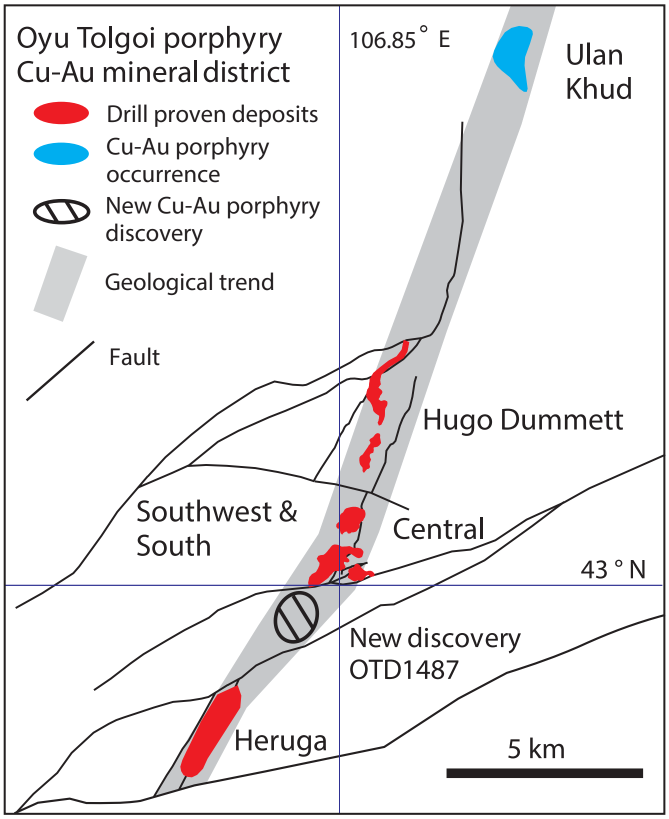


Figure 26. Map showing the distribution of porphyry copper deposits and exploration targets at Oyu Tolgoi, Mongolia (figure 1 on p. 1089 of Khashgerel and others, 2009).

a Cretaceous supergene chalcocite blanket that overlies hypogene ore at depth. For details on the Oyu Tolgoi deposits, see Kirwin and others (2003, 2005), Perelló and others (2001), Seltmann and Porter (2005), and Khashgerel and others (2006, 2008, 2009).

The deposit was discovered in 1995 and is being developed for both open-pit and underground mining (block caving). Open-pit mining at the near-surface southern ore bodies began in 2013 (Turquoise Hill Resources, 2013). An underground block-cave mine is planned to access the Hugo Dummet/North ore body.

Tsagaan-Suvarga

The Tsagaan Suvarga porphyry copper-molybdenum deposit lies within the late Paleozoic Kazakh-Mongol Arc about 150 km northeast of Oyu Tolgoi. The deposit is hosted in a multiphase intrusive complex (gabbro, diorite, syenite, syenogranite, granodiorite). Mineralization is associated with late-stage porphyry intrusions. Chalcopyrite-bearing quartz stockworks are developed over a 1-km by 300-m area, and ore has been traced to depths of 600 m. Molybdenites from the deposit were dated at 370.1 ±1.2 and 370.6±1.2 by Re-Os dating (Watanabe and Stein, 2000).

Tsagaan Suvarga contains about 1.3 Mt of copper. Copper and molybdenum are the major commodities (Seltmann and Porter, 2005; Perelló and others, 2001; Weixuan and others, 2007). The mine has not been developed, but plans were underway to construct a concentration plant to begin operation in 2015.

Prospects, Mineral Occurrences, and Related Deposit Types

There are at least 60 porphyry copper prospects in the Oyu Tolgoi tract, 52 of them in Mongolia and 8 in China. Of these, some 17 are considered significant because they have some measured amounts of mineralized rock, 14 in Mongolia and three in China. The 330 Ma-old Kharmagtai prospect, which shows all the geologic features of a porphyry copper deposit, is a good example. About 130 km north-northwest of Oyu Tolgoi, the Kharmagtai area has been explored by numerous drill holes and has a preliminary resource determined at 229 Mt at a copper grade of 0.35 percent. Because of uncertainties surrounding the mining laws in Mongolia, further development and exploration at Kharmagtai has been suspended for years.

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used to estimate undiscovered porphyry copper resources in the tract. There are three known porphyry copper deposits in the tract, the most significant of which is Oyu Tolgoi (table 2). Available grade and tonnage data suggest that the general model is appropriate on the basis of results of a *t*-test, applied at the 1-percent confidence level using log-transformed values for ore tonnage and grades of copper, molybdenum, silver, and gold. Test results indicate that data for these deposits are not distinguishable from the general model (table 3).

Estimates of Undiscovered Deposits and Rationale

The Oyu Tolgoi tract covers about 330,000 km^2. Three known deposits and 17 significant prospects are within the tract, with a concentration in the central part of the tract in Mongolia (fig. 24). The three deposits include the Oyu Tolgoi deposit, one of only a few deposits supergiant worldwide that contain more than 20 Mt of copper (Singer, 1995). Most of the significant prospects (those with some estimates of tonnage and (or) grade) are clustered in the central part of the tract, within about 400 km of Oyu Tolgoi.

The assessment team was influenced by the large number of extensively explored prospects in this tract. A large amount of copper was discovered in Mongolia between 1991 and 2010, and the team expects more discoveries will be made if and when exploration resumes.

The proportion of volcanic to plutonic rock types (fig. 25) and the presence of a few epithermal precious-metal deposits and prospects both indicate that the level of erosion is quite appropriate for the exposure and preservation of porphyry copper deposits. A large part of the tract is covered with thin surficial sediments that may conceal undiscovered deposits.

The level of past mineral exploration is quite variable. Much of the Mongolian part of the tract, particularly in the vicinity of Oyu Tolgoi, is relatively well explored, whereas the eastern and western ends of the tract in China have not received so much attention. Mineral-exploration and mining-lease maps of Mongolia (MRAM, 2003; Javkhlanbold, 2006) show coverage of the tract is nearly complete (with the exception of some large environmentally sensitive protected areas), indicating that much of the area has undergone scrutiny. The eastern and western parts of the tract in China have been evaluated for mineral resources at the reconnaissance level, and select areas, particularly in the eastern part of the tract, have been the site of mineral-resource surveys and exploration at map scales between 1:10,000,000 and 1:2,500,000. A few detailed investigations, also mainly in the east, have been carried out (see maps available at China Geological Survey, 2005).

The team estimated a 90-percent chance for 6 or more undiscovered deposits in the tract, a 50-percent chance of 14 or more deposits, and a 10-percent chance of 48 or more deposits, for a mean of 21 undiscovered deposits (table 9*A*).

Four assessment tracts (II-1, II-2, II-4, VIII-4, and IX-2) from Yan and others (2007) are largely coincident with the Chinese parts of the Oyu Tolgoi tract. The total mean expected number of undiscovered deposits in those tracts is about 8.3, but the numbers are not directly comparable with this assessment, as they cover only the Chinese part of the tract and also because part of the estimated deposits are Caledonian or Yanshanian in age.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 80 Mt copper is about twice the identified copper resources (38 Mt copper). Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 9*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 27).

Mongol-Altai Tract (142pCu8507)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Devonian through Permian calc-alkaline continental-arc rocks in Mongolia, China, Kazakhstan, and Russia

Location

The Mongol-Altai tract consists of numerous semicontinuous linear and curvilinear belts that as a whole are arcuate in shape (fig. 28), largely as a result of postemplacement deformation. The tract axis measures about 3,000 km in length and is nearly 1,000 km at its widest. The tract covers large parts of central and northern Mongolia. The eastern part of the tract straddles the border between China and Russia, whereas the western part covers large parts of southern Russia, as well as smaller areas in easternmost Kazakhstan and the northern part of Xinjiang Autonomous Region in China.

Tectonic Setting

The rocks that define the Mongol-Altai tract all appear to be related to continental arcs, along with some collision-related rocks. The widespread rocks in the western half of the tract, which are primarily in Russia and Kazakhstan and mainly Devonian in age, do not appear to have been assigned to named arcs. They may represent the end stages of the Kipchak and Tuva-Mongol Arcs. The central part of the tract includes igneous rocks of Devonian to Permian age (mainly Carboniferous), which are presumed to correspond to the Sayan-Transbaikal Arc (fig. 6; see Seltmann and Porter, 2005, fig. 2). The eastern extensions of the tract are defined by rocks of the Permian-Triassic Selenga-Gobi-Khanka Arc (fig. 6; see Seltmann and Porter, 2005, fig. 2), which are products of the last subduction-related igneous activity in the history of the CAOB.

Geologic Criteria

Calc-alkaline, intermediate-composition igneous map units with Devonian, Carboniferous, and Permian ages define the tract (fig. 29). Devonian and Permian rocks are the most abundant. Plutonic rock types include granite, granite-leucogranite, granodiorite, plagiogranite, granosyenite, quartz diorite, syenite, tonalite, and diorite, with lesser amounts of gabbrodiorite, quartz monzonite, monzodiorite, and alkaline granitoids. Extrusive rock types include dacite, rhyolite, and andesite, with lesser amounts of trachyte, trachydacite, and trachyandesite.

The Mongol-Altai tract is bound on the south by the Main Mongolian Lineament (fig. 6) and by the Altai Mountains. The rocks to the south help define the Kazakh-Tarim (142pCu8505) and Mongol-Altai (142pCu8506) tracts. On the north, the boundary is the southern margin of the Siberian Craton. The eastern margin of the tract is the eastern limit of the CAOB, beyond which the magmatic history is related to Mesozoic Pacific-margin subduction. The western boundary of the tract is an amagmatic region between Central Asia and the Ural Mountains.

Known Porphyry Deposits

There are no known porphyry copper deposits in the tract.

Prospects, Mineral Occurrences, and Related Deposit Types

Information was compiled for 56 porphyry copper prospects in the tract—2 in China, 1 in Kazakhstan, 6 in Russia, and 47 in Mongolia. Sixteen prospects, 1 in Kazakhstan, 4 in Russia, and 11 in Mongolia, are judged to be particularly significant (fig. 28). All prospects are described in appendix B and in the GIS database.

Table 9. Probabilistic assessment results for tract 142pCu8506, Oyu Tolgoi—Mongolia and China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
6	14	48	48	48	21.0	16.0	73	3	24	329,850	7

B. Results of Monte Carlo simulations of undiscovered resources.

[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	3,400,000	8,900,000	54,000,000	190,000,000	230,000,000	80,000,000	0.39	0.02
Mo	26,000	110,000	1,300,000	5,400,000	7,200,000	2,200,000	0.34	0.03
Au	53	170	1,300	4,800	6,000	2,000	0.38	0.03
Ag	150	1,100	14,000	66,000	93,000	26,000	0.34	0.04
Rock	820	1,900	11,000	37,000	46,000	16,000	0.40	0.02

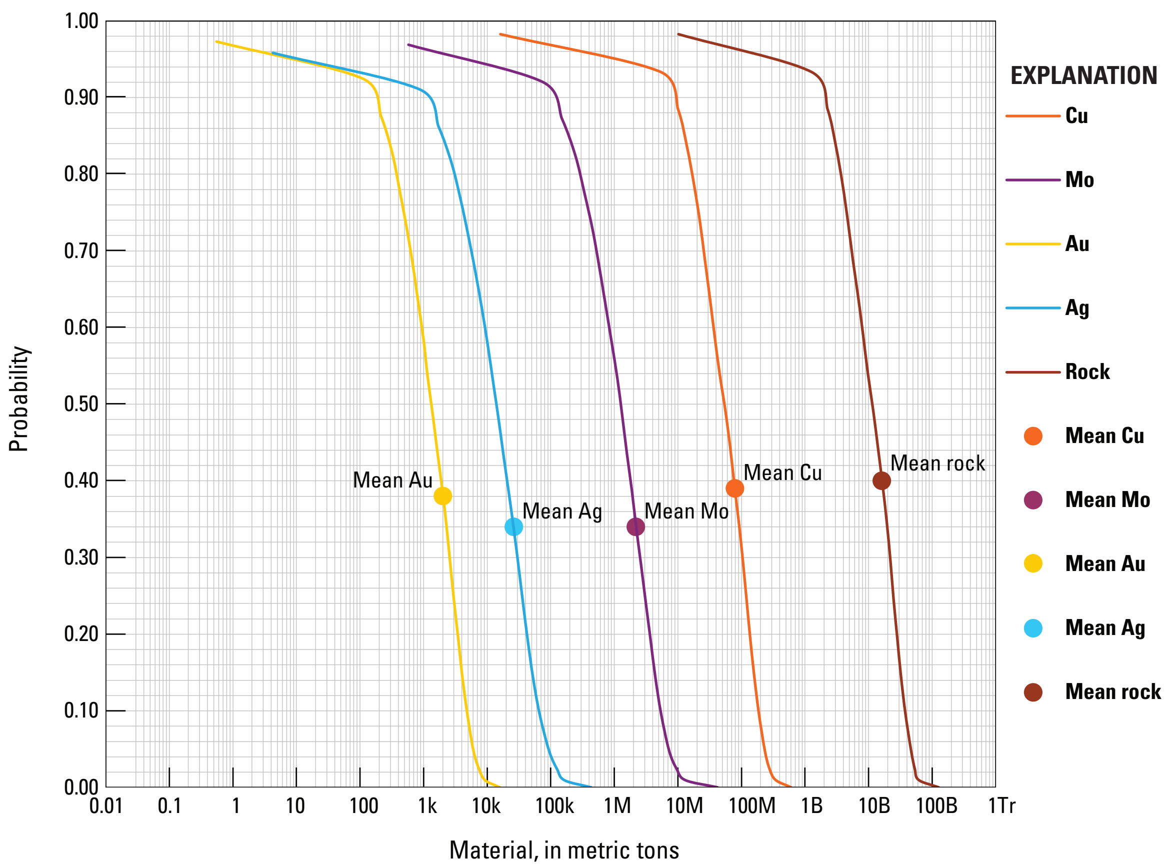
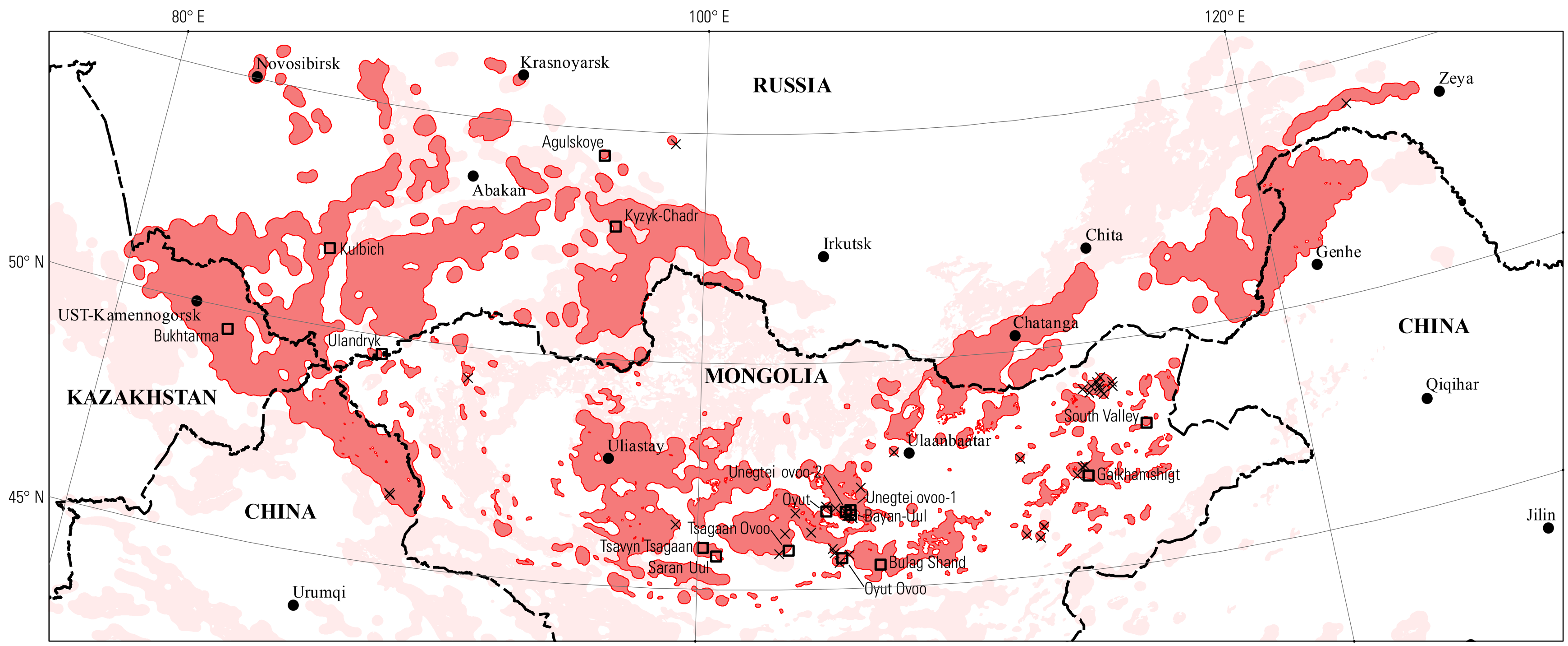
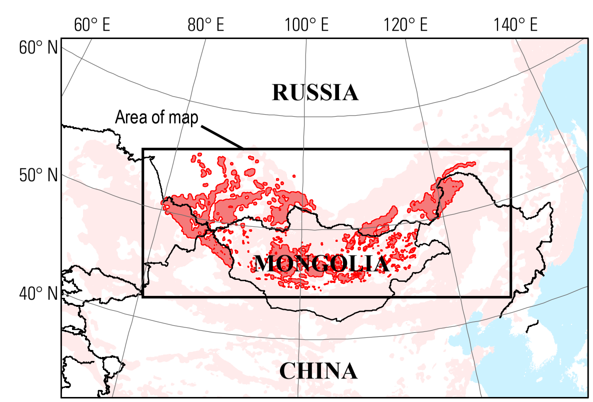


Figure 27. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8506, Oyu Tolgoi—Mongolia and China. k=thousands, M=millions, B=billions, Tr=trillions.



Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 102° E., latitude of origin 30° N.

0 100 200 300 400 KILOMETERS
0 100 200 MILES



EXPLANATION

Porphyry copper

- **Assessed porphyry copper tract 142pCu8507**
- **Other porphyry copper tracts**
- □ **Significant porphyry copper prospect**
- × **Other porphyry copper prospects (not labeled)**

Figure 28. Map showing the location, significant prospects, and prospects for permissive tract 142pCu8507, Mongol-Altai—Mongolia, Russia, China, and Kazakhstan.

