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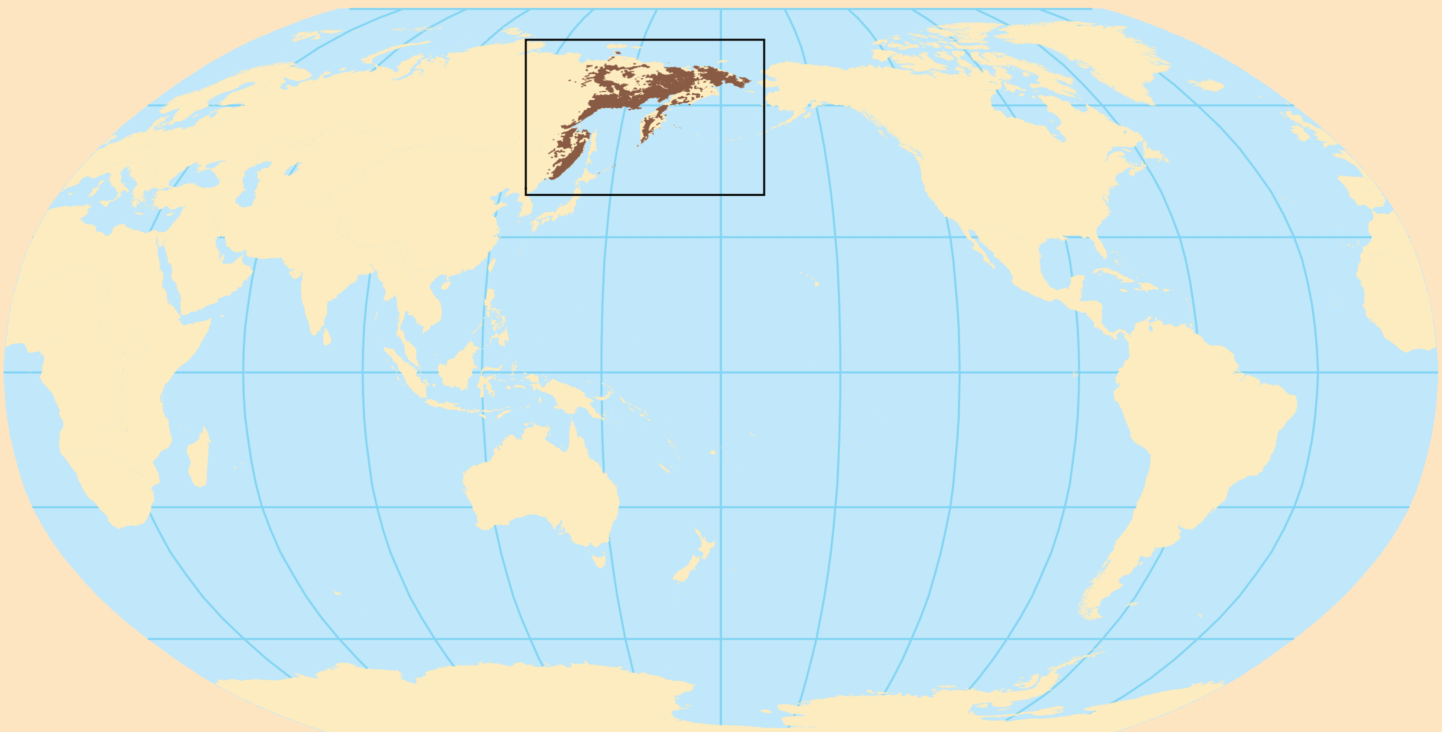
Porphyry Copper Assessment of Northeast Asia—Far East Russia and Northeasternmost China



Prepared in cooperation with the Russian Academy of Sciences

Scientific Investigations Report 2010–5090–W

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

Global Mineral Resource Assessment

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

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SALLY JEWELL, Secretary

U.S. Geological Survey
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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)
pound avoirdupois (lb)	0.4536	kilogram (kg)
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 × ore tonnage, metric tons	metric tons of metal

Acronyms and Abbreviations

ANOVA	analysis of variance
CIS	commonwealth of independent states
CRIRSCO	Committee for Mineral Reserves International Reporting
GIS	geographic information system
km	kilometer
lat	latitude
long	longitude
Ma	mega-annum/millions of years before the present
MRDS	mineral resource data system
Mt	million metric tons
PGE	platinum-group elements
SSIB	small-scale digital international boundaries
t	metric ton (tonne) or megagram (Mg)
USGS	U.S. Geological Survey
VSEGEI	A.P. Karpinsky Russian Geological Research Institute

Chemical Symbols

Ag	silver
Au	gold
B	boron
Cu	copper
Fe	iron
Hg	mercury
Mo	molybdenum
Ni	nickel
Pb	lead
Sb	antimony
Sn	tin
W	tungsten
Zn	zinc

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Porphyry Copper Assessment of Northeast Asia—Far East Russia and Northeasternmost China

By Mark J. Mihalasky[1], Steve Ludington[2], Dmitriy V. Alexeiev[3], Thomas P. Frost[1], Thomas D. Light[1], Deborah A. Briggs[1], Jane M. Hammarstrom[4], and John C. Wallis[1], with contributions by Arthur A. Bookstrom[1], and Andre Panteleyev[5]

Abstract

The U.S. Geological Survey assesses resources (mineral, energy, water, environmental, and biologic) at regional, national, and global scales to provide science in support of land management and decision making. Mineral resource assessments provide a synthesis of available information about where mineral deposits are known and suspected to be in the Earth's crust, which commodities may be present, and estimates of amounts of resources in undiscovered deposits.

A probabilistic mineral resource assessment of undiscovered resources associated with porphyry copper deposits in northeast Asia—composed mainly of Far East Russia and a small part of northeasternmost China—was completed as part of a global mineral resource assessment. Porphyry copper deposits are the main source of copper globally. Russia is an important source of copper, consistently ranking as 6th, 7th, or 8th in world production since 2000, and ranked 7th in 2014. Most of this production has been from magmatic copper-nickel-platinum-group element and volcanogenic massive sulfide deposit types.

The purpose of the assessment was to (1) compile a database of known deposits and significant prospects, (2) delineate permissive areas (tracts) for undiscovered porphyry copper deposits that may be present in the upper kilometer of the Earth's crust, and (3) provide probabilistic estimates of amounts of copper (Cu), molybdenum (Mo), gold (Au), and silver (Ag) that could be contained in undiscovered porphyry copper deposits in the tracts. The assessment was completed by the U.S. Geological Survey in collaboration with geologists from the Russian Academy of Sciences and industry consultants.

The database of known deposits, significant prospects, and prospects includes an inventory of mineral resources in two known porphyry copper deposits, as well as key characteristics derived from available exploration reports for 70 significant porphyry copper prospects and 86 other prospects. Resource and exploration and development activity are updated with information current through February 2013.

The delineation of permissive tracts and probabilistic estimation of resources in undiscovered deposits followed the U.S. Geological Survey form of mineral resource assessment. Descriptive models for porphyry copper deposits define the geologic characteristics that guided tract delineation. The fundamental geologic feature for delineation of a permissive tract for porphyry copper deposits is a subduction-related magmatic arc or belt of a given age. Frequency distributions of total tonnages and average grades compiled from thoroughly explored deposits worldwide were used as models of resource endowment for undiscovered deposits.

Five permissive tracts for the occurrence of porphyry copper deposits were delineated: three in northeastern Russia; one that extends across northeastern and southeastern Russia, including a small part of northeasternmost China; and one on the Kamchatka Peninsula.

The Kedon permissive tract (142pCu8510), with an area of about 31,000 km^2, is defined by Middle Devonian through Early Carboniferous volcanic and intrusive rocks that form a discontinuous continental arc built on the Omolon microcontinent. The tract includes one significant porphyry copper prospect. An estimated 1.2 undiscovered deposits could contain a mean of 4.5 Mt (million metric tons) and a median of 0.81 Mt of copper. Because of metamorphism, deep erosion, and mafic submarine volcanism, this tract is not considered particularly favorable for porphyry copper formation or preservation.

The Kolyma permissive tract (142pCu8512), with an area of about 555,000 km^2, is defined by Late Jurassic to Early Cretaceous volcanic and intrusive rocks that are part of island-arc, continental-arc, and collisional magmatic belts in the Kolyma-Omolon superterrane. The tract includes one world-class porphyry copper deposit (Peschanka, with 1,517 Mt of ore and 7.9 Mt of contained copper), as well as five significant porphyry copper prospects and at least 19 other prospects. An estimated 14 undiscovered deposits could contain a mean of 56 Mt and a median of 30 Mt copper. The eastern part of the tract that includes Peschanka deposit, as well as number of significant prospects along a trend that includes Peschanka, is considered to be highly favorable for porphyry copper deposit formation and preservation.

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The Chukotka permissive tract (142pCu8513), with an area of about 210,000 km^2, is defined by Early to Late Cretaceous volcanic and intrusive rocks in island-arc, continental-arc, and collisional magmatic belts in the Arctic Alaska–Chukotka microcontinent. The tract includes one significant porphyry copper prospect. An estimated 3.1 undiscovered deposits could contain a mean of 12 Mt and a median of 3.5 Mt of copper. The regional metallogenic environment, dominated by Mo-, W-, Sn-, and polymetallic-vein and hot-spring Hg prospects and deposits, does not appear to be particularly favorable for porphyry copper mineralization.

The Pacific Margin permissive tract (142pCu8514), with an area of about 1,140,000 km^2 (representing about one-half of the total area assessed), is defined by Cretaceous through middle Tertiary volcanic and intrusive rocks representing a series of continental- and island-arc complexes formed on, and accreted to the paleomargin of northeast Asia. The tract includes one medium-sized porphyry copper deposit (Lora, with 178 Mt of ore and 0.89 Mt of contained copper), 53 significant porphyry copper prospects, and at least 50 other smaller prospects. An estimated 40 undiscovered deposits could contain a mean of 150 Mt and a median of 95 Mt of contained copper. The tract as whole is comparable in tectonic setting, dimensions, and geologic age-range to the North American Cordillera of the United States and Canada.