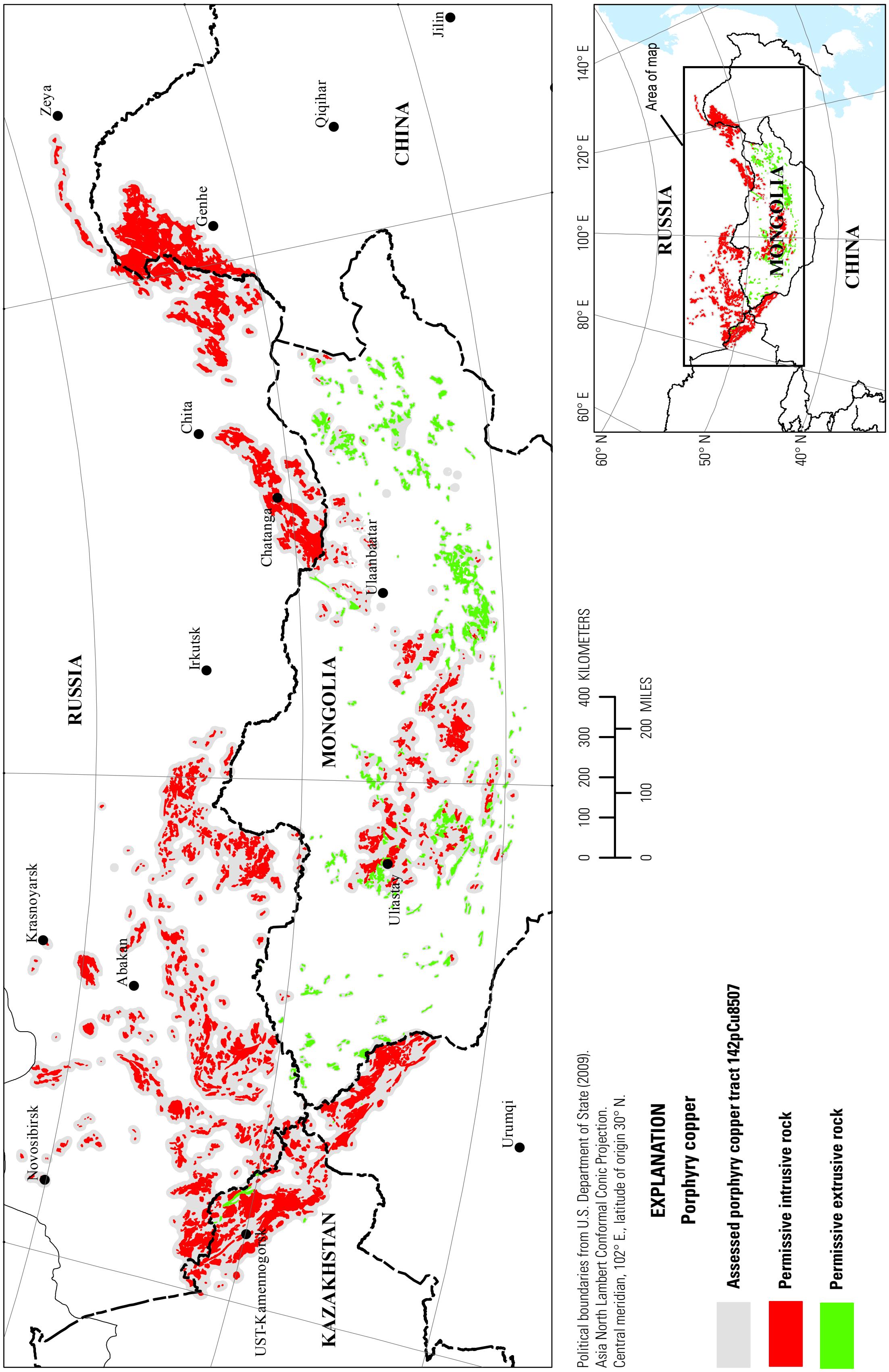


Figure 29. Map showing the distribution of permissive rocks used to delineate tract 142pCu8507, Mongol-Altai—Mongolia, Russia, China, and Kazakhstan.

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used, as there are no known deposits in the tract, and thus, no reliable information to guide the choice of a grade and tonnage model. There is no compelling geologic or metallogenic reason to suggest that either the porphyry Cu-Au or Cu-Mo grade and tonnage models would be more appropriate.

Estimates of Undiscovered Deposits and Rationale

The Mongol-Altai tract is the largest of the 11 Central Asia tracts and covers nearly 800,000 km^2. The 56 prospects in the tract are unevenly distributed, with approximately half of them in the south-central part of the tract in Mongolia in the Selenga Arc. The majority are in Mongolia, although large parts of the tract are in China, Russia, and Kazakhstan. This is probably mostly a function of data availability, as the mineral database of Dejidmaa and others (2002), which tabulates many minor mineral occurrences, has no available counterpart in the other countries. Few of these Mongolian prospects have been dated radiometrically, and it is possible that some of them are older and might equally as likely be assigned to the Mongol-Sayan tract (142pCu8504). It is expected that more prospects exist in Russia and Kazakhstan than were identified.

Similarly, the proportion of extrusive to intrusive rock types is noticeably different between the various digital geologic maps. The permissive map units in Russia and China appear to be mostly plutons, with very few associated volcanic rocks. The permissive map units on the Mongolian map (and to a lesser degree on the Kazakh map) shows a more balanced mix between plutonic and volcanic types (fig. 29). The plutonic units on the Russian map also show more compositional variety than the Mongolian map, which has many units lumped into two classes, granite and leucogranite. Conversely, the Mongolian map has a wide variety of volcanic compositions, whereas the Russian map has only one volcanic rock type, rhyolite. Because of these inconsistencies, it was difficult to decide whether the level of erosion was appropriate for the exposure and preservation of porphyry copper deposits, but overall, the erosion level seems appropriate. Some regions, mainly in the northeastern area of the tract, were considered too deeply eroded and were excluded.

The level of mineral exploration was considered to be very uneven, ranging from well explored in parts of Mongolia to moderately and poorly explored in the Kazakh, Chinese, and Russian parts of the tract. The western part of the tract, particularly the Altai Mountains, is rugged, remote, and difficult to access.

In Russia, the entire area is covered by geologic maps at 1:200,000 scale, but most of this mapping was completed before 1979, with the exception of a few areas in the northeast and northwest, which were mapped between 1996 and 2004 (Tikhomirova, S.R., written commun., 2011). Nearly all of Mongolia has been mapped at 1:200,000 scale (Javkhlanbold, 2006), and mineral-exploration and mining-lease maps of Mongolia (MRAM, 2003; Javkhlanbold, 2006) show that coverage of the Mongolian part of the tract is nearly complete, indicating that much of the area has undergone scrutiny. The Chinese part of the tract has been evaluated for mineral resources at the reconnaissance level, and select areas have been the site of mineral-resource surveys and exploration at map scales between 1:10,000,000 and 1:2,500,000.

The team estimated a 90-percent chance for 3 or more undiscovered deposits in this very large, long-lived tract, a 50-percent chance of 8 or more deposits, and a 10-percent chance of 36 or more deposits, for a mean of 15 undiscovered deposits (table 10*A*). It should be noted that this expected number of undiscovered deposits is about half the number of deposits (34) predicted using a deposit-density model based on tract area (Singer and Menzie, 2010) and may be conservative. However, the difficulty of identification of truly permissive lithologies from the map units undoubtedly inflates the tract area because some nonpermissive rocks are probably included.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered copper resources of is 53 Mt. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 10*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 29).

Indosinian Tracts in the Central Asia Orogenic Belt

The youngest tract in the CAOB is the Erdenet tract (fig.7). The oldest rocks in the tract are middle Permian, and the tract spans the late Variscan through Indosinian (also known as the Late Hercynian) orogenic stages.

Erdenet Tract (142pCu8508)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Middle Permian through Triassic igneous rocks in Russia and Mongolia that formed during and after closure of the Mongol-Okhotsk Ocean, possibly in a postconvergent environment

Location

The Erdenet tract consists of two sub-tracts, each about 800 by 200 km (fig. 31). The Erdenet Southwest sub-tract (142pCu8508a) is in north-central Mongolia and is the northern arm of the Selenga Arc. The Erdenet Northeast sub-tract (142pCu8508b) is in eastern Russia, about 300 km east of Lake Baikal. There is a gap of about 500 km between the two areas, characterized by middle to upper Permian metamorphic core complexes, where permissive rocks are absent and may have been removed by erosion.

Table 10. Probabilistic assessment results for tract 142pCu8507, Mongol-Altai—Mongolia, Russia, China, and Kazakhstan.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
3	8	36	36	36	15.0	12.0	84	0	15	785,570	2

B. Results of Monte Carlo simulations of undiscovered resources.

[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	860,000	3,100,000	29,000,000	140,000,000	180,000,000	53,000,000	0.37	0.03
Mo	0	22,000	660,000	4,000,000	5,600,000	1,500,000	0.32	0.06
Au	0	43	740	3,400	4,500	1,300	0.36	0.05
Ag	0	83	7,300	46,000	66,000	18,000	0.31	0.09
Rock	240	720	6,300	28,000	35,000	11,000	0.38	0.03

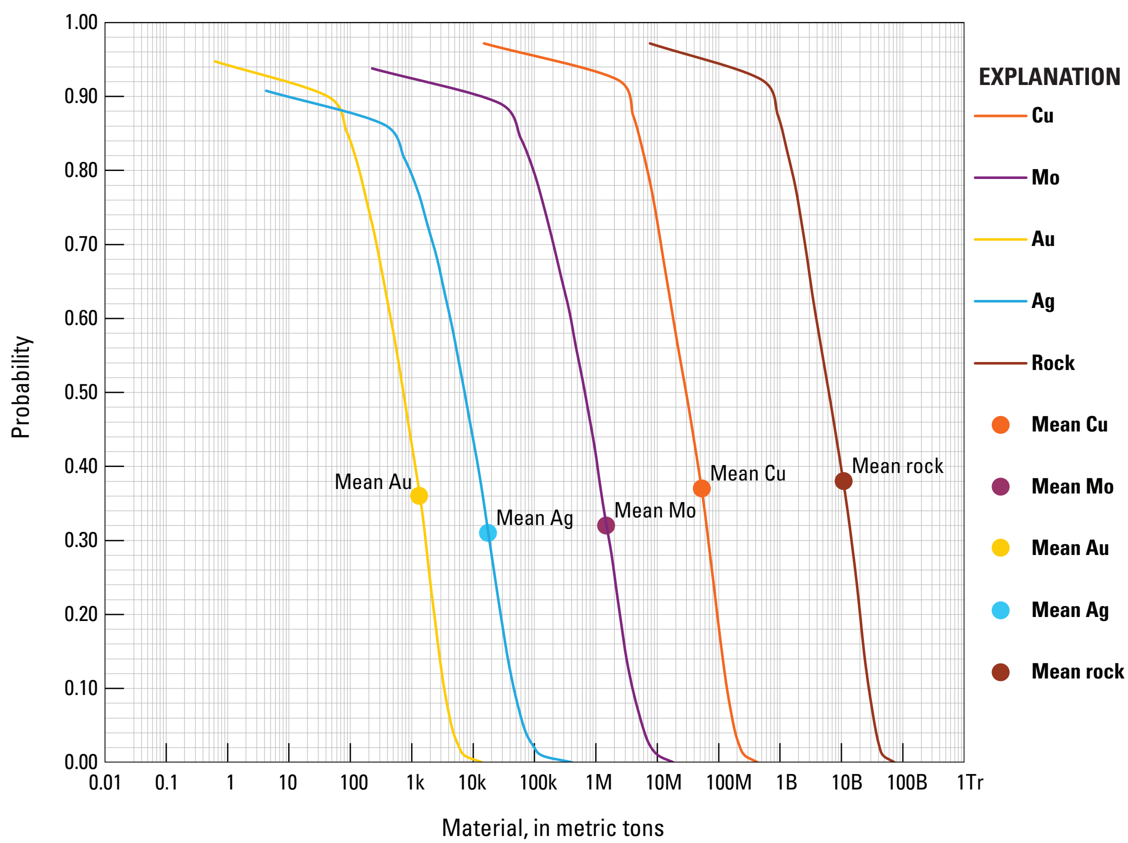


Figure 30. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in 142pCu8507, Mongol-Altai—Mongolia, Russia, China, and Kazakhstan. k=thousands, M=millions, B=billions, Tr=trillions.

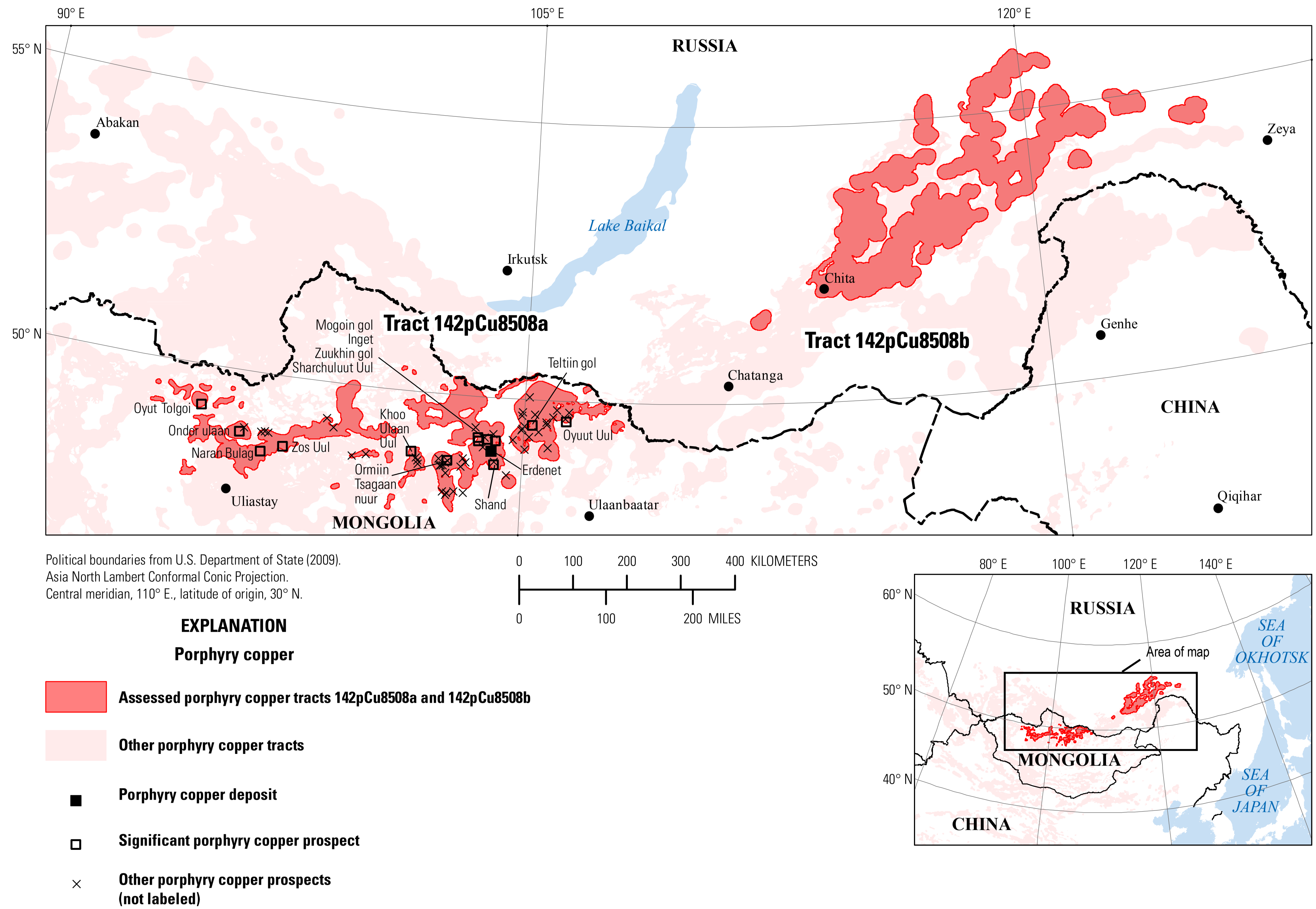


Figure 31. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8508, Erdenet—Mongolia and Russia. Sub-tracts 142pCu8508a and142pCu8508b are shown on the map.

Tectonic Setting

The tectonic history of this area is complex, and there is some significant contradictory evidence. The area, including the gap between the two parts of the tract, corresponds quite closely to the Mongolian-Transbaikalian Belt, as discussed by Jahn and others (2009) and Reichow and others (2010). It is also known as the Mongolian-Transbaikalian Rift (Zanvilevich and others, 1985). The rocks here are described as a group of more than 350 peralkaline, syenitic, and A-type granite plutons, with associated bimodal (basalt-rhyolite) volcanism, and are thought to have formed by partial melting of the mantle in response to deep continental rifting. This environment is affirmed by the study of Hegner and others (2006), who call this belt the Selenga-Vitim magmatic belt.

This is not a tectonic environment that is commonly associated with porphyry copper deposits. Nevertheless, the digital geologic maps of both Mongolia and Russia depict numerous permissive rock types, including diorite, tonalite, quartz diorite, and granodiorite plutons, along with exposures of andesite and dacite. Parfenov and others (2009) describe the area as the Permian through Jurassic Selenga continental arc that formed due to north-directed oblique subduction of Mongol-Okhotsk oceanic crust. The occurrence of the Erdenet porphyry copper deposit in Triassic intermediate-composition volcanic and plutonic rocks (Gerel and others, 2006; Munkhtsengel and others, 2007), along with numerous porphyry copper prospects in the area, also indicates that not all the rocks are peralkaline and (or) A-type. Although Munkhtsengel and others (2007) describe the intrusions at Erdenet as part of a continental arc, the Sr-isotope compositions of about 0.704 suggest that there was a minimal crustal component to the magmas and that they may have a postconvergent origin.

Geologic Criteria

The tract was divided into two sub-tracts on the basis of differences in available information and the presence of middle to upper Permian metamorphic core complexes, which form the gap between the northeastern and southwestern sub-tracts. The southwest part of the tract (142pCu8508a) contains all the known deposits and prospects. Undiscovered resources were estimated for this part but not for the northeast part (142pCu8508b), which contains no known porphyry copper prospects, although the igneous rocks appear to be permissive. The tract (both parts) was defined using primarily middle to upper Permian calc-alkaline, intermediate-composition igneous map units, as well as Early Triassic (transitional from Variscan to Indosinian; uppermost Paleozoic to lowermost Mesozoic) units (fig. 32). Plutonic units include granodiorite, granite, granite-leucogranite, quartz diorite, diorite, plagiogranite, tonalite, monzonite, monzodiorite, granosyenite, and syenite, with lesser amounts of alkaline granitoids. Extrusive units include primarily dacite, andesite, and rhyolite closely associated with permissive intrusive units, with lesser amounts of various trachytes. Also included are mixed volcanic-sedimentary units that were determined to be mainly composed of volcanic rocks, which in a few cases consist of mafic units spatially and temporally associated with intermediate and felsic units (gabbrodiorite, basalt-andesite, and basalt-dacite), that host (or are associated with units that host) numerous small porphyry copper prospects.

The Erdenet Southwest sub-tract tract is bound along its southern margin by the Jurassic-Cretaceous Mongol-Okhotsk Suture (fig. 7). Along its northern and northeastern margin, the tract is bound by Precambrian-Cambrian sutures and related structures along the southern margin of the Siberian Craton. The southwestern end of the tract is bound by Cambrian-Ordovician sutures and structures among cratonal terranes and arc and accretionary complexes within the core of the Mongolian Orocline.

Parts of the Erdenet Northeast sub-tract142pCu8508b are overlapped by the younger Jurassic and Cretaceous (Yanshanian) rocks included in the Manchuride tract (142pCu8509), which is described in the porphyry copper assessment of the Mesozoic of East Asia (Ludington and others, 2012b).

Known Porphyry Deposits

The only known porphyry copper deposit in the tract is the large (9 Mt of copper) Erdenet deposit in the Erdenet Southwest sub-tract in Mongolia. Erdenet, a site known since prehistoric time, was recognized as a major copper deposit in 1941, was intensively explored during the 1960s, and began production in 1978 (Japan International Cooperation Agency and Japan Oil, Gas and Metals National Corporation [JICA-JOGMEC], 2004). The estimated total resource is 2,370 Mt at a copper grade of 0.38 percent and a molybdenum grade of 0.013 percent (Singer and others, 2008; Gerel and Munkhtsengel, 2005; Gerel and others, 2005). There are no significant gold-bearing ores. The recent discovery of porphyry copper mineralization at depth at a site midway between the known, but undeveloped, Erdenet Central and Erdenet Southeast ore bodies, along with drilling results on the northwestern margins of the existing mine, demonstrate that there is nearly continuous mineralization that extends more than 10 km along a northwest-southeast trend.

The deposit is related to a suite of late Permian to early Triassic (about 250 Ma to about 210 Ma) intrusions that range in composition from diorite through granodiorite to granite (Gerel, 1999; Gerel and Munkhtsengel, 2005). Watanabe and Stein (2000), using Re-Os methods, determined a mineralization age on molybdenite from the deposit of about 241 Ma. The mineralized veins and veinlets in the deposit contain chalcopyrite, bornite, and molybdenite as the main ore minerals. The most abundant alteration assemblages are phyllic and peripheral intermediate argillic, which overprint an earlier potassic zone characterized by potassium feldspar, biotite, and magnetite (Gerel and Munkhtsengel, 2005).