The Kamchatka-Kuril permissive tract (142pCu8515), with an area of about 195,000 km^2, is defined by latest Cretaceous through Quaternary volcanic and intrusive rocks representing a series of continental- and island-arc complexes formed on, and accreted to the margin of northeast Asia. The tract includes 10 significant porphyry copper prospects, and at least 17 other smaller prospects. An estimated 8.9 undiscovered deposits could contain a mean of 34 Mt and a median of 20 Mt of contained copper. Significant prospects are present in the central part of the tract.

This mineral resource assessment of undiscovered resources in porphyry copper deposits of northeast Asia indicates that significant amounts of additional resources may be present. The mean estimate of undiscovered copper resources is about 260 Mt, nearly 30 times the amount of copper present in identified resources (about 8.8 Mt). The permissive tracts in northeast Asia delineated in this assessment—particularly the Pacific Margin and Kamchatka-Kuril tracts—are comparable in tectonic setting, dimensions, geologic age-range, and variety of permissive rock compositions to magmatic rocks in the North American Cordillera of the United States and Canada, which hosts numerous world-class porphyry copper deposits that have been thoroughly explored using systematic, scientific approaches since World War II. In contrast to the circum-Pacific Ocean porphyry copper belts in North, Central, and South America, porphyry copper exploration in the region covered by this assessment is relatively immature compared with many other parts of the world. With improved exploration approaches, up-to-date geologic and tectonic analysis, and refined mineral deposit models, northeast Asia may be host to many undiscovered porphyry copper deposits. To date, no modern large-scale porphyry copper deposit mining operations have been developed. Peschanka, a world-class deposit, which was discovered in the late 1960s to early 1970s, explored during 1970s and 1980s, and extensively drilled since 2010, will likely be the first large-scale porphyry copper mining operation in the region.

Introduction

Russia hosts a large variety of metallic and industrial mineral commodities and ranks among the leading global producers of copper. Russia is host to more than 100 copper deposits of various types and sizes (Petrov and others, 2009). In contrast to the rest of the world, where most of the copper production is derived from large, open-pit, relatively low-grade porphyry copper deposits (Nokleberg and others, 2005a), copper in Russia is produced primarily from magmatic copper-nickel- platinum-group element Cu-Ni-PGE and volcanogenic massive sulfide deposit types (Nokleberg and others, 2005a; Petrov and others, 2009). The majority of the copper reserves are in Cu-Ni-PGE magmatic sulfide ores at Norilsk on the Kola Peninsula in northwestern Russia (about 43 percent), followed by volcanogenic massive sulfide deposits (28 percent), sediment-hosted deposits (24 percent), and the remainder in other deposit types (Levine and Wallace, 2004; Petrov and others, 2009). Porphyry copper deposits are known in the Ural Mountains of western Russia; however, porphyry copper deposits historically have not been developed in eastern Russia.

A probabilistic mineral resource assessment of undiscovered resources associated with porphyry copper deposits in northeast Asia (fig. 1), including the Russian Far East and a small portion of northeasternmost China, was undertaken as part of a U.S. Geological Survey (USGS) global mineral resource assessment (GMRAP) (Briskey and others, 2001). The purpose of the assessment was to (1) compile a database of known prospects and deposits with identified mineral resource inventories, (2) delineate areas (or tracts of land) likely to contain undiscovered porphyry copper deposits in the upper kilometer of the Earth's crust (termed permissive tracts), (3) estimate numbers of undiscovered porphyry copper deposits within the permissive tracts, and (4) provide probabilistic estimates of amounts of copper, molybdenum, gold, and silver that could be contained in undiscovered porphyry copper deposits in the tracts.

Results of this assessment are provided at a scale of approximately 1:1,000,000 and can be used for the following:

- Evaluate known and undiscovered copper resources,
- Design and evaluate new mineral-exploration programs,
- Anticipate economic, environmental, and social impacts of mineral development, and
- Provide information for aiding in regional-scale land-use decisions where competing, or mutually-exclusive uses or environmental issues may coincide.

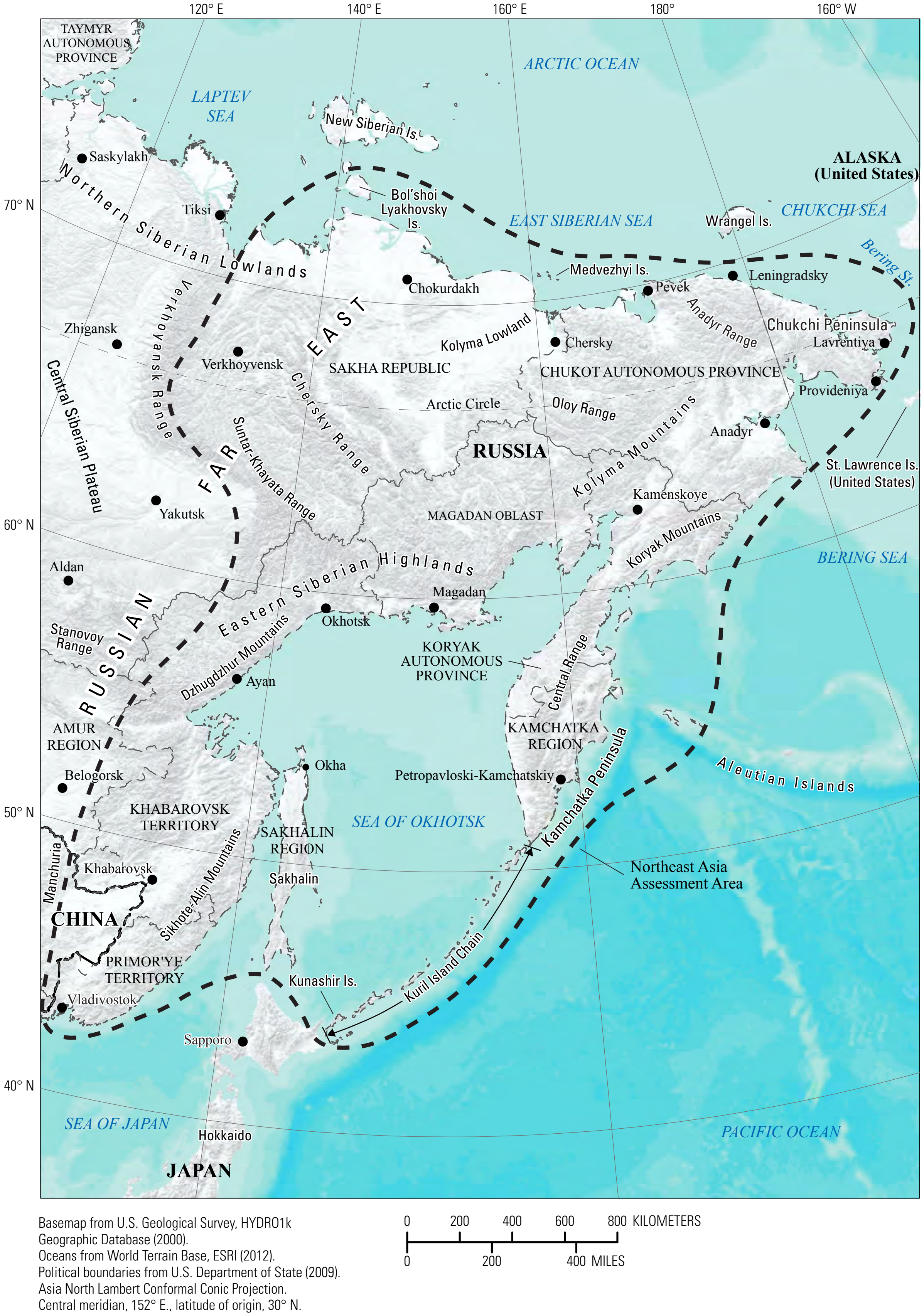


Figure 1. Geographic map of northeast Asia, showing locations of important geographic features, major regions, countries, and population centers.

The assessment was carried out by the USGS using the three-part form of mineral-resource assessment (Singer, 1993, 2007a,b; Singer and Berger, 2007; Singer and Menzie, 2010) in collaboration with geologists from the Institute of Geology, Russian Academy of Sciences, Moscow, and XDM Geological Consultants of Vancouver, British Columbia.

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 (since 2000) have adopted more rigorous definitions of terms for estimating mineral resources and mineral reserves and for reporting exploration information to comply with legal mandates (Committee for Mineral Reserves International Reporting Standards, 2004).

- **Mineral deposit.** A mineral concentration of sufficient size and grade that, under the most favorable of circumstances, is considered to have potential for economic development. This includes deposits under development (feasibility studies; ore bodies not yet excavated), actively producing deposits, and past-producing deposits.
- **Undiscovered mineral deposit.** A mineral deposit believed to exist 1 km or less below the surface of the ground, or an incompletely explored mineral occurrence or prospect that could have sufficient size and grade to be classified as a deposit.
- **Mineral prospect.** A mineral concentration that has been (or is being) examined to determine whether a mineral deposit may be present.
- **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 ore tonnages or other indicators, such as detailed descriptions of mineralization, that suggest the prospect is of high interest.
- **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 existing outside the tract is negligible.
- **Descriptive mineral deposit model.** A set of data in a convenient, standardized form that describes a group of mineral deposits having similar characteristics.
- **Grade and tonnage model.** Frequency distributions of the grades and sizes of thoroughly explored, and (or) completely mined out, individual mineral deposits that are classified by a descriptive mineral deposit model as being the same type.
- **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 (that can include measured, indicated, and inferred mineral resources at the lowest available cut-off grade). In addition, deposits that are not included in the models used for the assessment are considered to contain identified resources if they are characterized well enough to meet commonly used 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 as extensions to identified resources are not addressed explicitly in the assessment process.
- **I-type granite.** Granitoids that occur in an infracrustal subduction tectonic setting and derived from partial melting of a mafic, mantle-derived igneous source material (Winter, 2001, p. 349–358). Also referred to as one-mica granite.
- **S-type granite.** Granitoids that occur in a supracrustal subduction tectonic setting and derived from partial melting of peraluminous sedimentary source rocks (Winter, 2001, p. 349–358). Also referred to as two-mica granite.
- **A-type granite.** Granitoids that occur in an anorogenic or postorogenic, extensional or intracontinental rift setting, and derived from partial melting of generally anhydrous, lower-crustal source rocks by a variety of processes (Winter, 2001, p. 349–358). It is not uncommon for A-type granites to be alkaline in composition.