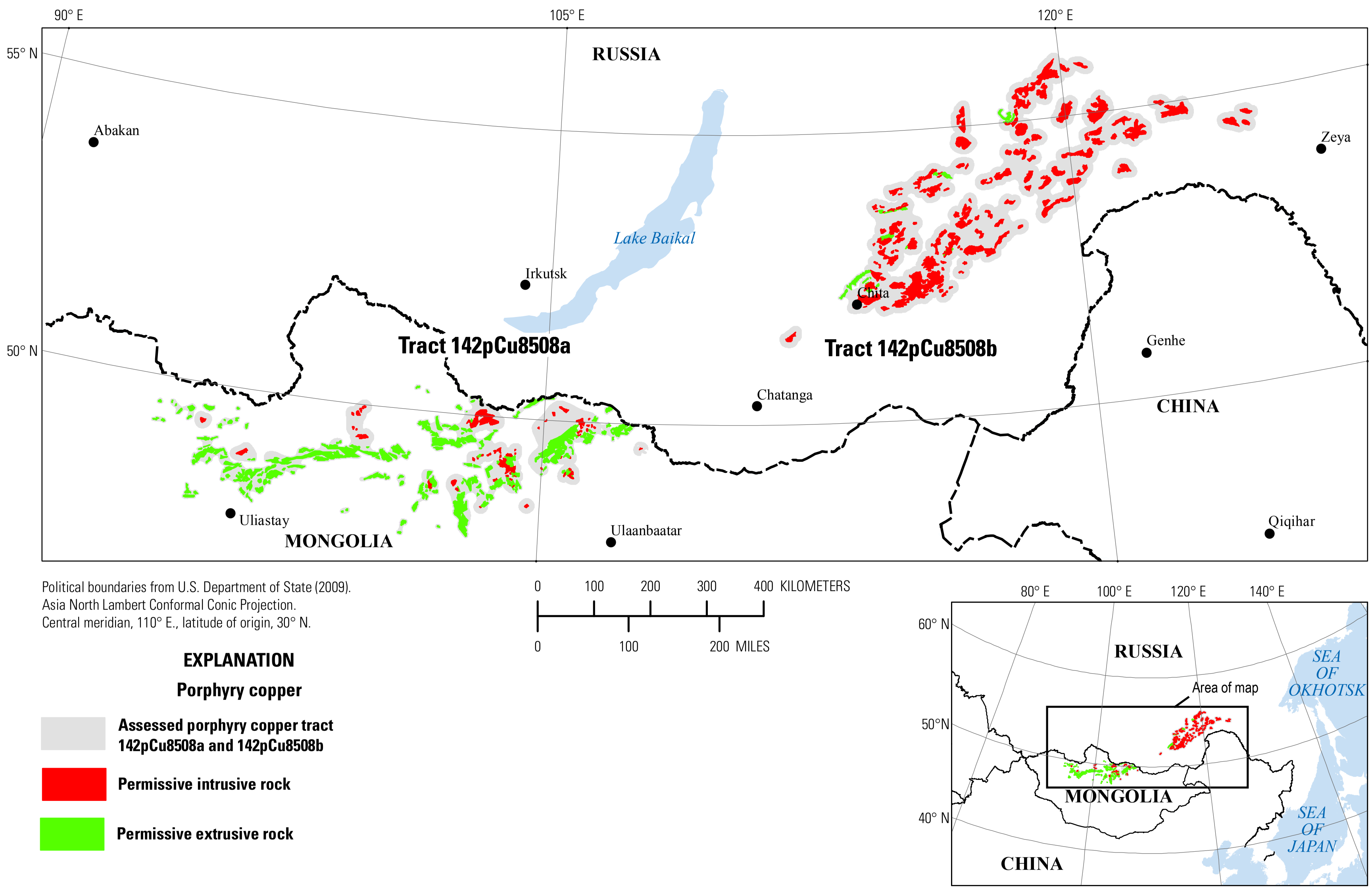


Figure 32. Map showing the distribution of permissive rocks used to delineate tract 142pCu8508, Erdenet—Mongolia and Russia. Sub-tracts 142pCu8508a and 142pCu8508b are shown on the map.

Prospects, Mineral Occurrences, and Related Deposit Types

Thirteen of the 63 documented porphyry copper prospects in the Erdenet Southwest sub-tract in Mongolia are considered to be significant. The majority of these are in north central Mongolia, within about 150 km of Erdenet (fig. 31, appendix B). This probably reflects the intense exploration that has been done in the vicinity of Erdenet. The lack of important prospects in the Erdenet Northeast sub-tract in Russia, where there are several molybdenum vein occurrences, may reflect deeper erosion levels or lower quality information.

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used to assess the Erdenet Southwest sub-tract (142pCu8508a). On the basis of ANOVA for the tonnage, copper grade, and molybdenum grade reported for the Erdenet deposit, the model is appropriate (table 3). Gold and silver grades are not reported. There is no compelling geologic or metallogenic reason to suggest that either the porphyry Cu-Au or Cu-Mo grade and tonnage models would be more appropriate.

Estimates of Undiscovered Deposits and Rationale

Estimates of numbers of undiscovered porphyry copper deposits were made only for the Erdenet Southwest sub-tract. The assessment team concluded that although the Erdenet Northeast sub-tract is broadly permissive on the basis of geology, insufficient information was available to warrant a quantitative assessment.

One world-class porphyry copper deposit, Erdenet, and 13 significant prospects are known in the Erdenet Southwest sub-tract in Mongolia (fig. 31). The significant prospects are distributed across the southwestern part of the tract, and most have detailed exploration sample grades and other metallogenic information. In addition, at least 56 other prospects have been identified (Nokleberg and others, 1999; Dejidmaa and others, 2002). The distribution of all these deposits, significant prospects, and prospects stands in marked contrast to the Erdenet Northeast sub-tract (fig. 31), where no porphyry copper-related occurrences were found in any of the datasets used for this assessment (although a few porphyry molybdenum occurrences and gold in quartz-sulfide veins associated with granitoid intrusions were noted).

The assessment team noted that the Erdenet Southwest sub-tract contains one of the largest porphyry copper deposits in Central Asia, Erdenet, which continues to be enlarged through extensions to the south, the result of continued exploration. The team also recognized the large number of significant and other prospects in this sub-tract but was cautious in interpreting this as an indicator of undiscovered deposits because such prospects are noticeably absent in the Erdenet Northeast sub-tract in Russia. Questions remain as to whether these prospects in Mongolia represent overzealous mineral-site cataloging, classification or nomenclature problems, or some other database artifact. It was also observed that mineral deposits in the Erdenet Northeast sub-tract in Russia are classified as molybdenum porphyry and other Mo-bearing mineralization, resulting in an unusual southwest-to-northeast metallogenic zoning pattern in this tract.

The unusual distribution of mineral occurrences and metallogenic zoning from southwest-northeast across the tract also appears in the Mongolian and Russian geologic map units. The permissive units on the Russian geologic map show mainly plutonic types, with very few volcanic rocks. The permissive units on the Mongolian geologic map show a more balanced mix between plutonic and volcanic types (see fig. 32). The intrusive units on the Russian map show wider compositional variety than the Mongolian map, which has many units lumped into a “granite, leucogranite” category. Conversely the Mongolian map has a wide variety of volcanic unit compositions, whereas the Russian map has only one volcanic rock type, “dacite.” Because of these inconsistencies among the geologic maps, it was difficult to determine whether the level of erosion was appropriate for the exposure and preservation of porphyries, but if the Mongolian map is used as an indicator, the level of erosion would be deemed appropriate (as it would appear is borne out by the presence of many deposits, significant prospects, and prospects). The Erdenet Northeast sub-tract is either more deeply eroded or, more likely, represents an artifact of mapping style, intent, or rock classification. The presence of molybdenum porphyry suggests that the area is not too deeply eroded. Those regions considered too deeply eroded, such as the rocks of the Barzugin Batholith to the northeast, were excluded from the tract.

The level of mineral exploration is considered to be high (for the Erdenet Southwest sub-tract in Mongolia) to moderate (for the Erdenet Northeast sub-tract in Russia) relative to other regions in Central Asia. In the Erdenet Northeast sub-tract, maps showing geologic research in the 1910s and 1930s (Tikhomirova, S.R., written commun., 2011) indicate that the part of the tract near the Russian-Mongolian border had undergone study by 1917 and that by 1938 most of the tract had some level of exploration, with the exception of the central-northeast region. The degree to which the area has been mapped at large scales (for example, 1:50,000 scale) is not known, but it appears that nearly all of the 1:200,000 geologic research and mapping in the tract region (carried out by the A.P. Karpinsky Russian Geological Research Institute (VSEGEI)) was done before 1979, with the exception of a few places in the south-central and western part of the tract, which was done between 1996 and 2004 (Tikhomirova, S.R., written commun., 2011).

The Erdenet Southwest sub-tract in Mongolia has been thoroughly mapped and investigated. Some of the central-south and central-north regions of the sub-tract, as well as few areas in the west, have been mapped at 1:50,000 scale. Mineral-exploration and mining-lease maps of Mongolia

(MRAM, 2003; Javkhlanbold, 2006) indicate that much of the region, with the possible exception of the west-central area, has undergone some level of targeted study. There are also several small protected areas throughout the western and central parts of the tract that may be underexplored.

For the Erdenet Southwest subtract (142pCu8508a), the team estimated a 90-percent chance for 2 or more undiscovered deposits, a 50-percent chance of 6 or more deposits, and a 10-percent chance of 20 or more deposits, for a mean of 9 expected undiscovered deposits (table 11*A*). For the Erdenet Northeast sub-tract (142pCu8508b), no estimates were made.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 34 Mt copper in the Erdenet Southwest sub-tract exceeds the identified copper resources at the Erdenet and Erdenet Southeast deposits (9.2 Mt copper). Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 11*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 33).

Assessment of Tracts in the Tethyside Region

The tectonically active Tethyside (Alpine-Himalayan) orogenic belt extends from southern Europe across parts of the Middle East through the Himalayas to the Pacific Ocean. The eastern Tethysides are bordered on the north by the Tarim and North China Cratons (fig. 2). Three permissive tracts are described within the eastern Tethysides in the study area (figs. 4, 7, and 8). As shown in figure 4, parts of these tracts in China are overlapped by younger (Mesozoic and Cenozoic) tracts that are assessed in a report on the Mesozoic of East Asia (Ludington, and others, 2012b) and a report that covers the Tibetan Plateau (Ludington and others, 2012a).

Early Paleozoic Through Indosinian in the Tethyside Region

Magmatic belts in East Asia generally young from the CAOB in the north to the Himalayas in the south. Whereas the tectonic development of the CAOB is related to Paleozoic through Indosinian subduction, collision, and terrane amalgamation associated with the evolution of the Paleo-Asian Ocean, the geodynamics of East Asia (from central China and southwards) are related to Cambrian through Triassic subduction and evolution of the Paleotethys and Neotethys Oceans and subsequent and ongoing collision as India subducts under the Tibetan Plateau (Pirajno, 2013). In central China, the east-west-trending Qinling-Dabie orogen records a series of collisions between the North China and South China Cratons and the southern Tarim Craton and Tibetan fold belt.

Qinling-Dabie Tract (142pCu8701)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: Paleozoic through Triassic island arcs and continental arcs in central China

Location

The Qinling-Dabie tract extends for about 4,200 km from eastern Hubei Province in China westward through central China along the border with Pakistan to the Tajikistan-Afghanistan border (fig. 34). The tract is long and narrow and corresponds approximately to the Kunlun and Qinling mountain ranges and includes the northern part of the Pamir Mountains (fig. 1).

Tectonic Setting

The tract outlines an assemblage of Paleozoic through Triassic igneous rocks in central China and westward that includes a Cambrian-Ordovician island arc, a Devonian continental arc related to north-directed subduction of the Paleotethys Ocean beneath the North China and Tarim Cratons (fig. 2), and Permian-Triassic rocks formed as a result of the collision of the North China and Tarim Cratons (Manchurides) with the Eurasian Continent (Altaids)

The Qinling-Dabie orogen lies between crustal blocks of northern and southern China, and consists of the complex suture(s) by which they are joined (Meng and Zhang, 2000). A Cambrian-Ordovician island arc was formed offshore of the southern margin of the northern blocks and then accreted in middle Paleozoic time (Meng and Zhang, 2000; Ratschbacher and others, 2003). This was overprinted by a Devonian Andean-style continental arc related to subduction on the northern margin of the Paleotethys Ocean (Lerch and others, 1995; Stampfli and Borel, 2002). The lower Paleozoic rocks were then overprinted by a Permian-Triassic continental arc during the closure of the Paleotethys Ocean (Ratschbacher and others, 2003) and final accretion of northern and southern blocks (Meng and Zhang, 2000). Some of these rocks are postconvergent and are probably related to Triassic slab breakoff (Sun and others, 2002). At the western end, the tract is made up of the North Kunlun and Northern Pamir Terranes (Robinson and others, 2004), northeast of the Karakorum lateral fault.

Geologic Criteria

Igneous rocks that define the tract are Paleozoic through Triassic in age and mostly I-type (Schwab and others, 2004). All of the dated porphyry copper deposits and prospects are Indosinian (Permian-Triassic) in age, but the intimate mixture of Caledonian, Variscan, and Indosinian permissive rocks throughout the tract dictates the inclusion

Table 11. Probabilistic assessment results for sub-tract 142pCu8508a, Erdenet Southwest—Mongolia.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
2	6	20	20	20	8.9	6.7	75	1	9.9	61,430	16

B. Results of Monte Carlo simulations of undiscovered resources.

[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	280,000	1,700,000	20,000,000	81,000,000	120,000,000	34,000,000	0.35	0.04
Mo	0	3,400	380,000	2,300,000	3,600,000	920,000	0.29	0.09
Au	0	14	480	2,100	2,900	850	0.35	0.08
Ag	0	0	4,300	27,000	42,000	11,000	0.27	0.13
Rock	62	410	4,200	17,000	23,000	6,800	0.37	0.04

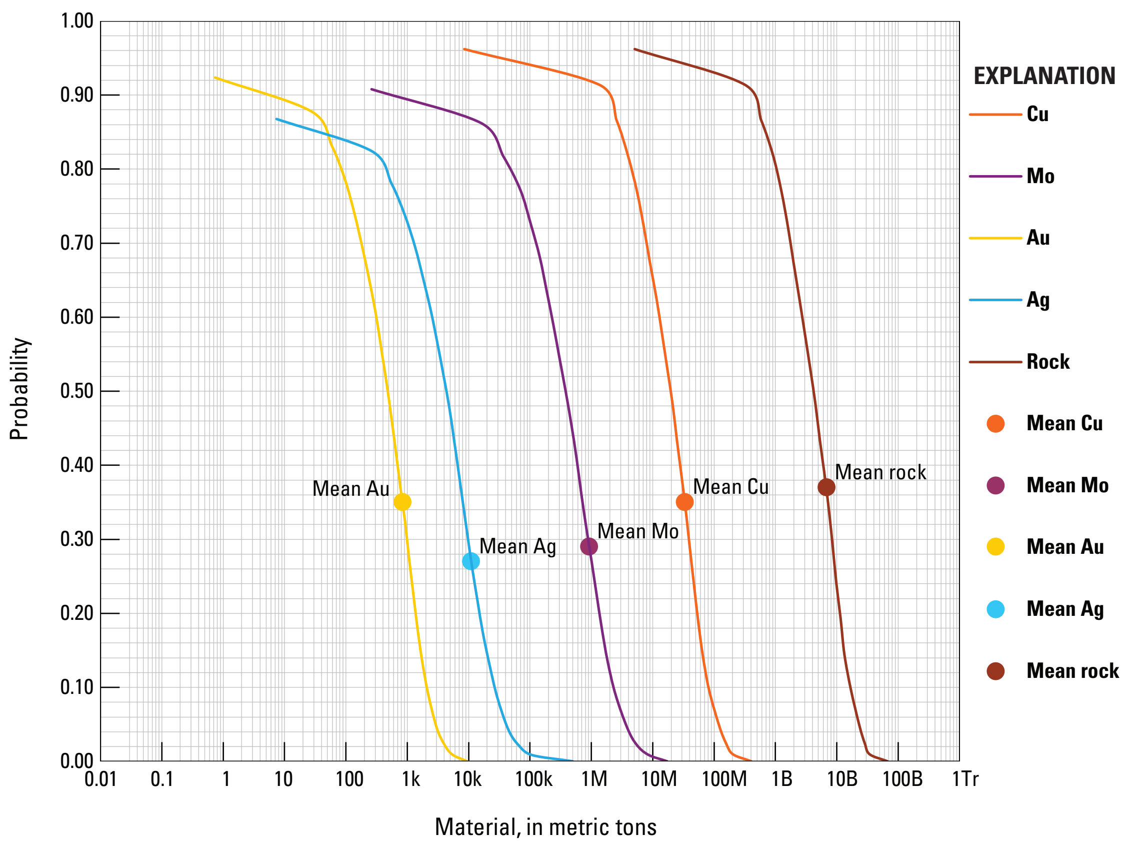
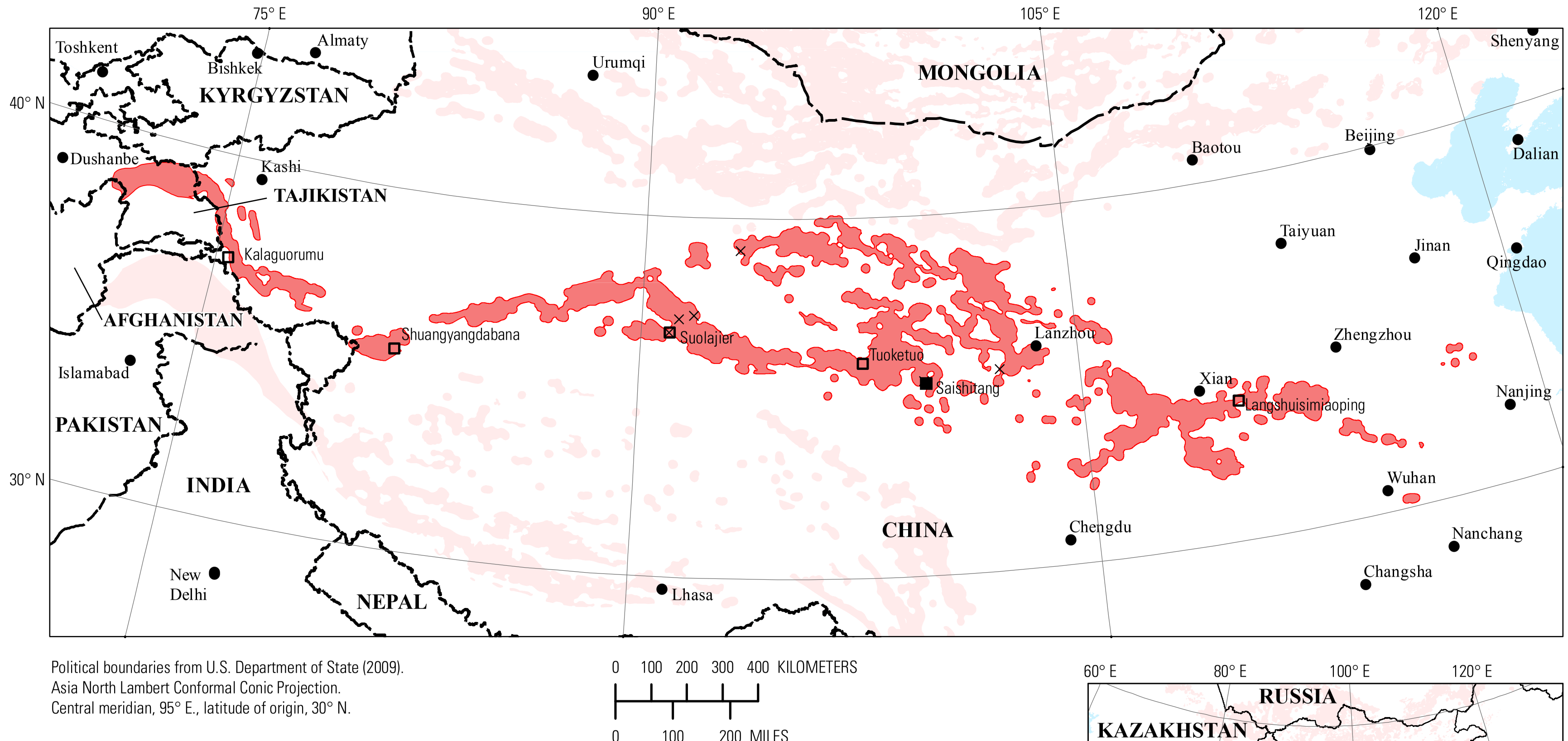
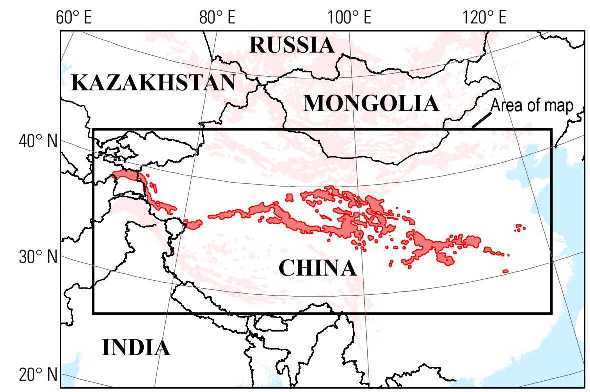


Figure 33. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8508a, Erdenet Southwest—Mongolia. k=thousands, M=millions, B=billions, Tr=trillions.



Political boundaries from U.S. Department of State (2009).
Asia North Lambert Conformal Conic Projection.
Central meridian, 95° E., latitude of origin, 30° N.



EXPLANATION

Porphyry copper

- **Assessed porphyry copper tract 142pCu8701**
- **Other porphyry copper tracts**
- ■ **Porphyry copper deposit**
- □ **Significant porphyry copper prospect**
- × **Other porphyry copper prospects (not labeled)**

Figure 34. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8701, Qinling-Dabie—China and Tajikistan.

of all of these rocks in the tract definition. The eastern and western parts of the tract contain principally intrusive rocks (fig. 35); monzonites are more common in the east, and syenites are more common in the west. Volcanic rocks are much more widespread in the central third of the area.

During the Mesozoic and Cenozoic, vertical tectonics resulted in the formation of a number of basins that are interspersed within the tract and help form its margins. Many of the igneous rocks that make up the tract have been subjected to regional metamorphism of varying grades. It seems likely that many of these arc rocks are exposed at paleodepths exceeding those at which porphyry copper deposits are likely to be found. However, it was not practical to delineate these areas at the scale of this assessment. Some of the known mineral deposits are Paleozoic volcanogenic massive-sulfide deposits, which implies that some of the arc volcanism was submarine and not highly prospective for porphyry copper deposits (Sillitoe, 1980).

The tract was defined using primarily calc-alkaline, intermediate-composition plutonic and volcanic map units of Paleozoic and early Mesozoic age (fig. 35). Plutonic units include monzonite and granodiorite through diorite. Volcanic units include primarily trachyte, andesite, and rhyolite closely associated with permissive intrusive units.

The Qinling-Dabie tract is bounded on the north by structures along the southern margins of the Tarim and North China Craton blocks and to the south by structures along the northern margins of the South China Craton block and the younger orogenic fold belts of the Tibetan Plateau. These structures mainly include various Caledonian and Variscan sutures and faults on the north side of the tract and Caledonian and Indosinian sutures and younger faults on the south side of the tract. The nature, location, orientation, extent, and component parts of these structural features, and the regions they enclose, varies tremendously from map to map and journal article figure to figure (particularly as depicted at regional scales). Because these bounding features are not well constrained, the tract boundaries were not truncated or clipped to any one dataset of tectonic contacts. The extent of the tract was primarily controlled and adjusted by the selection of appropriate map units and the distribution of mineral deposits.

Because of overly generalized map unit descriptions and the overall lack of attribution of texture or alteration, it was often impossible to unequivocally discriminate or subdivide permissive from nonpermissive units. The assessment team is aware that because of metamorphism, deep erosion, and submarine volcanism, many areas within this tract are probably not permissive for the occurrence of porphyry copper deposits.

Known Porphyry Deposits

There is only one porphyry copper deposit, Saishitang, known within the tract (fig. 34).

Saishitang

Saishitang, in eastern Qinghai Province, is listed as a porphyry copper deposit by Singer and others (2008). The deposit has recently gone into production, and the mine site is clearly visible on Google Earth imagery. Saishitang is referred to by several other authors, however, as a skarn deposit (Chen and others, 2007; Zhao and Lin, 1993). It is apparently Indosinian in age (226 Ma) (Wu and others, 2010), but no description of the deposit was found. It is large (greater than 100 Mt) but has copper and gold grades that are consonant with it being a skarn deposit. It is retained and considered as a deposit because of its size and active mining status.

Prospects, Mineral Occurrences, and Related Deposit Types

There are 11 identified prospects in the tract, five of which are considered significant (fig. 34, appendix B). The only prospect for which detailed information is available is the Huangnan project. Dunbar (2008) describes copper-gold porphyry-type and skarn mineralization in this area in easternmost Qinghai Province. The porphyry-style mineralization there appears to be related to the peripheral parts of a Triassic granodiorite pluton.

Liangshuisimiaoping is reported by Yan and others (2007) to be Paleozoic in age. It has a reported copper resource of 134,000 t at 1 percent copper, small and quite atypical for a porphyry deposit. The copper grade would indicate that this, too, is likely to be a skarn deposit.

Probabilistic Assessment

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used. Because Saishitang, the only known deposit in the tract, is primarily a skarn deposit, no reliable grade information was available to guide the choice of a grade and tonnage model. The high average-reported copper grade at Saishitang (1.13 percent copper) is much higher than the median copper grade of 0.44 percent copper in the general porphyry copper model and supports the interpretation of a skarn or a porphyry copper, skarn-related deposit. There is no other compelling geologic or metallogenic reason to suggest that either the porphyry Cu-Au or Cu-Mo grade and tonnage models would be more appropriate.

Estimates of Undiscovered Deposits and Rationale

The Qinling-Dabie tract contains one deposit, Saishitang, and at least 11 known significant prospects. The significant prospects are distributed across the entire east-west extent of the tract, and most have some basic exploration and metallogenic information. One significant prospect, Liangshuisimiaoping, has reported resources 134,000 t of copper, but this may be associated with skarn mineralization. Much of the tract, however, is characterized by volcanogenic massive-sulfide deposits.

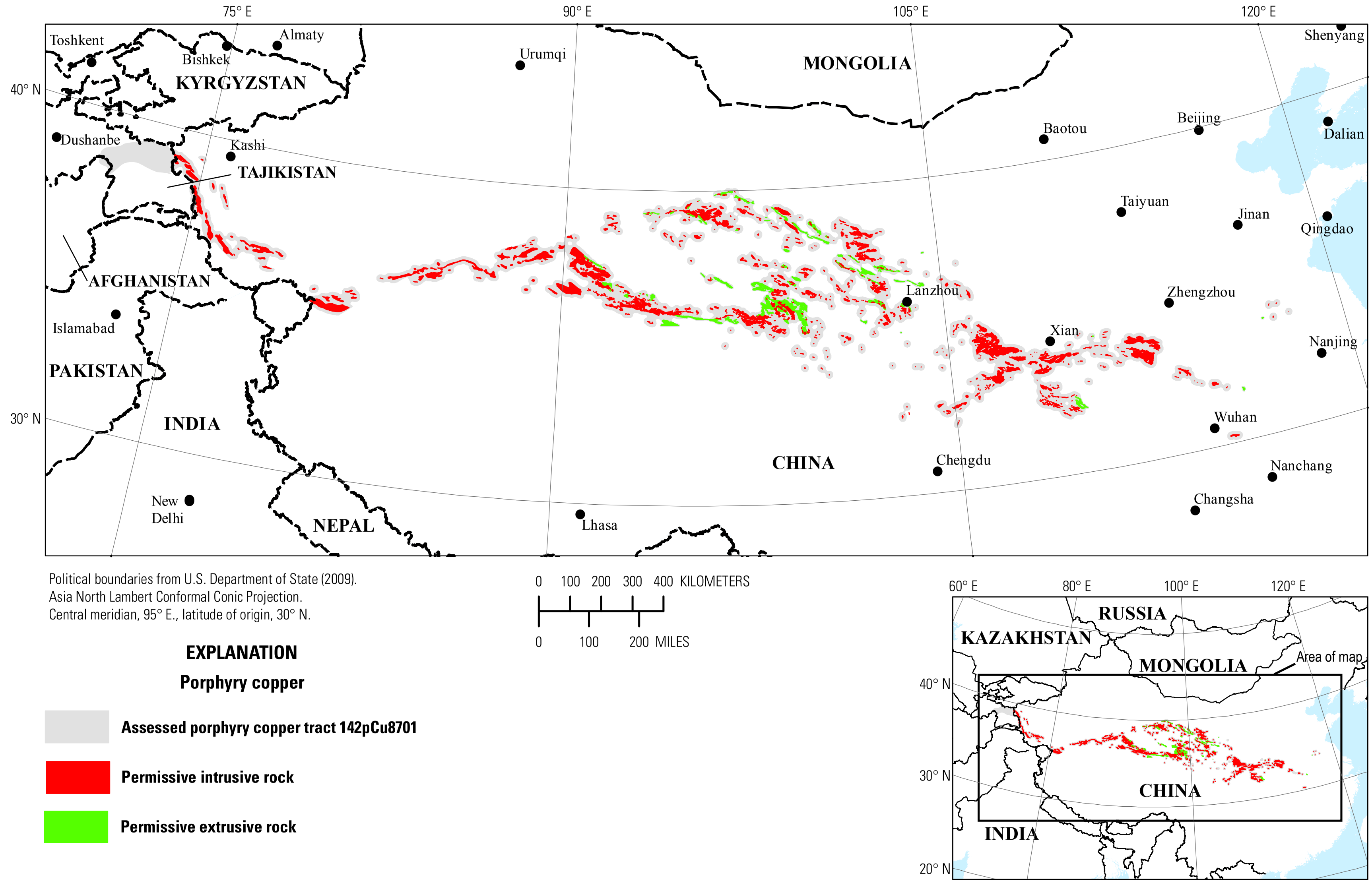


Figure 35. Map showing the distribution of permissive rocks used to delineate tract 142pCu8701, Qinling-Dabie—China and Tajikistan.

Most of the tract region, particularly in the west, is at high altitudes, in steep terrain, and extremely remote. This region has been the site of repeated magmatic activity for more than 300 million years, and deep structures have provided easy paths for ascent of magmas and fluids. At the local scale, the geology is likely less studied and understood and relatively underexplored for minerals.

Deposit-model based prospecting for porphyry copper deposits in China began only in the 1960s. Most of the tract has been evaluated for mineral resources at small map scales (1:10,000,000 or larger), and in the central and eastern half of the tract, mineral-resource surveys, exploration, and detailed investigations have been undertaken (see maps available at China Geological Survey, 2005). Physical examinations of the surface geology have been extensive, and it is probable that any outcropping deposits would have been found. Based on available information and the experience of the assessment team, the history and level of mineral exploration was considered to be moderate to high.

The team estimated a 50-percent chance of 3 or more deposits, a 10-percent chance of 20 or more deposits, and a 5-percent chance of 30 or more deposits, for a mean of 8 undiscovered deposits (table 12*A*). Uncertainty related to the level of erosion is reflected in the large uncertainty in the number of deposits estimated (C_v = 118 percent).

A previous assessment (Yan and others, 2007) covered part of the most favorable parts of this tract with five tracts (X-1, X-4, X-5, X-6, and X7) and estimated 6.7 mean undiscovered deposits, compared with the estimate of 8 made here (table 12*A*).

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources was 32 Mt of copper, about 20 times the copper resources reported for Saishitang. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 12*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 36).

Late Paleozoic, Mesozoic, and Early Cenozoic Tracts

The southernmost tracts included in the study area are the Jinsajiang and Tethyan Gangdese tracts, which represent the easternmost part of the Tethysides (fig. 8), the superorogenic collage that borders the Eurasian Continent on the south (Şengör and others, 1988). Permissive tracts for Tethyan porphyry copper deposits west of the Tethyan-Gangdese tract are described by Zürcher and others (in press). Permissive tracts for Yanshanian (mostly Jurassic and Cretaceous) and Cenozoic, porphyry copper deposits that formed after the amalgamation of the Asian Continent in postconvergent settings in East Asia are described in Ludington and others (2012b) and a report that covers the Tibetan Plateau (Ludington and others, 2012a).

Jinsajiang Tract (142pCu8702)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global porphyry copper model, Cu-Au subtype (Singer and others, 2008)
Geologic Feature Assessed: An assemblage of Carboniferous, Permian, and Triassic igneous rocks in southwestern China that formed both as island arcs and continental arcs during subduction of the Paleotethys Ocean below the South China Craton and Qiangtang Terrane

Location

The Jinsajiang tract is semifragmented and arcuate in shape, extending for about 2,100 km from the Xizang Autonomous Region in China (western Tibet) through Qinghai, Sichuan, and Yunnan Provinces (fig. 37). The eastern part of the tract is about 1,200 km long and as much as 500 km wide, whereas the western part is about 400 km long and 100 km wide. With the exception of southeastern part, the tract is located on the Tibetan Plateau.

Tectonic Setting

There is no real consensus about the tectonic history of this area. Plate-tectonic reconstructions (Stampfli, 2010; Stampfli and Borel, 2002) suggest that the following is a plausible scenario. The Paleotethys Ocean was established by the end of Devonian time. Subsequent subduction of that ocean beneath the South China Craton resulted in continental-arc rocks in Carboniferous and early Permian time. At the same time, the Qiangtang Terrane was drifting north across the Paleotethys Ocean, and south-directed subduction resulted in the emplacement of continental-arc rocks there. In the Late Triassic, the Yidun island arc developed in mid-ocean before being accreted to the Songpan-Ganzi fold belt and South China during the Indosinian orogeny, at the close of the Triassic (fig. 8).

Hou and others (2007) delineate a similar history, and name the arcs that constitute the tract as the Yidun, Jiangda-Weixi, Zugong-Jinghong (see their fig. 2). Porphyry copper deposits can be linked with certainty only to the Yidun (also called Zhongdian) Arc. Until these rock suites can be delineated spatially at an appropriate scale, it is not possible to further refine the tract area. As such, it was necessary to use all felsic and intermediate-composition rocks of Carboniferous through Triassic age to define the tract.

Geologic Criteria

The tract was defined using primarily calc-alkaline, intermediate-composition igneous map units Variscan through Indosinian age (fig. 38). Intrusive units are primarily Indosinian, with lesser amounts of Variscan, and include granite, quartz monzonite, granodiorite, diorite, quartz diorite, monzonite, and syenite. The isolated area in the western part of the tract contains only diorite intrusions, and very little is known about these rocks. Extrusive units are primarily andesite.

Table 12. Probabilistic assessment results for tract 142pCu8701, Qinling-Dabie—China and Tajikistan.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
0	3	20	30	30	8.0	9.4	118	1	9	403,220	2

B. Results of Monte Carlo simulations of undiscovered resources.

[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	11,000,000	91,000,000	130,000,000	32,000,000	0.32	0.17
Mo	0	0	170,000	2,400,000	3,700,000	850,000	0.28	0.27
Au	0	0	230	2,200	3,100	800	0.31	0.25
Ag	0	0	1,800	28,000	44,000	10,000	0.27	0.32
Rock	0	0	2,100	19,000	26,000	6,400	0.33	0.17

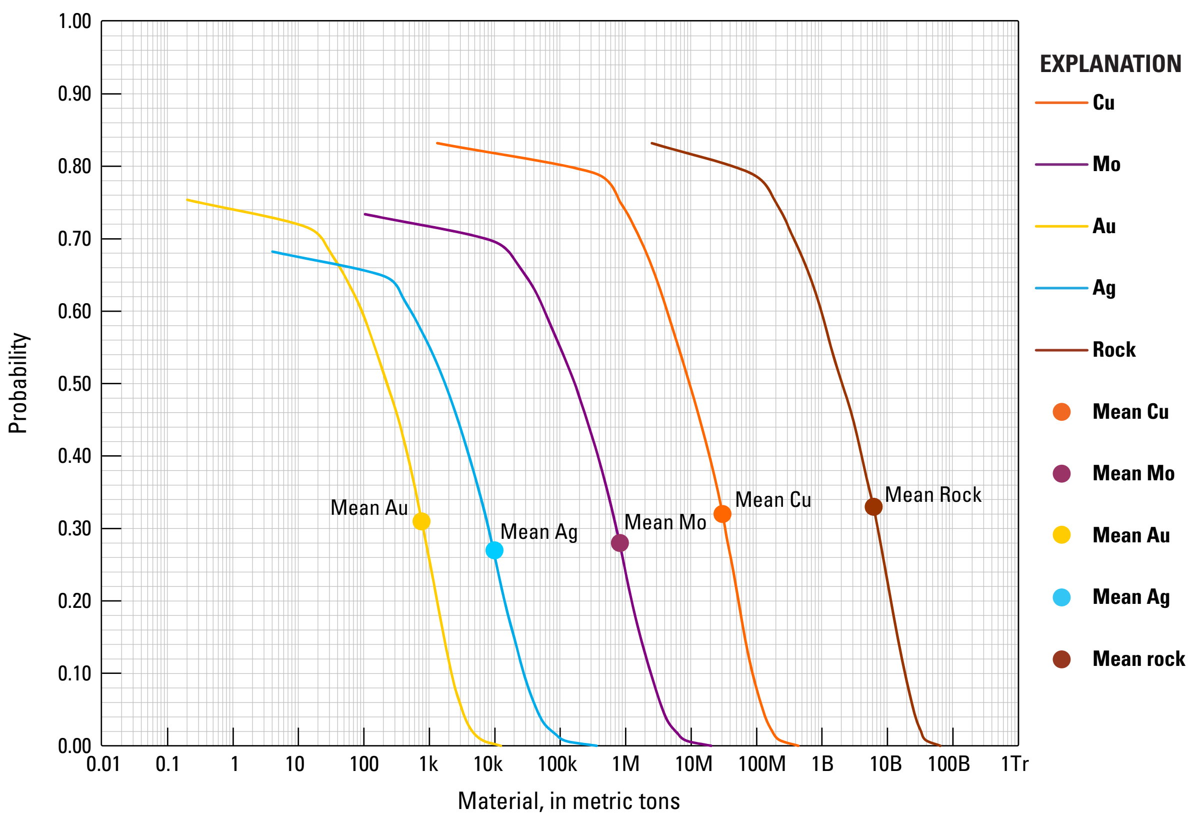


Figure 36. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8701, Qinling-Dabie—China and Tajikistan. k=thousands, M=millions, B=billions, Tr=trillions.

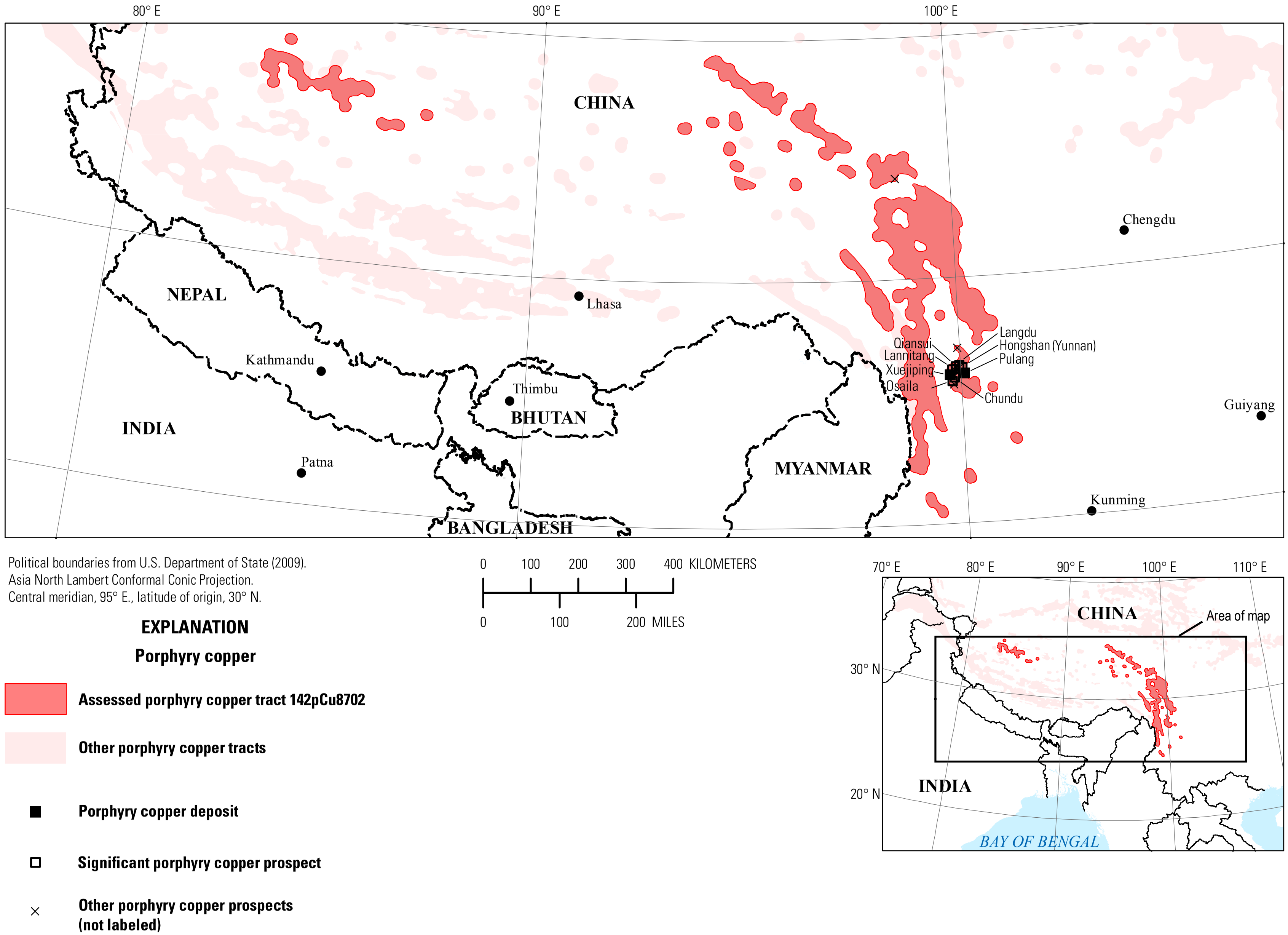


Figure 37. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8702, Jinsajiang—China.