Russian Resource Categories

The Russian system for classifying mineral resources differs from systems used in the west, and can cause confusion when reading the literature. The Russian system consists of seven categories based on the level of certainty and characterization of the resources: A, B, C1, and C2 (referred to as reserves), and P1, P2, and P3 (referred to as resources) (Henley, 2004). Reserve categories A, B, and C1 are fully explored, C2 is evaluated, and P resource categories are prognostic. In terms of mining and exploration activity, these categories can be stated as follows: A = production; B = delineation of ore blocks; C1 = feasibility study; C2 = prefeasibility study; P1 = initial trenching and drilling; P2 = target identification; and P3 = regional reconnaissance (Henley, 2004).

For additional information on the Russian system of reserve and resource classification, see Diatchkov (1994), Jakubiak and Smakowski (1994), Kotlyar (1996), and Henley (2004). Based on Russian classification criteria, less than 60 percent of Russia's copper resides in proven or probable reserves (64.5 Mt of A+B+C1 and 22.1 Mt of C2), whereas more than 40 percent resides in prognostic resources (65.1 Mt of P1+P2+P3) (Petrov and others, 2009). These values do not take into account the small proportion of non-economic reserves.

Report Format

This report begins with a description of porphyry copper deposit models followed by a brief overview of the geologic setting for porphyry copper deposits in northeast Asia. Subsequent sections on assessment data and assessment methods discuss the nature and quality of the data used for the assessment and the assessment methods, including details of the processes used to delineate permissive tracts, estimate numbers of undiscovered deposits, and estimate probable amounts of undiscovered resources associated with porphyry copper deposits. A brief description of each permissive tract is presented in a section on permissive tracts, followed by a summary of the exploration history of the study area, and a summary of results. The last section of the main report is a discussion of the significance of the results of the study.

Details for each permissive tract are presented in appendixes A through E. Appendix F is an Excel workbook containing information about the porphyry copper deposits and prospects included in this assessment. Porphyry copper permissive tracts, deposits, and prospects are included in appendix G as spatial data in Esri geographic information system (GIS) files (geodatabase format). Appendix H contains an Excel workbook with geologic time scales used by geoscientists in Russia, China, and Mongolia. The absolute ages assigned to periods and epochs are not consistent among workers. The scales also function as a key for system, series, and epoch abbreviations that are typically used in Asian geologic literature and on maps. Appendix I provides a brief biography of the assessment team members.

Considerations for Users of this Assessment

Assessment products represent a synthesis of current, publically available information. Ideally, assessments are done on a recurring basis, at a variety of scales, because available data and understanding of ore deposit genesis change over time. The economic viability of the deposits used to construct the tonnage and grade models used for assessment varies widely, so care must be exercised when using the results of this assessment to answer questions that involve economics. Furthermore, the estimates of the number of undiscovered deposits made in this assessment represent deposits that are likely to exist, not necessarily deposits that are likely to be discovered (Singer, 2007a,b). In some cases, the assessment team was aware of significant prospects, revealed by past or current exploration efforts, that are believed to be deposits, but that do not yet have a citable grade and tonnage data. These probable deposits are treated here as undiscovered deposits, albeit ones with a high degree of certainty of existence.

As well as exploring for deposits in new regions, the mineral industry explores for extensions of identified resources. Undiscovered resources in the form of unidentified extensions to identified resources are not estimated in this assessment, although they are commonly a substantial part of newly discovered copper resources each year (see for example, Mihalasky and others, 2011).

This assessment considers the potential for concealed deposits within 1 km of the Earth's surface. However, exploration for such deposits may, for reasons such as accessibility, be so prohibitive that deposits will not be discovered in the near term. If they are discovered, the logistics and costs associated with mining a deeply buried porphyry deposit could impede or prevent their development given current or near-term metal prices and technology. Nevertheless, there are ore bodies around the world that are mined to depths exceeding 1 km.