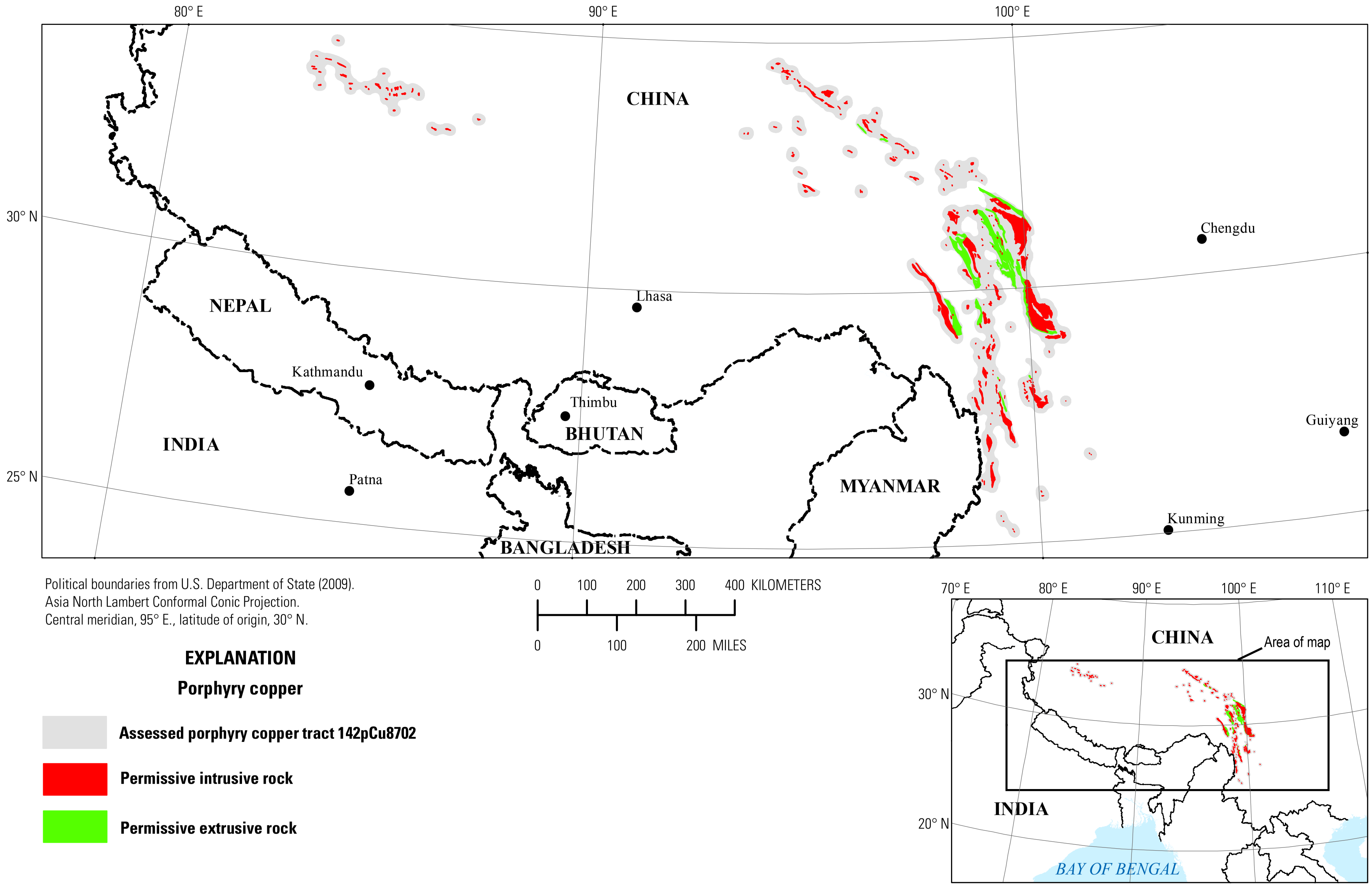


Figure 38. Map showing the distribution of permissive rocks used to delineate tract 142pCu8702, Jinsajiang—China.

The eastern part of the Jinsajiang tract is bounded on the west and southwest by Variscan and early Mesozoic sutures separating major orogenic belts and terranes of the Tibetan Plateau, to the northeast by early Mesozoic sutures, and to the southeast by early Mesozoic sutures and structures along the western margin of the South China Craton block. The isolated western part of the tract has no clear bounding structures but is generally flanked to the north by a major Caledonian suture and to the south by early Mesozoic intraterrane structures. Areas where Tertiary basins were judged to be deeper than 1 km and areas intruded by post-Triassic intrusions were excluded.

The Songpan-Ganzi fold belt includes closely spaced Late Triassic granitoid rocks that include ~224-Ma adakite-like I-type plutons, ~215-Ma shoshonitic and high Ba-Sr granites, and ~205-Ma monzonites (Yuan and others, 2010). Rapid crustal uplift associated with formation of the monzonites and the lack of coeval volcanic rocks mapped in this area indicate levels of exposure below those at which porphyry copper deposits might occur, so the plutons in this area were excluded as nonpermissive.

The southern extension of the arc assemblage was included in the Sukhothai tract in a report on Southeast Asia (Hammarstrom and others, 2013). The Sukhothai tract delineates a similar assemblage of Carboniferous through Triassic rocks that were formed as both island arcs and continental arcs by subduction of oceanic crust of the Paleotethys Ocean below the South China Craton block in Yunnan and below Indochina (the Loei and Truongson volcanic arcs).

Known Porphyry Deposits

There are two porphyry copper deposits in the Jinsajiang tract, Xuejiping and Pulang (fig. 37, table 2). Both deposits are in the Yidun (or Zhongdian) island arc.

Pulang

The Pulang porphyry copper deposit (Li and others, 2011b; Singer and others, 2008) has been discovered and partially explored only in the 21st century, although small copper showings had been known in the area for a long time (Li, 2006). The rocks at Pulang are quite mafic and indicative of an island-arc environment. The deposit is inferred to be similar to the diorite-type porphyry copper model of Arshamov and Andrakhmanov (2008) and perhaps to gold-rich porphyry deposits in British Columbia that are related to mafic alkaline rocks (Anonymous, 2010; see Mihalasky and others, 2011, for a discussion on alkaline rock-related porphyry copper deposits). K-Ar ages of hydrothermal alteration minerals at Pulang range from 235 to 182 Ma, but a Re-Os date on molybdenite is about 213 Ma, fixing the mineralization date as Late Triassic or Indosinian (Zheng and others, 2004). A subsequent Re-Os date by Li and others (2011b) is also 213 Ma (they also determined several ^{40}Ar-^{39}Ar ages on secondary biotite from Pulang of about 215 to 210 Ma). Rb-Sr isochron ages of nearby rocks range from about 240 to 220 Ma (Liu and others, 1993). Another recent summary of the ages from this area was given as 220 to 209 Ma by Cao and others (2010).

Singer and others (2008) reported a small resource of about 300,000 t of copper for Pulang, but recent development appears to have increased its size markedly. A newer resource number is given by Chen and others (2008) of 160,000,000 t at 0.57 percent copper, 0.004 percent molybdenum, and 0.18 g/t gold for a contained copper resource of 912,000 t. Wang (2008) and Wang and others (2009a), using GIS three-dimensional techniques, have estimated that the resource is about 3.35 Mt of copper and suggest that it may be as much as 6 Mt. Li and others (2011b) report the results of new drilling that permit a resource delineation of 1,229 Mt at a copper grade of 0.34 percent and a gold grade of 0.18 g/t, yielding a contained copper resource of about 4.18 Mt.

Xuejiping

Xuejiping is west of Pulang, in the western Zhongdian, or inner belt (Li and others, 2011b; Leng and others, 2007). Hou and others (2007) call it a “large” deposit. Rui and others (2005) give an age of 225 Ma for Xuejiping, similar to Pulang. Xuejiping has a reported resource of about 300,000 t of copper (Hou and others, 2007), who described the deposit as six ore bodies of veinlets and disseminated chalcopyrite, pyrite, and magnetite in dioritic and monzonitic porphyry in the Sanjiang igneous district. They also quoted a grade of 0.60 percent copper. Other sources reported 60 Mt of ore at 0.5 percent copper and 1.4 g/t silver (Kirkham and Dunne, 2000). In 2003, production was reported to be 200 t/day from 30- to 80-m-thick ore zones with grades of 0.63 percent copper and 0.06 g/t gold (China Gold International, 2003). Li and others (2011b) give a resource, based on more recent development work, of 240 Mt at a copper grade of 0.5 percent, indicating a copper content of 1.2 Mt (table 2).

Cao and others (2006) mention that Pulang, Hongshan, and Xuejiping are the main porphyry copper deposits in Zhongdian county, confirming that Xuejiping and Pulang are discrete deposits. They also mention two new prospects without giving locations (Pushang and Disuga). Leng and others (2007) make clear that Xuejiping (medium-scale) and Pulang (super-large) are distinct deposits, with similar geochemical signatures (light-REE enriched, heavy-REE depleted, large-ion lithophile element enriched, high field strength element depleted), interpreted to be due to partial melting of the Ganzi-Litang oceanic slab, which may have been contaminated with some crustal material.

Prospects, Mineral Occurrences, and Related Deposit Types

Eleven prospects, including two prospects primarily defined as skarns, are present within the tract. Ten of them are in the Yidun Arc near Pulang and Xuejiping, and one is much farther north (fig. 37, appendix B).

Langdu, Qiansui, Songnuo, Chundu, Hongshan, and Zhujiding are in the eastern Yidun porphyry belt. Langdu (about 0.5 Mt), Qiansui (about 0.5 Mt), Chundu (about 0.8 Mt), and Hongshan (about 1 Mt) have inferred copper resources (Li and others, 2011b). Yaza (about 0.2 Mt) is also noted by Li and others (2011b), but it is unclear whether it is properly classified as a porphyry copper or a Pb-Zn-Ag polymetallic vein occurrence (Yaza is not included in the database accompanying this report). Songnuo is hosted in a small quartz monzonite porphyry stock, and Leng and others (2008) dated zircons from the pluton by SHRIMP U-Pb methods at about 221 Ma. Li and others (2011b) give a date of 217 Ma for Langdu. Little information (in the English language literature) is available for Zhujiding. It is associated with a fine-grained alkaline granite dike swarm, and based on a single sample, has an average copper grade of 0.56 percent (Fei and others, 2010).

Gaochiping, Lannitang, Osaila, and A're are porphyry copper prospects in the western Yidun porphyry belt. Lannitang (about 1 Mt) and Osaila (about 0.5 Mt) have inferred copper resources (Li and others, 2011b).

Hongshan and Gaochiping are listed by Hou and others (2007) as porphyry-related copper skarn deposits, but little detailed information is given. Hongshan was also referred to as an active mine ("skarn-porphyry") in a news release in 2003 (China Gold International, 2003).

Bishop (2008) described two strongly altered areas identified by Hyperion hyperspectral data in the region. One of them appears to correspond to the Pulang deposit, but the other is about 20 km to the north and about 15 km east of the Hongshan prospect, which is otherwise unidentified but can be clearly confirmed on satellite imagery. There are apparently many more similar prospects in the area, as Zuo and others (2009) provide a figure indicating the approximate location of "22 porphyry copper deposits" in the area, but they are not identified and the figure has no coordinates. Leng and others (2008) state that, "there are lots of skarn and porphyry copper deposits associated with the Indosinian porphyry bodies in the Zhongdian arc . . ."

Changdagao, about 500 km north and west of the deposits and prospects around Pulang, is mentioned only by Yan and others (2007), who refer to it as Eocene and related to the Yulong group of deposits but tabulate its age as Cretaceous. Changdagao is not in the Yulong group; it is about 100 km northeast of that belt. However, Hou and others (1991) indicated that they believed it to be Triassic in age. Because it falls geographically in the Jinsajiang tract, it is noted here.

Probabilistic Assessment

Grade and Tonnage Model Selection

The Cu-Au porphyry copper grade and tonnage model of Singer and others (2008) was used. Pulang, the largest known deposit in the tract, is a porphyry Cu-Au deposit (table 1). The reported gold grade for Xuejiping is 1.4 g/t, but no molybdenum is reported. Although the results of a Student's *t*-test rejected the porphyry Cu-Au model, the porphyry Cu-Au grade and tonnage model of Singer and others (2008) was chosen for the following reasons: (1) the gold grade reported for Xuejiping may not be representative of the average grade for the whole deposit; (2) the Yidun Arc that makes up much of the tract is an island arc, with mostly mafic rocks, and island arcs tend to produce gold-rich porphyry deposits; and (3) the 250 Ma Phu Kham deposit in the Sukhothai tract in Laos is a gold-rich porphyry. In addition, statistical tests of Phu Kham and Pulang, excluding Xuejiping, are compatible with the Cu-Au grade and tonnage model, and the Sukhothai tract (142pCu7021) was assessed using the Cu-Au model (Hammarstrom and others, 2013). To be consistent, it was decided that the Cu-Au porphyry copper grade and tonnage model would be used for the Jinsajiang tract as well.

Estimates of Undiscovered Deposits and Rationale

The Jinsajiang tract includes two porphyry copper deposits and at least 11 known significant prospects (fig. 37, appendix B). All of the significant prospects, except for the Changdagou, are clustered around the two deposits in the southern part of the tract, and seven of the prospects contain partially delineated resources ranging from 0.5 to 1 Mt of copper.

The deposits and prospects are all associated with the Yidun Arc in the Zhongdian region, which has been recognized by Leng and others (2008) as an important copper-producing area. Extensive hydrothermal alteration is present in the Yidun Arc, and the relative proportions of extrusive and intrusive rock mapped suggests that much of the area appears to be exposed at an appropriate erosion level to preserve porphyry deposits.

With the exception of the western and southernmost parts, the tract has been evaluated for mineral resources at small map scales (1:10,000,000 or larger; see maps available at China Geological Survey, 2005). In the eastern part of the tract, and particularly the southeastern area, mineral-resource surveys, exploration, and detailed investigations have been undertaken (see maps available at China Geological Survey, 2005) but not as extensively as in regions to the north of the Jinsajiang tract. The history and level of mineral exploration is considered to be moderate to low and limited.

The team estimated a 90-percent chance for 2 or more undiscovered deposits in the tract, a 50-percent chance of 4 or more deposits, and a 10-percent chance of 14 or more deposits, for a mean of 6 expected undiscovered deposits (table 13*A*). A previous assessment (Yan and others, 2007) covered a small part of this tract (tract XI-4b) and estimated 4.2 mean undiscovered deposits.

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources of 20 Mt copper far exceeds the identified copper resources (~4.5 Mt copper). Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 13*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 39).

Table 13. Probabilistic assessment results for tract 142pCu8702, Jinsajiang—China.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
2	4	14	14	14	6.3	4.6	73	2	8.3	111,690	7

B. Results of Monte Carlo simulations of undiscovered resources using the Cu-Au subtype model.

[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	300,000	1,000,000	10,000,000	52,000,000	72,000,000	20,000,000	0.33	0.04
Mo	0	0	30,000	360,000	560,000	110,000	0.26	0.21
Au	33	100	850	3,500	4,600	1,400	0.36	0.04
Ag	0	0	2,000	18,000	35,000	6,700	0.24	0.15
Rock	74	240	2,200	10,000	13,000	4,000	0.34	0.04

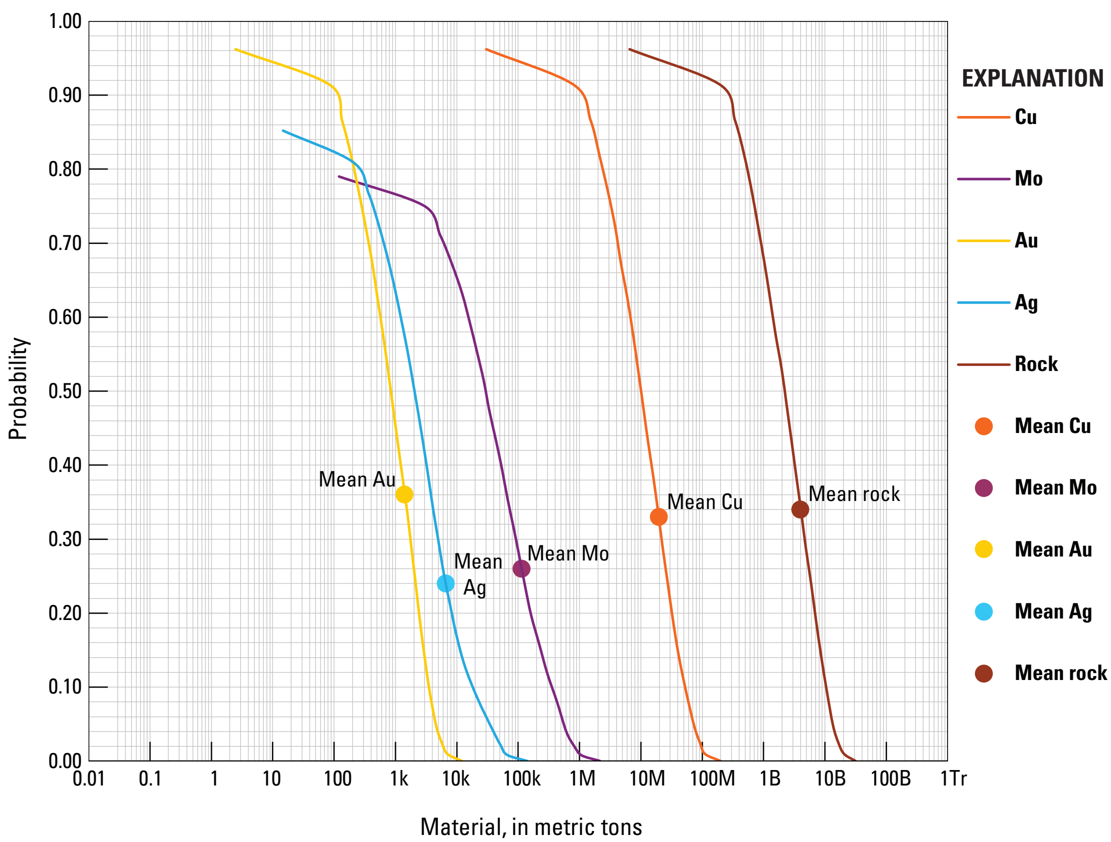


Figure 39. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8702, Jinsajiang—China. k=thousands, M=millions, B=billions, Tr=trillions.

Tethyan-Gangdese Tract (142pCu8706)

Descriptive model: Porphyry copper (Cox, 1986a; Berger and others, 2008; John and others, 2010)
Grade and tonnage model: Global Cu-Au-Mo porphyry copper model (Singer and others, 2008)
Geologic Feature Assessed: Late Triassic, Yanshanian (Jurassic and Cretaceous), and early Tertiary igneous rocks in southwestern China that were formed during subduction of the Tethys Ocean below the southern margin of Asia

Location

The Tethyan-Gangdese tract extends for about 3,000 km, from northern Yunnan Province through western Sichuan, southwestern Qinghai, most of Xizang (Tibet), and into northern India and Pakistan (fig. 40). At the widest part, it is nearly 700 km from north to south. The tract is entirely within the Himalayas and the Tibetan Plateau, and most of it is at altitudes exceeding 4,000 m.

Tectonic Setting

Arc magmatism was continuous in the Tethyan–Gangdese area from the Late Triassic until the final closure of Neotethys Ocean in the early Tertiary. Magmatism apparently first migrated north (many of the plutons in the northern part of the tract are Jurassic), then retreated back south due to steepening of the subducting slab, culminating in emplacement of the large composite Gangdese batholith in the Late Cretaceous and early Tertiary in the southern part of the tract (Ji and others, 2009). The very youngest of these rocks, whose ages may extend to as young as 40 Ma (Wen and others, 2008), can probably be considered collision related and probably resulted from a composite process of subduction, slab roll back, and subsequent break off (Ji and others, 2009). Some of the rocks along the Bangong-Nujiang Suture, between the Qiangtang and Lhasa Terranes (fig. 8), may have formed as a result of south-directed subduction of the Paleotethys Ocean below the Lhasa Terrane, just before its accretion to Qiangtang in Late Cretaceous time (Qiu and others, 2004; Li and others, 2011a). Isotopic (Sr, Sm-Nd and Hf) data from Mesozoic rocks of the Gangdese batholith (Ji and others, 2009; Chu and others, 2009) show little or no evidence of incorporation of old crustal material.

West of China, a similar history is preserved in the high Himalaya of northern India and Pakistan. The Kohistan-Ladakh island-arc terrane formed during Early Cretaceous to Eocene time as a mid-Tethyan ocean subduction zone (Petterson, 2010; Ravikant and others, 2009; Schaltegger and others, 2002). These rocks are thus analogous to the Early Cretaceous rocks along the Bangong-Nujiang Suture. This arc and areas further inboard (north) were also overprinted by calc-alkaline continental margin granitoids (analogous to the Gangdese batholith) immediately preceding the final collision of India with Asia. Magmatism in the two areas (Kohistan-Ladakh island arcs in India and Pakistan and Gangdese batholith in China) is known collectively as the Trans-Himalayan magmatism (Wen and others, 2008).

Geologic Criteria

The intrusive and extrusive rocks that define this tract are now accepted by most to be related to subduction of the Tethyan Ocean below the Qiangtang and Lhasa Terranes during their accretion to Asia. The tract was defined using primarily calc-alkaline, intermediate-composition igneous map units with Yanshanian to early Tertiary ages but is mainly Cretaceous (fig. 41). Plutonic units include granite, monzonite, granodiorite, quartz diorite, and diorite. According to Wen and others (2008), the majority of the rocks are of intermediate composition, and the most typical is a biotite-hornblende diorite or granodiorite. Extrusive units include primarily andesite, with a few other felsic compositions closely associated with permissive intrusive units.

The Tethyan Gangdese tract is bounded on the south by the Himalayan India-Asia (Indus-Tsangpo) Suture (fig. 8) and along its northern boundary by early Mesozoic and older sutures separating major orogenic belts and terranes of the Tibetan Plateau. At least two other major east-west-trending, early and late Mesozoic sutures extend through the interior of the tract. The extent of the tract was primarily controlled and adjusted by the selection of appropriate map units and the distribution of mineral deposits.

The part of the tract that is in India and Pakistan is highly schematic. It is based primarily on the geologic map of Qureshi and others (1993), augmented by the schematic maps of Ravikant and others (2009), Schaltegger and others (2002), and Hildebrand and others (2001). This part of the tract likely includes large nonpermissive areas due to metamorphism, deep erosion, and the presence of some collision-related peraluminous granites (Petterson, 2010).

Known Porphyry Deposits

Xietongmen/Newtongmen

The Xietongmen/Newtongmen deposit, with a U-Pb age of 176–171 Ma and a Re-Os age on molybdenite of 174 Ma (Tafti and others, 2009, 2014), belongs to this tract. However, at the time of completion of the assessment of the Tibetan Plateau, this deposit was believed to be Cenozoic in age, and was assessed in that study (Ludington and others, 2012a), where a description of the deposit can be found. Thus the Tethyan Gangdese tract was assessed as if there were no fully delineated porphyry copper deposits in the tract, although the Duolong prospect area is reported to contain a preliminary inferred resource of more than 5 Mt of copper.

Prospects, Mineral Occurrences, and Related Deposit Types

There are only four documented porphyry copper prospects within the tract, Garqiong, Duolong, Ri'a, and Shesuo, all discovered since 2000. They are all Cretaceous in age and are near the Bangong-Nujiang Suture (fig. 8). However, one of them (Duolong) is an important discovery and may contain as much as 5 Mt of copper.

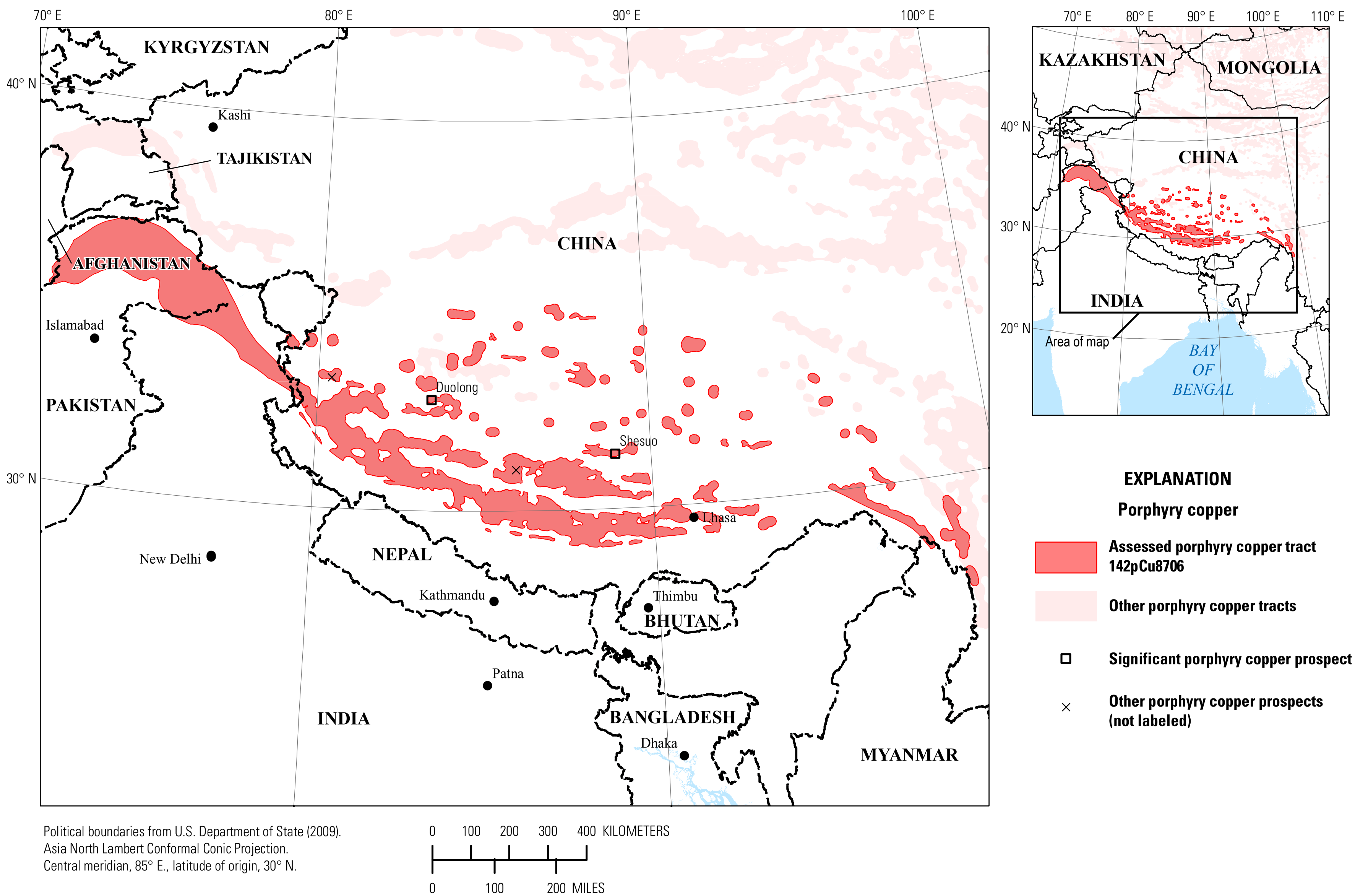


Figure 40. Map showing the location, known deposits, significant prospects, and prospects for permissive tract 142pCu8706, Tethyan-Gangdese—China, India, and Pakistan.

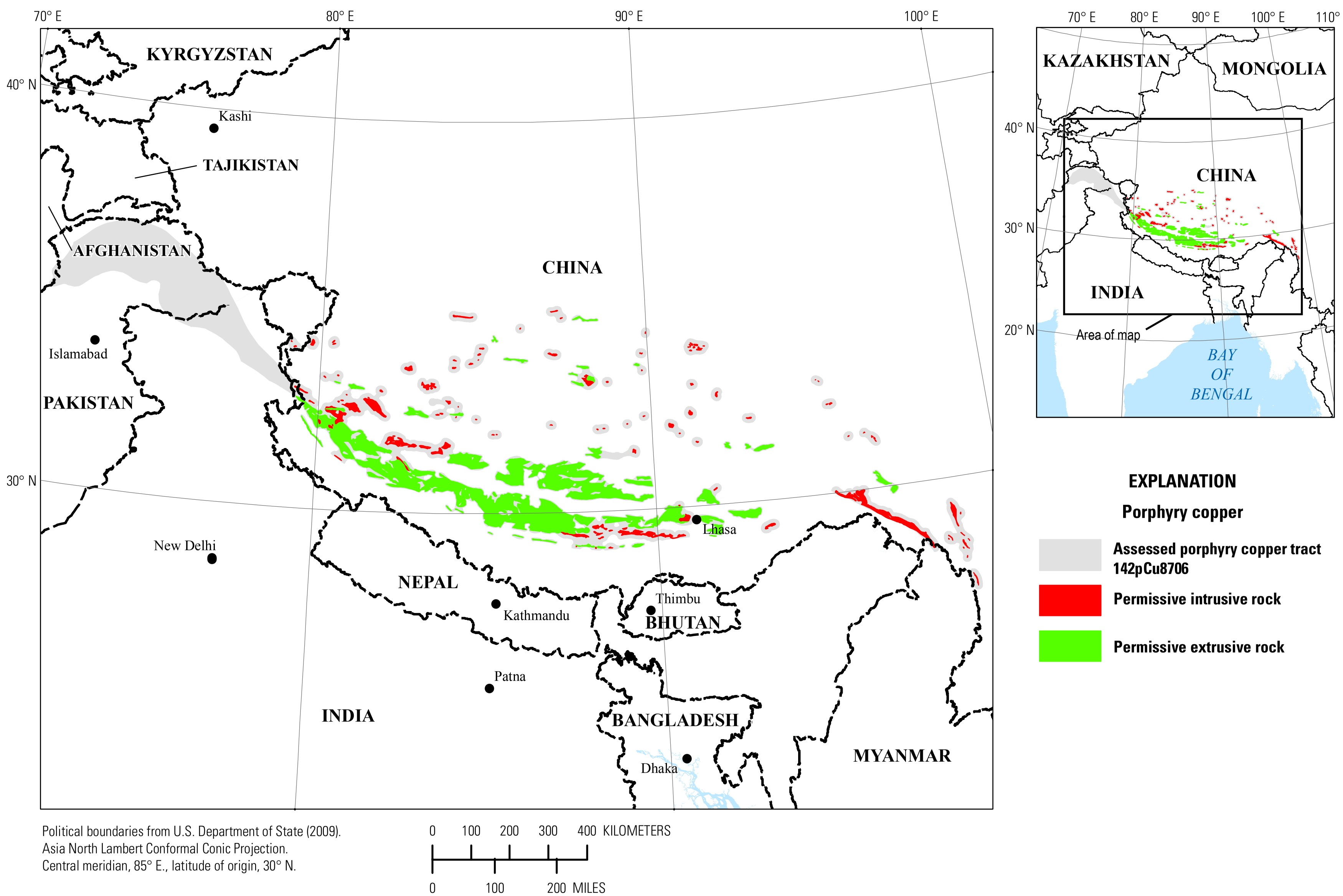


Figure 41. Map showing the distribution of permissive rocks used to delineate tract 142pCu8706, Tethyan-Gangdese—China, India, and Pakistan.

Duolong (Li and others, 2011a; Xin and Qu, 2006; She and others, 2006) is located in western Tibet, about 800 km west of Lhasa. The ore-bearing rocks are described as being calc-alkaline quartz diorite and granodiorite, with samarium-neodymium (Sm-Nd) isotopic characteristics that suggest origin in an island arc. The age of the volcanic host rocks and barren and mineralized porphyries ranges from about 122 to 106 Ma (Li and others, 2008a; Li and others, 2011a). On the other hand, Qu and Xin (2006), who suggest an age of about 128 Ma, characterize the rocks as shoshonitic high-potassium calc-alkaline and suggest a postconvergent origin on the basis of trace-element characteristics. The age of mineralization was determined to be about 118 Ma (Re-Os age on molybdenite; She and others, 2006), whereas ^{40}Ar-^{39}Ar dates on alteration minerals are about 115 Ma (Li and others, 2011a). The altered rocks at Duolong can be clearly seen on Google Earth imagery.

Tse (2008) cited a resource of 2 Mt of copper for Duolong as reported in a 2005 bulletin of the China Ministry of Land and Resources. Another resource estimate of about 15 Mt of copper was reported by Rui and others (2005), but the basis for this estimate was not given. If this speculative resource is accurate, this would make Duolong one of the larger deposits in the world. The most recent grade and tonnage information are those in Li and others (2011a) (see appendix B), which indicates a tonnage of nearly 750 Mt, a copper grade of 0.72 percent, and a gold grade of 0.23 g/t. Because the Duolong deposit is not fully characterized, it is considered to be a prospect, albeit one that will certainly become a deposit once drilling is concluded.

Probabilistic Assessment

Grade and Tonnage Model Selection

Because there are no known porphyry copper deposits in the tract, the general porphyry copper grade and tonnage model of Singer and others (2008) was used. There is no compelling geologic or metallogenic reason to suggest that either the porphyry Cu-Au or Cu-Mo grade and tonnage models would be more appropriate.

Estimates of Undiscovered Deposits and Rationale

There are no known deposits and four known porphyry copper prospects, and very little is known of the exploration history. The tract is large (~290,000 km^2), remote, and difficult to access, and it seems likely that is relatively underexplored, as there was little expectation that there might be deposits here until the last decade. Based on the relative proportions of extrusive and intrusive rock mapped (fig. 41), as well as the widespread mineral occurrences, much of the area appears to be exposed at an appropriate erosion level to preserve porphyry deposits.

Based in part on the limited exploration history and the large size of the tract, the team estimated that there is an 50-percent chance of four or more undiscovered deposits. The assessment team also was influenced by the evidence of Ji and others (2009), who argue from trace and isotopic geochemistry that the entire Gangdese batholith represents an Andean-type arc. The Duolong prospect will almost certainly soon advance to deposit status, thus an estimate of one or more undiscovered deposits was made at the 90th percentile confidence level. The discovery of these prospects where porphyry copper deposits were not previously suspected suggests that more porphyry systems will be found here, so a 10-percent chance of 18 or more deposits was estimated in this tract (table 14*A*).

A previous assessment (Yan and others, 2007) covered a small part of the tract, primarily the part that represents the Jurassic and Early Cretaceous arc along the Bangong-Nujiang Suture that separates the Qiangtang and Lhasa Terranes (Tract XI-1). They estimated 3.5 mean undiscovered deposits, compared with the present team's estimate of 7 (table 14*A*). Tracts XI-2 and XI-3 of Yan and others (2007) correspond to much of the southern part of the Tethyan Gangdese tract, and their definition of the tract includes Jurassic and Cretaceous rocks, but their deposit estimates, which totaled 13.2 mean undiscovered deposits, were focused almost entirely on the highly productive Miocene Gangdese belt, which was assessed by Ludington and others (2012a).

Probabilistic Assessment Simulation Results

The mean estimate of undiscovered resources for the tract is 28 Mt copper. Estimated amounts of copper, molybdenum, gold, silver, and the total volume of mineralized rock are reported in table 14*B*. Results of the Monte Carlo simulation are also presented as cumulative frequency plots (fig. 42).

Summary of Probabilistic Assessment Results

Simulation results are summarized in table 15. The quantile estimates (for example the median, which represent the 50-percent quantile) are linked to each tract simulation and, therefore, should not be added. However, mean estimates can be added to obtain total amounts of metal and mineralized rock that can be compared between tracts.

The assessment indicates that 97 undiscovered deposits could be present in 11 of the permissive tracts (which were quantitatively assessed) that host 20 known porphyry copper deposits (table 2). Mean estimates of numbers of undiscovered deposits within a tract (table 15) range from about 2 to 21, with coefficients of variation ranging from a low of 73 (relatively certain) to a high of 118 (relatively uncertain). Most of the undiscovered deposits (21) are associated with the large Oyu Tolgoi tract (142pCu8506), which contains the supergiant porphyry copper deposit Oyu Tolgoi.

Table 14. Probabilistic assessment results for tract 142pCu8706, Tethyan-Gangdese—China, India, and Pakistan.

A. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density.

[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; 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}/100,000 km²)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	4	18	18	18	7.2	6.3	88	0	7.2	289,650	2

B. Results of Monte Carlo simulations of undiscovered resources.

[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	320,000	13,000,000	73,000,000	110,000,000	28,000,000	0.33	0.07
Mo	0	0	260,000	2,000,000	3,200,000	770,000	0.28	0.16
Au	0	0	310	1,900	2,700	710	0.32	0.14
Ag	0	0	2,700	22,000	38,000	8,800	0.27	0.22
Rock	0	73	2,900	15,000	22,000	5,700	0.35	0.07

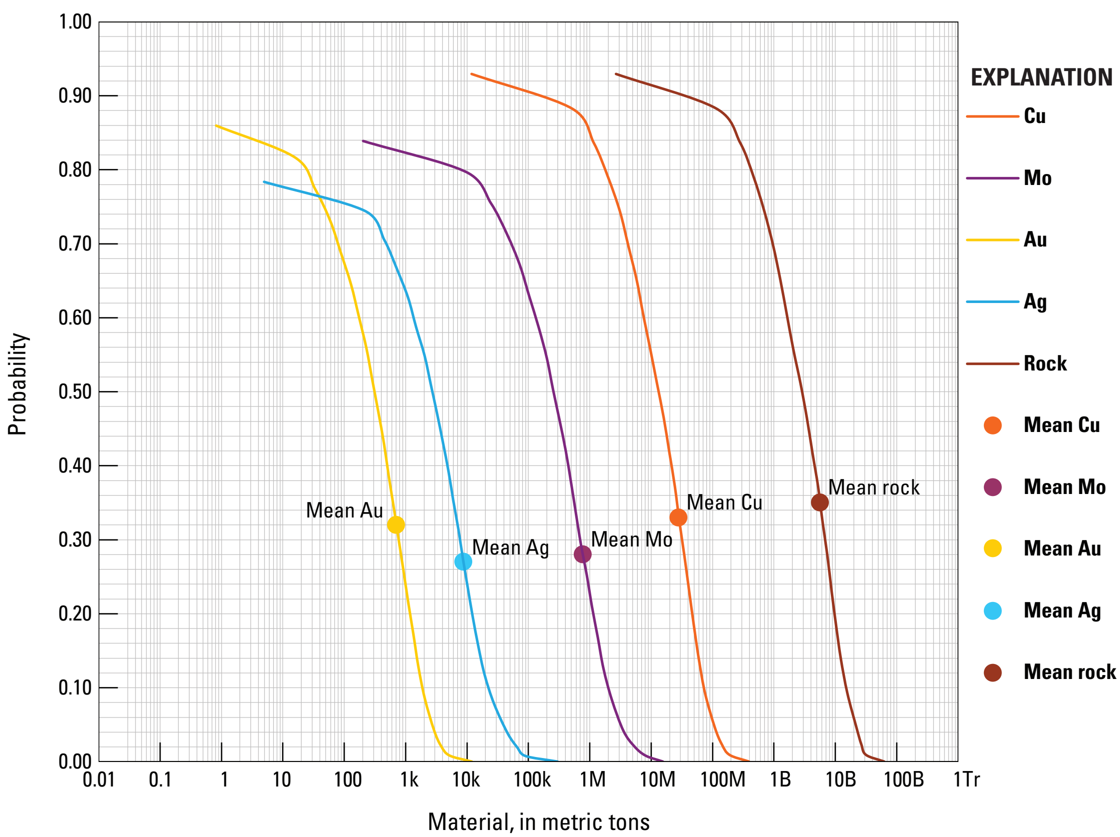


Figure 42. Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in porphyry copper deposits in tract 142pCu8706, Tethyan-Gangdese—China, India, and Pakistan. k=thousands, M=millions, B=billions, Tr=trillions.