Permissive tracts are based on geology, irrespective of political boundaries. Therefore, some tracts cross international boundaries or include lands that already have been developed for other uses, or withdrawn from mineral development as protected areas. The tracts are constructed at a scale of approximately 1:1,000,000 and are not intended for use at larger scales. For additional information about proper use of the tracts, see the completeness and accuracy statements in the metadata of the accompanying GIS files.

Porphyry Copper Deposit Models

Porphyry copper deposits are the most important source of copper (Cu) in the world. The primary (hypogene) ore minerals in porphyry copper deposits are chalcopyrite (copper-iron-sulfide, $CuFeS_2$) and bornite (CuFeS). These and other copper-bearing minerals occur in and around stockworks of intersecting veinlets in hydrothermally altered porphyritic igneous intrusions and their host rocks. In some deposits, supergene processes alter the original copper minerals to form chalcocite (Cu_2S) (Sillitoe, 2005).

Molybdenum (Mo), silver (Ag), and gold (Au) are important coproducts in many deposits.

Porphyry copper deposits typically form in subduction-related, convergent tectonic settings, where continental- and (or) island-arc magmatism occurs (Sillitoe, 2010; John and others, 2010). These deposits are associated with the roots of volcanic systems (fig. 2), specifically, shallowly emplaced calc-alkaline, or less commonly, alkaline plutons, typically of intermediate to felsic composition. The Andes of South America are a classic province for continental-arc magmatism (Kay and others, 1999; Richards and others, 2001). Magma associated with these deposits is typically hydrous, oxidized, rich in sulfur, and has likely undergone complex processes of differentiation (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 to a degree 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 postconvergent (also known as postsubduction or postcollisional) tectonic settings after active subduction had ceased (Richards, 2009; Hou and others, 2011; Ludington and others, 2013) as shown by the examples in figures 2*C*–*E*. The geology and mineralization style characteristic of these deposits are broadly similar to those of classical porphyry copper deposits, however, the magmas in these systems originated from as yet poorly understood processes. Richards (2009) presents a model that is based on the remelting of previously subduction-modified arc lithosphere triggered by asthenospheric upwelling and crustal extension, or mantle lithosphere delamination. Such previously subducted lithosphere would contain small amounts of chalcophile and siderophile elements, and would be a fertile source for hydrous, oxidized, gold-rich (but comparatively sulfur-poor) magmas. Most magmas associated with postconvergent porphyry copper-gold deposits are mildly alkaline (shoshonitic), rather than calc-alkaline, enriched in gold, and form isolated complexes and (or) broad magmatic fields, in contrast to linear magmatic arcs (Richards, 2009; Hou and others, 2010). Examples of porphyry copper deposits formed in postconvergent or non-arc geodynamic settings include the Gangdese porphyry copper belt of Tibet (Hou and others, 2009), Bingham in the western United States, and Grasberg in Indonesia (Richards, 2013).

In this assessment of northeast Asia, available information suggests that the few porphyry copper deposits known in the region formed in the convergent arc settings illustrated in figures 2*A* and 2*B*. Both continental and island-arc complexes are recognized in the study area. Postconvergent porphyry copper deposits have not yet been recognized in the study, although the complex geodynamic setting of the area, abundance of igneous rocks of appropriate compositions and levels of exposure implies that postconvergent porphyry copper deposits are likely to be present in some areas.

Descriptive Models

The descriptive mineral deposit models used for this assessment include the porphyry copper models of Cox (1986 a,b,c), Singer and others (2008), and John and others (2010). A recent review of salient features of porphyry copper deposits by Sillitoe (2010) is also pertinent, as well as reviews by Cooke and others (2005) and Seedorff and others (2005). The distribution and characteristics of porphyry copper deposits in northeast Asia are described in English language papers by Volkov and others (2006), Seltmann and others (2010), Chitalin and others (2011), and metallogenic studies by Nokleberg (2010) and Nokleberg and others (2003, 2005a,b, 2006).

Grade and Tonnage Models

Grade and tonnage data are used to characterize subtypes, size, and metal endowment of porphyry copper deposits. Models are constructed from well-characterized porphyry copper deposit ore tonnages and average grades, based on the total production, reserves, and resources at the lowest possible cutoff grade, as described in Singer and others (2008). These grade and tonnage models, combined with estimates of numbers of undiscovered deposits, provide a means of translating geologists' resource assessments into estimates of undiscovered metal endowment (Singer, 1993, 2007a).

Singer and others (2008) compiled global porphyry copper grade and tonnage models for several porphyry copper subtypes, as well as a general model that includes both gold- and molybdenum-rich subtypes. Subtypes of porphyry copper deposits are defined on the basis of copper (Cu), gold (Au), and molybdenum (Mo) grades, where gold grades are reported in parts per million (ppm) or the equivalent grams per metric ton (g/t):

- Porphyry Cu-Au, where Au (ppm) / Mo (percent) $\geq$ 30; or average Au grades >0.2 ppm
- Porphyry Cu-Mo, where Au (ppm) / Mo (percent) $\leq$ 3; or average Mo grades >0.03 percent

Statistical comparisons are made between any known deposits in a permissive tract and global grade and ore tonnage models to determine the appropriate model for quantitative assessment. A two-sample Student's *t*-test and (or) analysis of variance (ANOVA) is used to make these determinations (Trochim, 2006). In a Student's *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 represent distinct populations. The general model that includes both subtypes typically is used if insufficient data are available for statistical tests.