Table 15. Summary estimates of numbers of undiscovered porphyry copper deposits for the Central Asian Orogenic Belt and eastern Tethysides.

[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; 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]

Tract	Tract Name	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100,000 km^2)
		N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
142pCu8501	Solonker	1	2	15	15	15	5.5	5.383	97	1	6.5	250,100	3
142pCu8502	Kazakh-Tian-shan	1	2	8	8	8	3.4	2.7	80	3	6.4	89,610	7
142pCu8503	Gobi-Amur	0	1	3	6	6	1.5	1.8	115	1	2.5	56,090	4
142pCu8504	Mongol-Sayan	1	6	24	24	24	9.8	8.4	86	4	14.0	575,100	5
142pCu8505	Kazakh-Tarim	3	5	25	25	25	10.0	8.4	83	4	14.0	344,290	4
142pCu8506	Oyu Tolgoi	6	14	48	48	48	21.0	16.0	73	3	24.0	329,850	7
142pCu8507	Mongol-Altai	3	8	36	36	36	15.0	12.0	84	0	15.0	785,570	2
142pCu8508a	Erdenet South-west	2	6	20	20	20	8.9	6.7	75	1	9.9	61,430	16
142pCu8701	Qinling-Dabie	0	3	20	30	30	8.0	9.4	118	1	9.0	403,220	2
142pCu8702	Jinsajiang	2	4	14	14	14	6.0	5.0	73	2	8.0	111,690	7
142pCu8706	Tethyan-Gang-dese	1	4	18	18	18	7.2	6.3	88	0	7.2	289,650	2
Total		NA	NA	NA	NA	NA	97.0	NA	NA	20	117.0	3,296,600	NA

Mean estimated copper in undiscovered deposits, 370 Mt, represents about five times the 77 Mt of copper in identified resources (table 16). Mean estimates for other commodities that may be present in undiscovered porphyry copper deposits in the assessed area are as follows: 10,000 t of gold, 9.7 Mt of molybdenum, and 120,000 t of silver. Mean, median, and identified copper, molybdenum, and gold resources are compared on a tract by tract basis in figure 43.

No porphyry copper resources have been identified in two tracts, Mongol-Altai (142pCu8507) and Tethyan Gangdese (142pCu8706). Mean and median estimated undiscovered copper resources exceed identified resources in all of the other tracts (table 16, fig. 43*A*). Identified molybdenum resources exceed both mean and median estimated undiscovered molybdenum resources for the Jinsajiang (142pCu8702) tract (table 16, fig. 43*B*). Gold resources reported for the Duobaoshan deposit (164 t) in the Gobi-Amur tract (142pCu8503) exceed the estimated undiscovered gold resources for that tract (table 16). For all the other tracts, mean estimated gold resources exceed identified gold resources (fig. 43*C*).

Discussion

The CAOB and eastern Tethysides incorporate ancient examples of all known environments of porphyry copper formation—subduction related island arcs, continental arcs, and back-arc extensional and (or) other postconvergent settings. These geologic environments for porphyry copper formation are more readily recognized in modern settings where plate boundaries are more obvious, such as the continental arcs of the Andes of South America and the island arcs of the South Pacific. The CAOB and eastern Tethysides record the complex and now fragmented evolution of two of the planet's major ancient oceans, the Paleo-Asian and Tethys Oceans, respectively. Compared to most porphyry copper belts in more modern settings, these areas are generally less thoroughly explored.

The 2001 discovery of the Oyu Tolgoi porphyry copper deposit in Mongolia prompted further extensive exploration in Mongolia within the Oyu Tolgoi tract. Many of the other tracts apparently have also recently started to be explored for porphyry copper deposits. The remoteness, harsh terrain, and lack of infrastructure have impeded exploration in many areas. The increasing use of remote-sensing techniques, such as surface-alteration mapping using ASTER or other hyperspectral data, will likely identify many new near-surface target areas for porphyry copper deposits for follow-up field-based studies in the assessment region (see, for example, Zhang and others, 2007; Liu and others, 2013). In addition, geophysical studies are needed to target buried deposits. In the past few years, an enormous amount of geochronological and geochemical data has been published for China. These topical studies, combined

Table 16. 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 in the Central Asian Orogenic Belt and eastern Tethysides.

[t, metric tons; Mt, million metric tons; NA, not applicable]

Tract	Tract name	Identified copper resources (t)	Estimate of undiscovered copper resources (t)		Identified molybdenum resources (t)	Estimate of undiscovered molybdenum resources (t)		Identified gold resources (t)	Estimate of undiscovered gold resources (t)		Mean estimate of undiscovered silver resources (t)	Mean estimate of rock (Mt)
			Mean	Median		Mean	Median		Mean	Median		
142pCu8501	Solonker	250,000	22,000,000	7,600,000	125,020	600,000	140,000	0	540	180	7,500	4,500
142pCu8502	Kazakh-Tianshan	8,700,000	14,000,000	5,500,000	261,170	370,000	78,000	118	330	120	4,300	2,700
142pCu8503	Gobi-Amur	3,300,000	5,900,000	1,100,000	128,800	170,000	1,400	164	150	8	2,000	1,200
142pCu8504	Mongol-Sayan	5,100,000	38,000,000	21,000,000	470,596	1,100,000	2,600,000	131	950	500	13,000	7,700
142pCu8505	Kazakh-Tarim	6,710,000	39,000,000	21,000,000	119,280	1,100,000	420,000	131	980	520	13,000	7,900
142pCu8506	Oyu Tolgoi	39,000,000	80,000,000	54,000,000	717,660	2,200,000	1,300,000	1,447	2,000	1,300	26,000	16,000
142pCu8507	Mongol-Altai	0	53,000,000	29,000,000	0	1,500,000	660,000	0	1,300	740	18,000	11,000
142pCu8508a	Erdenet Southwest	9,000,000	34,000,000	20,000,000	308,100	920,000	380,000	0	850	480	11,000	6,800
142pCu8701	Qinling-Dabie	1,400,000	32,000,000	11,000,000	0	850,000	170,000	61	800	230	10,000	6,400
142pCu8702	Jinsajiang	4,500,000	20,000,000	10,000,000	122,900	110,000	30,000	225	1,400	850	6,700	4,000
142pCu8706	Tethyan-Gangdese	0	28,000,000	13,000,000	0	770,000	260,000	0	710	310	8,800	5,700
Total		77,000,000	370,000,000	NA	2,300,000	9,700,000	NA	2,300	10,000	NA	120,000	74,000

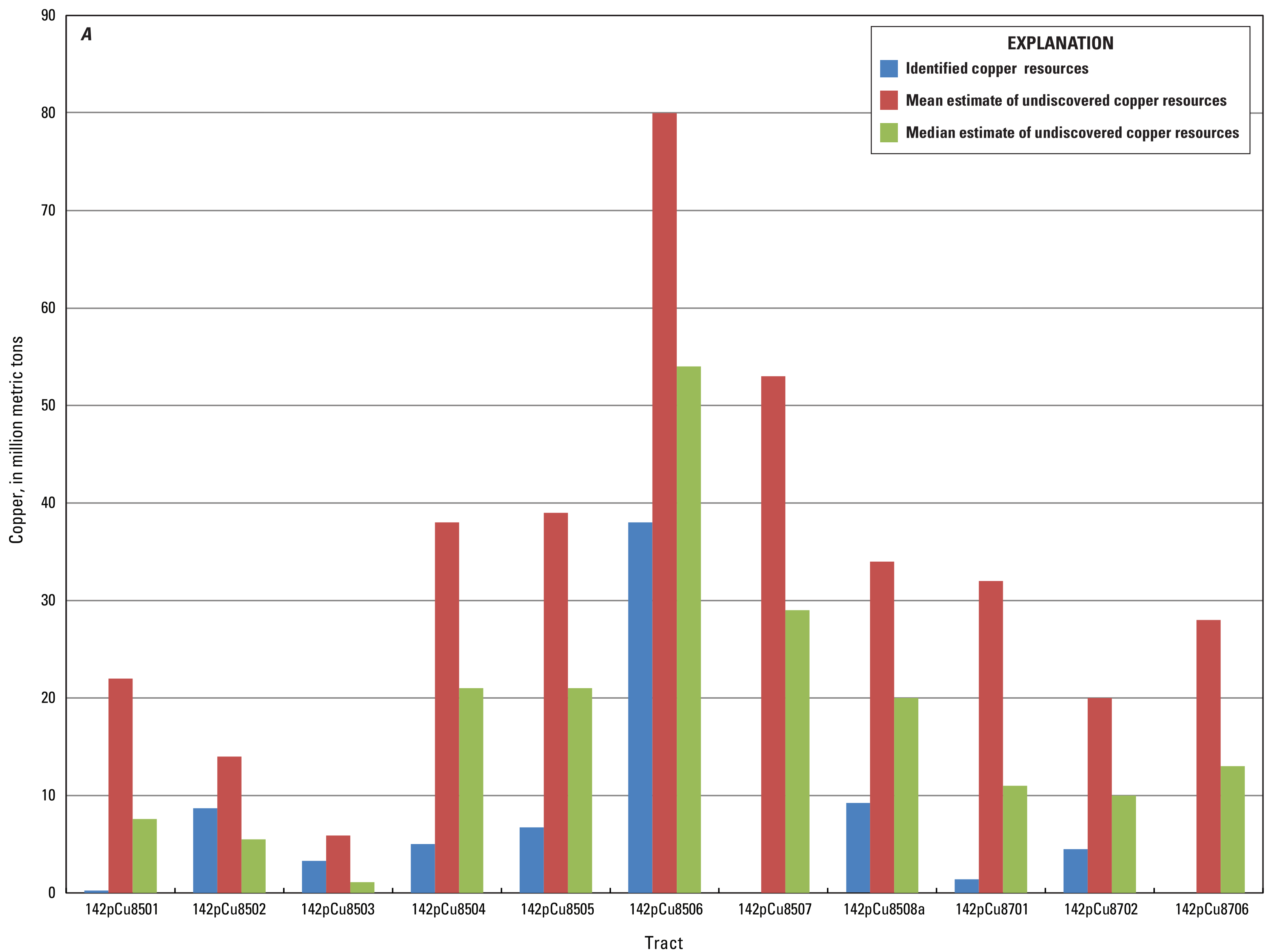


Figure 43. Bar charts comparing identified resources in known deposits (table 16) with mean and median estimates of undiscovered resources (table 16) for each tract in the Central Asian Orogenic Belt and eastern Tethysides. *A*, Copper. *B*, Molybdenum. *C*, Gold.

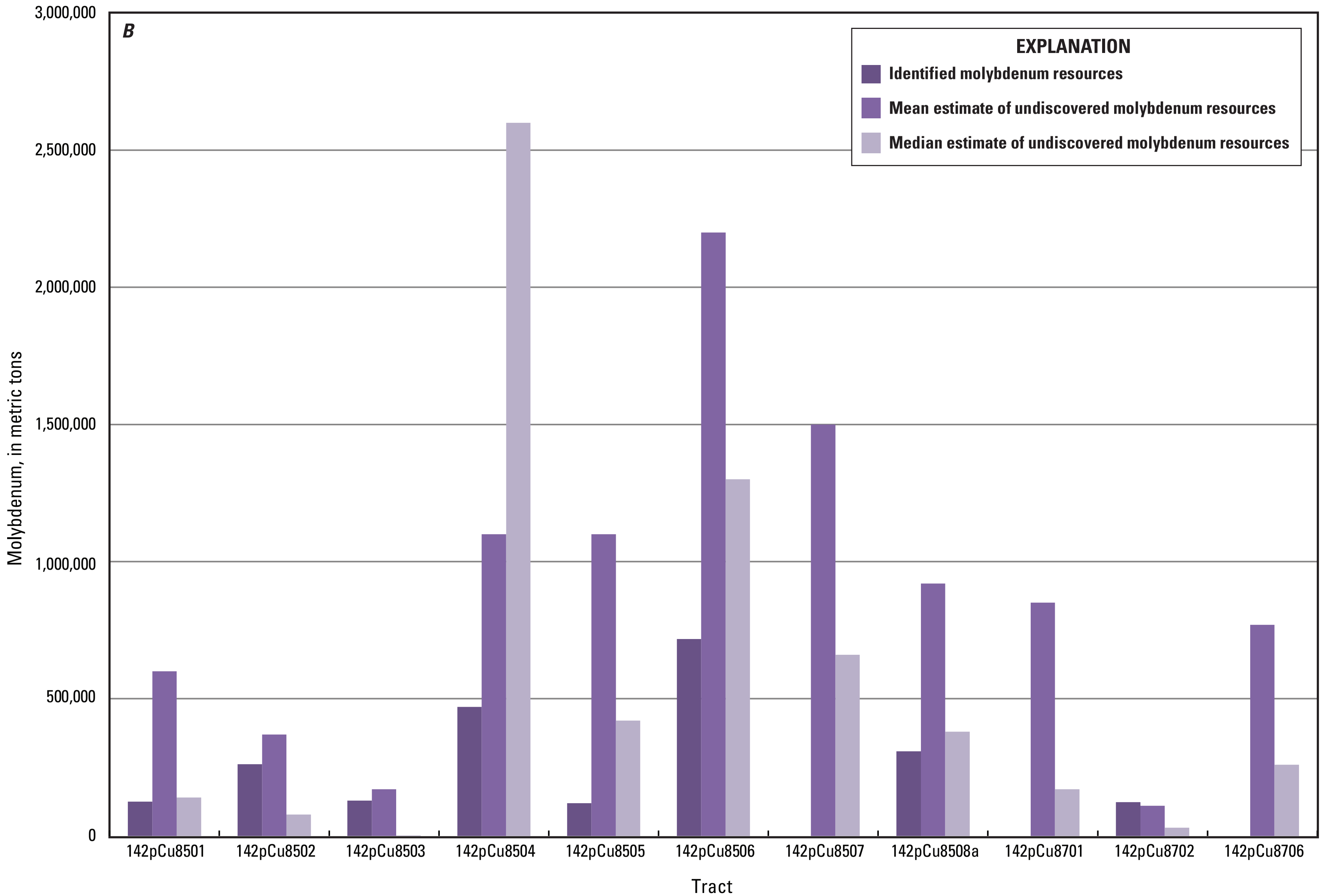


Figure 43.—Continued

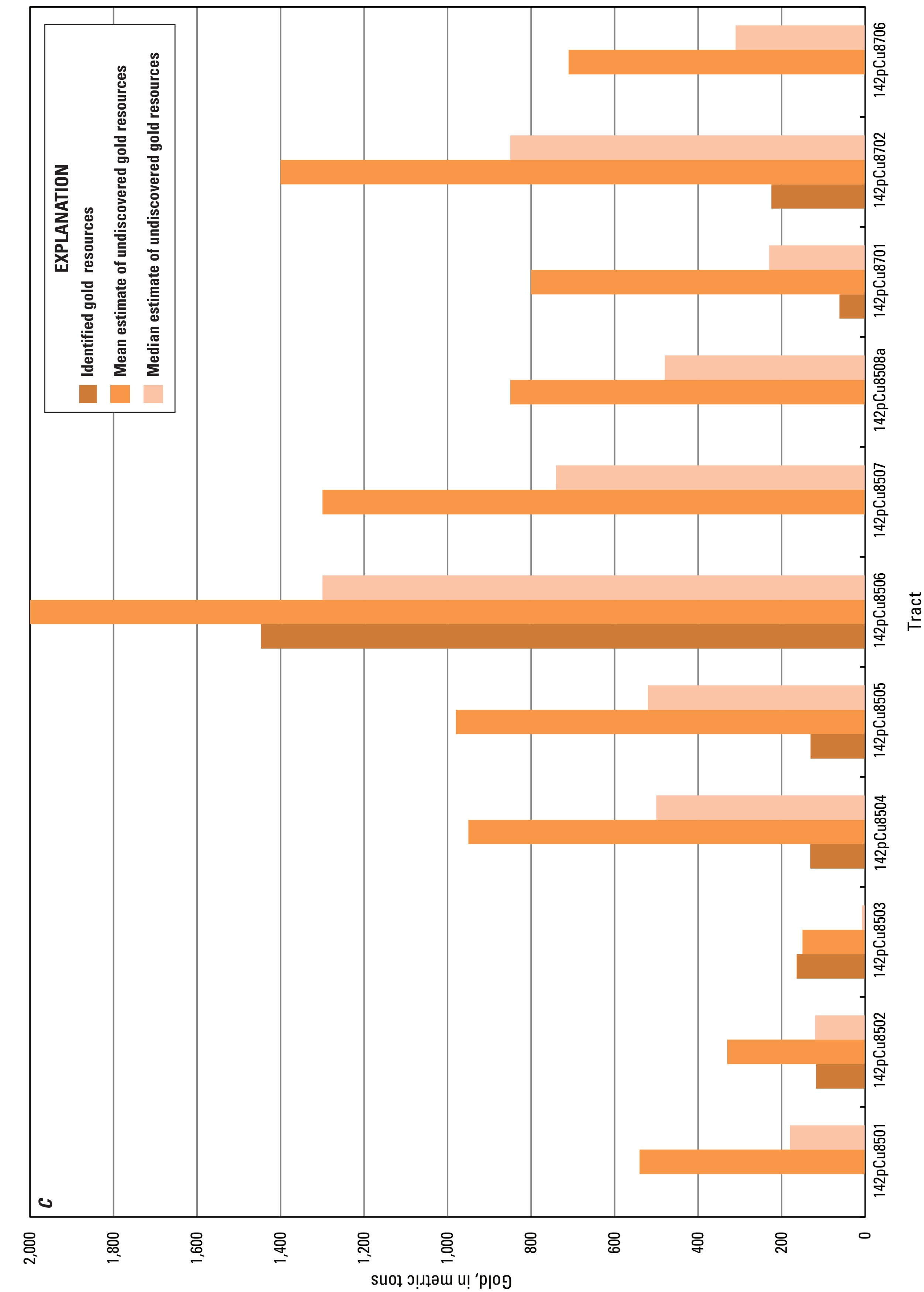


Figure 43.—Continued

with detailed field mapping, will provide data to refine, and probably decrease and subdivide, the areas of permissive rocks for porphyry copper deposits in the CAOB.

The estimate of undiscovered copper resources of about 370 Mt is more than 20 times as large as current world copper production. Several major discoveries have been made in the region in recent years (Oyu Tolgoi, Bozshakol, Aksug, Tuwu, Pulang). Continued expansion of exploration in the region should lead to continued discoveries.

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Appendix A. Principal Sources of Information Used for the Porphyry Copper Assessment of the Central Asian Orogenic Belt and Eastern Tethysides

Table A1. Geologic maps used for the porphyry copper assessment of the Central Asian Orogenic Belt and eastern Tethysides.