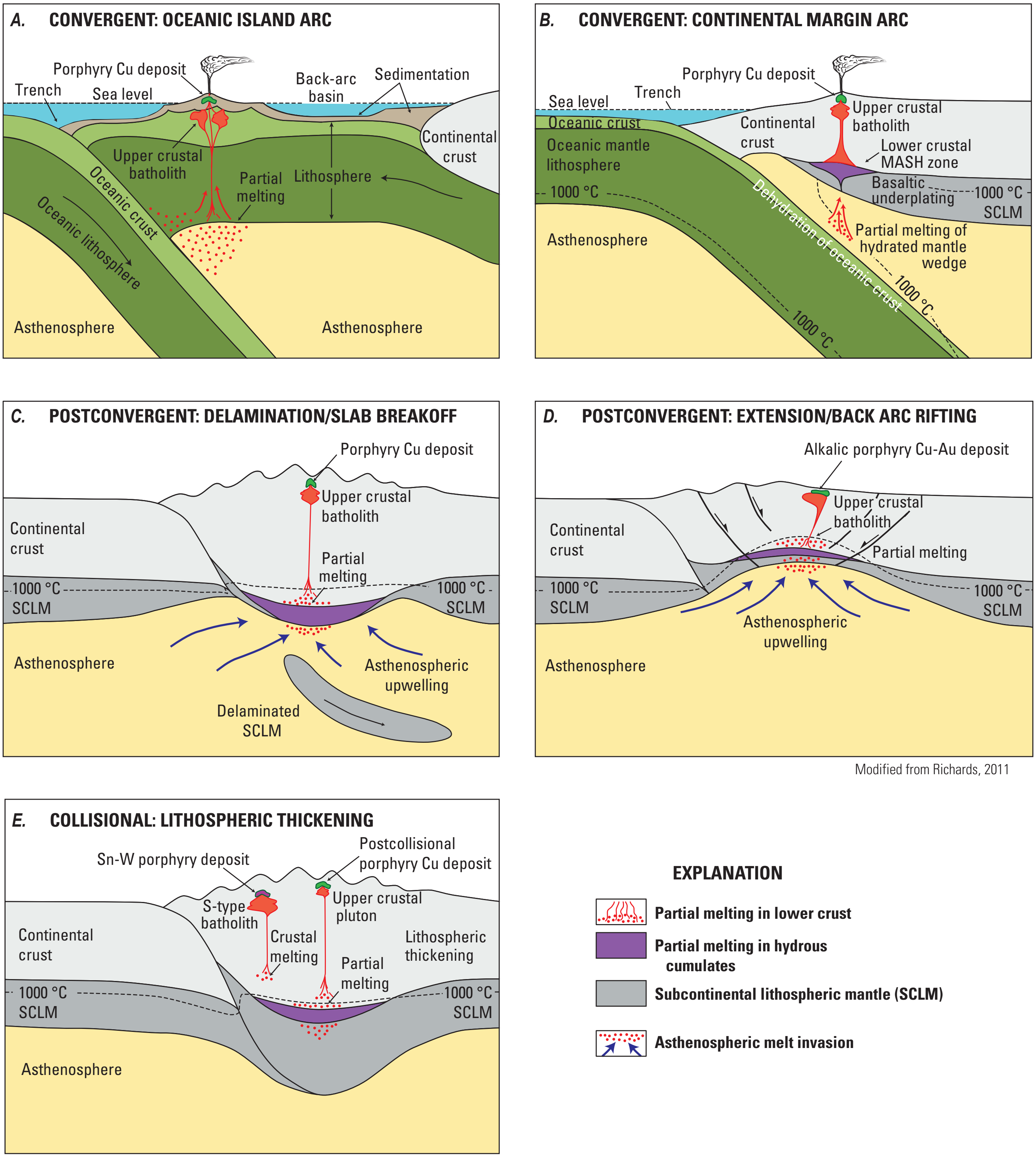


Figure 2. Models for tectonic settings of porphyry copper deposits. *A* and *B*, arc-related subduction settings. *C, D,* and *E*, non-arc-related settings that can occur after subduction has ceased (postcovergence). Cu, copper; Au, gold, Sn, tin; W, tungsten. MASH, zone of melting, assimilation, storage, and homogenization. Based on models of Richards (2009, 2011).

Geologic Setting for Porphyry Copper Deposits in Northeast Asia

The size of the northeast Asia assessment region (fig. 1) is about 4 million km^2, and roughly equivalent in extent to that of Alaska and the Rocky Mountain regions of Canada and the United States. All major rock types and compositions are present, representing all geologic ages, Archean through Quaternary (Petrov and Streinikov, 2008).