Name or title	Scale or resolution	Citation
	China	
Geological map of the People's Republic of China	1:2,500,000	China Geological Survey (2004a)
Regional geology of Anhui Province	1:500,000	Bureau of Geology and Mineral Resources of the Anhui Province (1987)
Regional geology of Gansu Province	1:1,000,000	Bureau of Geology and Mineral Resources of the Gansu Province (1989)
Regional geology of Henan Province	1:500,000	Bureau of Geology and Mineral Resources of the Henan Province (1989)
Regional geology of Hubei Province	1:500,000	Bureau of Geology and Mineral Resources of the Hubei Province (1990)
Regional geology of Jiangsu Province and Shanghai Municipality	1:500,000	Bureau of Geology and Mineral Resources of the Jiangsu Province (1984)
Regional geology of Nei Mongol (Inner Mongolia) Autonomous Region	1:500,000	Bureau of Geology and Mineral Resources of the Nei Mongol Autonomous Region (1990)
Regional geology of Ningxia Hui Autonomous Region	1:350,000	Bureau of Geology and Mineral Resources of the Ningxia Hui Autonomous Region
Regional geology of Shaanxi Province	1:500,000	Bureau of Geology and Mineral Resources of the Shaanxi Province (1989)
Regional geology of Xinjiang Uygur Autonomous Region	1:500,000	Bureau of Geology and Mineral Resources of the Xinjiang Uygur Autonomous Region (1993)
Map of igneous rocks of the Pamir region	~1:10,000,000	Schwab and others (2004)
Regional geology of Qinghai Province	1:1,000,000	Bureau of Geology and Mineral Resources of the Qinghai Province (1991)
Regional geology of Sichuan Province	1:1,000,000	Bureau of Geology and Mineral Resources of the Sichuan Province (1991)
Regional geology of Xizang (Tibet) Autonomous Region	1:500,000	Bureau of Geology and Mineral Resources of the Xizang Autonomous Region (1993)
Regional geology of Yunnan Province	1:1,000,000	Bureau of Geology and Mineral Resources of the Yunnan Province (1990)
	Mongolia	
Geological map of Mongolia	1:1,000,000	Mineral Resources Authority of Mongolia and others (1998)
	Russian Federation	
Geological Map of Russia and CIS	2,500,000	Petrov and Streinikov (2008)
State geological map of the Russian Federation, new series, sheet N-46,(47) Abakan, map of mineral resources	1:1,000,000	Zuev and others (2000)
Geological and mineral resource maps of the USSR, sheet N-49 Chita	1:1,000,000	Kalinina and Malykh (1956), Kalinina (1956)
State Geological Map of the USSR, new series, sheet N-(44),45 Novosibirsk	1:1,000,000	Grigor'ev and others (1987)
	Other areas	
Tectonic map of China and adjacent regions	5,000,000	Ren (1999)
Russia, Mongolia, China	various	Naumova and others (2006); Nokleberg and others (2004)
Afghanistan	various	Peters and others (2007)
Geological map of India	1:1,000,000	Orr and Associates (2007)
Geological map of Pakistan	1:1,000,000	Qureshi and others (1993)

Table A2. Mineral occurrences used for the porphyry copper assessment of the Central Asian Orogenic Belt and eastern Tethysides.

Name or Title	Citation
Mineral deposits database and thematic maps of Central Asia	Seltmann and others (2010)
Geological features of major ore deposits in the Sanjiang Tethyan Metallogenic Domain	Hou and others (2007)
Deposits in China	China Geological Survey (2005, 2004a)
Porphyry copper deposits of the world: database, map, and grade and tonnage models	Singer and others (2008)
MMAJ mineral deposit database	Metal Mining Agency of Japan (1997)
World Minerals Geoscience database	Natural Resources Canada (2010); Kirkham and Dunne (2000)
Porphyry copper and molybdenum deposits of the USSR	Laznica (1976)
Mineral resources of the western part of the Mongol-Okhotsk foldbelt	Gerel (1999)
Mongolian commodities: Cu location map series	Mineral Resources Authority of Mongolia (2003)
Distribution map of mineral deposits and occurrences in Mongolia	Dejidmaa and others (2002)
Mineral resources data system (MRDS)	U.S. Geological Survey (2011)
GSJ Mineral Resources Map of East Asia	Kamitani and others (2007)

Table A3. Other maps used for the porphyry copper assessment of the Central Asian Orogenic Belt and eastern Tethysides.

[NA, not applicable]

Name or title	Scale or resolution	Citation
Magnetic anomaly map of the People's Republic of China	1:5,000,000	China Geological Survey (2004b)
Magnetic anomaly map of the USSR	1:10,000,000	A.P. Karpinsky Russian Geological Research Institute (1978)
Magnetic anomaly data in the Former Soviet Union	1:2,500,000	Racey and others (1996)
Copper geochemical map	1:12,000,000	China Geological Survey (2010)
EMAG2— Earth magnetic anomaly grid	2-arc minute	National Geophysical Data Center (2009)

Appendix B. Excel Workbook for Deposits, Significant Prospects, and Prospects for the Porphyry Copper Assessment of the Central Asian Orogenic Belt and Eastern Tethysides

[Available online only as an Excel workbook at http://pubs.usgs.gov/sir/2010/5090/X/]

Appendix C. Spatial Data

A file geodatabase (.gdb) and an Esri map document (.mxd) are included with this report. The file geodatabase contains three feature classes. These may be downloaded from the USGS Web site at http://pubs/usgs.gov/sir/2010/5090/X/ as zipped file **SIR2010-5090-X_database.zip**.

The file geodatabase is **142pCu_CAOB_Tethys** and contains the following three feature classes:

tracts_142pCu_CAOB_Tethys—A polygon feature class that represents permissive tracts for East and South East Asia. 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 feature class.

mineral_sites_142pCu_CAOB_Tethys—A point feature class for locations of known deposits (identified resources that have well-defined tonnage and copper grade), significant prospects, and prospects. Feature-class 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 feature class.

boundary_142pCu_CAOB_Tethys—A polygon feature class showing countries within and adjacent to the assessment region. The feature class is extracted from the country and shoreline boundaries maintained by the U.S. Department of State (2009).

These three feature classes are included in an Esri map document (version 10.1 Service Pack 1): **142pCu_CAOB_Tethys.mxd**.

Reference Cited

U.S. Department of State, 2009, Small-scale digital international land boundaries (SSIB)—Lines, edition 10, and polygons, beta edition 1, *in* Boundaries and sovereignty encyclopedia (B.A.S.E.): U.S. Department of State, Office of the Geographer and Global Issues.

Appendix D. Assessment Team

Dmitriy V. Alexeiev, Senior Scientist with the Geological Institute of the Russian Academy of Sciences (RAS) in Moscow, Russia. He received M.A. and Ph.D. degrees in geology from Moscow State University in 1985 and 1993, respectively. He worked as a mapping geologist in the Karatau area of southern Kazakhstan between 1985 and 1993. From 1993 to 2005 he was with RAS Institute of Oceanology and has been with RAS Geological Institute from 2006 to the present. His studies focus on the tectonic evolution of the Paleozoic Kazakhstan Tian-Shan region and the Mesozoic to Cenozoic Russian Far East. His work with the USGS has included regional tectonic syntheses, terrane models, and the evolution of arc systems through time for Kazakhstan, Central Asia, and the western circum-Pacific.

Arthur A. Bookstrom, Research geologist, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, United States. He received a B.A. in geology from Dartmouth College (1961), an M.S. in geology from the University of Colorado (1964), and a Ph.D. in geology from Stanford University (1975). He worked as a mine geologist at the Climax molybdenum mine in Colorado, El Romeral magnetite mine in Chile, and the Rochester silver mine in Nevada. He has done exploration-project work at sites in Colorado, Nevada, and Montana, as well as regional exploration for molybdenum in Colorado and regional exploration for gold in Nevada, Montana, and Saudi Arabia. His work with the USGS has included regional geologic studies, metallogenic studies, mineral-environmental studies, and mineral-resource assessments.

Deborah A. Briggs, GIS Specialist, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, United States. She received a B.S. in Geotechnical Engineering at the University of Idaho (1988) and a Geographic Information System (GIS) certificate at Eastern Washington University (2006). She has spent the past 7 years data-mining, synthesizing, and validating geoscientific data from the literature and existing databases for global- and regional-scale assessments of copper, potash, and platinum-group metal-mineral resources.

Lian Changyun, Geological Survey of China, Beijing, China. Participant in initial porphyry copper assessment of China and a coauthor of “Quantitative assessment of the resource potential of porphyry copper systems in China” by Yan and others (2007).

Andrei F. Chitalin, Consultant, Moscow, Russia. Consultant in exploration geology throughout the world, with a focus on Russia. Presented a talk on porphyry copper deposits of Russia at the 2009 annual meeting of the Geological Society of America and participated in a postmeeting assessment workshop hosted by the U.S. Geological Survey in Vancouver, Washington.

Thomas P. Frost, Research geologist, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, United States. He completed his B.A. in Geology in 1975 at U.C. Santa Barbara and his Ph.D. at Stanford in 1987. He has experience as a marine geologist working on environmental hazards associated with oil leasing in the Gulf of Alaska and Cook Inlet, a petrologist working on rheologic modeling of mafic and felsic magma interaction in granitic plutons in the Sierra Nevada, and a geochemist doing geochemical surveys and geologic mapping. Recent work includes the Interior Columbia Basin Ecosystem Management Project, which was charged with assessing forest-landscape–aquatic-social-economic conditions in the Columbia Basin and developing adaptive management plans for Federal lands in the basin. He has participated in porphyry copper mineral resource assessments of Russia, Mongolia, northern China, and Kazakhstan.

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Thomas D. Light, Research geologist, retired, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, United States. Participated in data compilation and 2009 assessment workshops.

Steve Ludington, Research geologist, USGS , Geology, Minerals, Energy, and Geophysics Science Center, Menlo Park, Calif., United States. He received a B.A. in geology from Stanford University (1967) and a Ph.D. in geology from the University of Colorado (1974). He worked as an exploration geologist in Colorado, New Mexico, and Arizona before joining the USGS in 1974. His work with the USGS has included regional geologic studies, metallogenic and geochemical studies, wilderness studies, and mineral-resource assessments. He has done mineral-resource assessment work in the United States, Costa Rica, Bolivia, Mongolia, Afghanistan, and Mexico and was a coordinator for the 1998 USGS National Mineral Resource Assessment.

Mark J. Mihalasky, Research geologist, USGS, Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Wash., United States. He received a B.S. in Geology in 1984 from Stockton State College, a M.S. in 1988 from Eastern Washington University in Geology, and a Ph.D. in Earth Sciences in 1999 from the University of Ottawa. He has worked as an exploration geologist and GIS consultant, Assistant Professor of Earth and Marine Geology and Coastal Research and Center Director of Research at Stockton University, New Jersey, and, since joining the USGS in 2008, a geospatial analyst and resource assessment scientist. He has experience in economic geology, mineral and interdisciplinary natural-resource assessments, and quantitative analysis and modeling of geospatial data. He has been involved with metallic mineral resource assessments (gold, silver, copper) in Nevada, China, Afghanistan, and western Asia (eastern Russia, Mongolia, northern China, Kazakhstan), diamond resources in Mali and the Central African Republic, and interdisciplinary natural resource assessments in Madagascar, Gabon, and the United States.

Robert J. Miller, GIS Specialist, USGS Geology, Minerals, Energy, and Geophysics Science Center, Menlo Park, California, United States. GIS specialist and a coauthor with Warren J. Nokleberg on many publications on the metallogenesis of northeast Asia.

Andre Panteleyev, an economic geologist, formerly with the British Columbia Department of Mines the British Columbia Geological Survey. He received his B.Sc. (Honours, 1964), M.Sc. (1969), and Ph.D. (1976) from the University of British Columbia. He specialized in economic geology studies at Queen’s University from 1967 to 1969, and is registered as a Professional Engineer (P.Eng.) with the Association of Professional Engineers and Geoscientists of British Columbia. He specializes in intrusion-related and subvolcanic mineralized environments, conceptual mineral deposit modeling, the genetic interrelationships of mineral deposits, regional metallogeny, methodologies and applications of regional mineral potential assessments, and multisector land-use negotiations. His work experience includes nine field seasons in the Canadian Cordillera with Kennco Explorations (Western), Ltd., (a Canadian subsidiary of Kennecott Copper Corporation) doing porphyry copper exploration. He has worked and lectured extensively in Canada, Mongolia, China, Argentina, Bolivia, Chile, and Perú, as well as the United States, El Salvador, Fiji, Mexico, and Sweden.

Gilpin R. Robinson, Jr., Research geologist, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Virginia, United States. He received a B.S. in geology from Tufts University (1973) and a Ph.D. in geology from Harvard University (1979). He is a geologist, geochemist, and mineral resources specialist working on mineral-resource assessments and other projects, including geologic mapping, studies of the origin and genesis of metal and industrial mineral deposits, and geochemical modeling.

Qiu Ruizhao, Geological Survey of China, Beijing, China. Participant in initial porphyry copper assessment of China and a coauthor of "Quantitative assessment of the resource potential of porphyry copper systems in China" by Yan and others (2007).

Reimar Seltmann, Director, Centre for Russian and Central EurAsian Mineral Studies (CERCAMS) at the Natural History Museum, London, United Kingdom. He is an economic geologist focused on mineral deposit case studies mainly related to ore-bearing granitoids and metallogeny of central Asia. He coordinates an industry-funded research network "Metallogeny of the Altaids: Terrane reconstructions leading to new target regions," where he contributed ore-deposits research on deposits including Oyu Tolgoi, Almalyk, Dzhezkazgan, Udokan. He has produced a number of original research papers, monographs, metallogenic maps and reference guidebooks on metal provinces of the former Soviet Union, Mongolia, and China.

John C. Wallis, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Washington, United States. Wallis is a GIS and illustrator/graphics specialist. He received a B.S. in Geology (1997) and a B.S. in Biology (1998) from Eastern Washington University. He has been working in mineral assessments for the past 7 years by providing research, GIS and graphics/illustrations support used in this and other global- and regional-scale assessments of copper, potash, and platinum-group metal-mineral resources.

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Appendix E. Geologic Time Correlation Charts

Description

Geologic maps prepared using Russian, Chinese, and Mongolian standards employ stratigraphic charts that differ slightly from one other and from standards used in other parts of the world (see fig. E1). The charts show correlations among series-epoch map symbols and durations for Phanerozoic and Precambrian Eons as used in Russia (Katalog Mineralov, 2005), China (Ma and others, 2002) and Mongolia (Mineral Resources Authority of Mongolia and others, 1998).

The time-stratigraphic boundaries shown are not definitive. The original sources should be consulted for each region in question. For comparisons with the International Stratigraphic Chart, see International Commission on Stratigraphy (2010).

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Mineral Resources Authority of Mongolia, Geological Survey, and Mongolian Academy of Sciences, Institute of Geology and Mineral Resources, 1998, Geological map of Mongolia: Ulaanbaatar, Mineral Resources Authority of Mongolia, Geological Survey, and Mongolian Academy of Sciences, Institute of Geology and Mineral Resources, 1 map on 14 sheets, 30 p., scale 1:1,000,000.

Divisions of geologic time, as used in Russia, Mongolia, and China.

Eon	Era	System - Period				Series - Epoch (Russia)				Series - Epoch (Mongolia)			Series - Epoch (China)				
		Color	Sym.	Name		Color	Sym.	Name	Start date	Sym.	Name	Start date	Sym.	Name	Start date	Magmatic stage	
Phanerozoic	Cenozoic - KZ (CZ)		Q	Quaternary			Q_4	Holocene	0.01	Q_4	Holocene		Q_4	Holocene	0.01	Himalayan	Y^{2}_{6}
							Q_{1-3}	Pleistocene	1.6	Q_{1-3}	Pleistocene	1.7	Q_{1-3}	Pleistocene	2.48		
			N	Neogene	Tertiary (R)		N_2	Pleiocene	6.7	N_2	Pleiocene		N_2	Pleiocene	5.1		
							N_1	Miocene	24.6	N_1	Miocene	24	N_1	Miocene	24.6		
			E (Pg)	Paleogene			E_3	Oligocene	38	E_3	Oligocene		E_3	Oligocene	38		
							E_2	Eocene	54.9	E_2	Eocene		E_2	Eocene	54.9		Y^{1}_{6}
							E_1	Paleocene	65	E_1	Paleocene	65	E_1	Paleocene	65		
	Mesozoic - MZ		K	Cretaceous			K_2	Upper/Late	97.5	K_2	Upper/Late	97	K_2	Upper/Late	95	Yanshanian	$Y^{3(2)}_{5}$
							K_1	Lower/Early	144	K_1	Lower/Early	146	K_1	Lower/Early	135		$Y^{3(1)}_{5}$
			J	Jurassic			J_3	Upper/Late	163	J_3	Upper/Late	161	J_3	Upper/Late	152		$Y^{2(3)}_{5}$
							J_2	Middle	188	J_2	Middle	178	J_2	Middle	180		$Y^{2(2)}_{5}$
							J_1	Lower/Early	213	J_1	Lower/Early	208	J_1	Lower/Early	205		$Y^{2(1)}_{5}$
			T	Triassic			T_3	Upper/Late	231	T_3	Upper/Late	235	T_3	Upper/Late	230	Indosinian	Y^{1}_{5}
							T_2	Middle	243	T_2	Middle	241	T_2	Middle	240		
							T_1	Lower/Early	248	T_1	Lower/Early	245	T_1	Lower/Early	250		

Era	Period symbol	Period	Katalog Mineralov (2005) symbol	Epoch	Start (Ma)	Mongolia symbol	Epoch	Start (Ma)	Ma and others (2002) symbol	Epoch	Start (Ma)	Orogeny	Intrusive symbol
Paleozoic - PZ	P	Permian	P_2	Upper/Late	258	P_2	Upper/Late	256	P_2	Upper/Late	255	Variscan (Hercynian)	Y^{3}_{4}
			P_1	Lower/Early	286	P_1	Lower/Early	290	P_1	Lower/Early	290		
	C	Carboniferous	C_3	Upper/Late	300	C_3	Upper/Late	303	C_3	Upper/Late	325		Y^{2}_{4}
			C_2	Middle	320	C_2	Middle	323	C_2				
			C_1	Lower/Early	360	C_1	Lower/Early	363	C_1	Lower/Early	362		
	D	Devonian	D_3	Upper/Late	374	D_3	Upper/Late	377	D_3	Upper/Late	375		Y^{1}_{4}
			D_2	Middle	387	D_2	Middle	386	D_2	Middle	385		
			D_1	Lower/Early	408	D_1	Lower/Early	409	D_1	Lower/Early	408		
	S	Silurian	S_2	Upper/Late	421	S_2	Upper/Late	424	S_2	Upper/Late	424	Caledonian	Y^{3}_{3}
			S_1	Lower/Early	438	S_1	Lower/Early	439	S_1	Middle	428		
										Lower/Early	438		
	O	Ordovician	O_3	Upper/Late	448	O_3	Upper/Late	443	O_3	Upper/Late	458		Y^{2}_{3}
			O_2	Middle	478	O_2	Middle	464	O_2	Middle	468		
			O_1	Lower/Early	505	O_1	Lower/Early	510	O_1	Lower/Early	510		
	Є (Cm)	Cambrian	$Є_3$	Upper/Late	523	$Є_3$	Upper/Late	517	$Є_3$	Upper/Late	523		Y^{1}_{3}
			$Є_2$	Middle	540	$Є_2$	Middle	536	$Є_2$	Middle	536		
			$Є_1$	Lower/Early	570	$Є_1$	Lower/Early	570	$Є_1$	Lower/Early	600		
References:			Katalog Mineralov (2005)			Mongolia, Geological Survey, and Mongolian Academy of Sciences, Institute of Geology and Mineral Resources (1998)			Ma and others (2002)				

Figure E1. Correlations among geologic time division duration and symbols as used in Russia (Katalog Mineralov, 2005), China (Ma and others, 2002), and Mongolia (Mineral Resources Authority of Mongolia and others, 1998). Start dates are millions of years ago (Ma).

Division of Geologic time, as used in Russia, Mongolia, and China															
Eon	Color	Epoch - Period - Stage (Russia)						Epoch - Period - Stage (Mongolia)			Epoch - Period - Stage (China)				
		Sym.	Color	Name	Color	Sym.	Start date	Sym.	Name	Start date	Sym.	Name	Start date	Magmatic stage	
Proterozoic		PR_2		Vendian		V	650±50	V	Vendian	610	Z_2	Sinian	700	Proterozoic	Y^3_2
				Riphean		R_3 (PR_{23})	1,000±50	R_3	Riphean		Z_1		800		
						R_2 (PR_{22})	1,350±20	R_2			Pt_3	Early Late Proterozoic	1,000		
						R_1 (PR_{21})	1,650±50	R_1		1,650	Pt_2	Middle Proterozoic	1,850		Y^2_2
		PR_1		Upper/Late		PR_{12}	1,900±50	PR_1	Lower Proterozoic	2,500	Pt_1	Early Proterozoic	2,600		Y^1_2
				Lower/Early		PR_{11}	2,500±50								
Archean		AR_2		Upper/Late			3,150±50	AR_2	Upper Archean	3,000–3,200?	Ar_3	Late Archean	3,000	Archean	Y^3_1
		AR_1		Lower/Early			not defined	AR_1	Lower Archean	not defined	Ar_2	Middle Archean	3,500		Y^2_1
											Ar_1	Early Archean	not defined		Y^1_1
References:		Katalog Mineralov (2005)						Mineral Resources Authority of Mongolia, Geological Survey, and Mongolian Academy of Sciences, Institute of Geology and Mineral Resources (1998)			Ma and others (2002)				

Figure E1.—Continued

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