The region is characterized by orogenic systems consisting of fragments of continental and oceanic crust that collided with, or were accreted to, the Siberian craton and other contemporaneous and older lithotectonic terranes and superterranes. Orogenesis responsible for the tectonic configuration of the region took place over more than approximately 260 million years, beginning in the late Permian. Major episodes of accretion and magmatism occurred in the Late Triassic, Late Jurassic, Late Cretaceous, and middle- and late Tertiary (with ongoing activity into the present-day). Porphyry copper deposits formed within plutonic-volcanic arcs and magmatic belts in subduction and collisional settings that developed during the assembly of these orogenic systems (Nokleberg, 2010).

Regional-scale features discussed are shown in figures 3 and 4. Features in northeastern, southeastern, and easternmost Russia are shown in figures 5, 6, and 7, and are discussed in greater detail in the appendixes. More comprehensive reviews of the geologic setting and tectonic evolution of northeast Asia and surrounding regions are given by Nokleberg and others (2000, 2005a), Nokleberg (2010), and Parfenov and others (2011), from which much of this material is drawn.

Northeast Asia consists of a subset of orogenic systems that form part of the larger Asian continent (Şengör and Natal'in, 1996; fig. 3). The region of northeastern Russia (the area northwest, north, and northeast of the Sea of Okhotsk; see figs. 3 and 4) consists of four principal systems: (1) the Precambrian Siberian Craton, (2) the Late Jurassic to Early Cretaceous Verkhoyansk-Kolyma system, (3) the Early Cretaceous Chukotalaskides system, and (4) the northern part of the Late Cretaceous to Tertiary Nipponides system (fig. 3). The central part of this region is occupied by the Verkhoyansk-Kolyma orogenic system (Şengör and Natal'in, 1996), the core of which is the Verkhoyansk-Kolyma tectonic collage and the Kolyma-Omolon superterrane (fig. 4, VK and KOM, respectively; Parfenov and others, 2010). First-order accretionary and collisional boundaries separate these two core tectonic domains from the surrounding orogenic systems. These include (1) the Verkhoyansk thrust-fold belt (VR, fig. 4), which separates them from the Siberian Craton on the west, (2) the South Anyui tectonic collage (SA, fig. 4), which separates them from the Chukotalaskides on the northeast, and (3) the West Koryak fold-thrust belt, or the Penzhina-Anadyr tectonic collage (PA, fig. 4), which separates them from the Koryak Highlands and Kamchatka Peninsula region of the Nipponides on the southeast (KOR, WK, and OK, fig. 4).

The region of southeastern Russia and northeasternmost China that lies southwest of the Sea of Okhotsk (figs. 1 and 3) marks the eastern termination of the Paleozoic Central Asian Orogenic Belt (CAOB), a junction of five orogenic systems: (1) the Precambrian Siberian Craton, (2) the Neoproterozoic to early Mesozoic Altaids system, (3) the late Paleozoic to early Mesozoic Manchurides system, (4) the Late Cretaceous to Tertiary Nipponides system, and (5) the Precambrian North China block (fig. 3; ages are approximate time of tectonic assembly; also see fig. 6). The most important of these systems, with respect to the assessment region, is the Nipponides. The Nipponides (Şengör and Natal'in, 1996) are composed of the Mongol-Okhotsk (MO), Badzhal (BD), and Sikhote-Alin (HS) tectonic collages (fig. 4; Parfenov and others, 2010). This package of collages is separated from the Archean to Permian Bureya-Jiamusi superterrane (fig. 6) and other massifs to the west by a Late Cretaceous accretionary boundary that was subsequently modified by later middle Tertiary regional-scale strike-slip faulting (Natal'in, 2007; Nokleberg, 2010; Parfenov and others, 2011).

Plutonic-Volcanic Arcs and Magmatic Belts

Magmatism in the assessment region accompanied collisional and accretionary events that occurred during the (1) Paleozoic, (2) the middle to late Mesozoic, and (3) the Cenozoic, and continue to the present day.

Russian Northeast Mainland

The important magmatic arcs and belts of the Russian northeast mainland (that is, the Verkhoyansk-Kolyma tectonic collage and Chukotalaskides region, north of the Mongol-Okhotsk Suture; see figs. 1, 3, and 4) include the following:

(a) Arcs and magmatic belts that formed on or along the margin of the Kolyma-Omolon superterrane (KOM, fig. 4):

- The Devonian and early Carboniferous Kedon continental margin arc (kd, fig. 4).
- The Late Jurassic and Early Cretaceous Uyandina-Yasachnaya Arc (uy, fig. 4).
- The Late Jurassic and Early Cretaceous Main and Northern granite belts (ma and nb, fig. 4; also see the red Mainly Mesozoic collision granite plutons around the Kolyma Loop Structures on fig. 5).
- The Late Jurassic Oloy Arc (ol, fig. 4; also see Alazeya-Oloy fold zone on fig. 5).

(b) Plutonic and volcanic belts that formed on or adjacent to Arctic Alaska–Chukotka microcontinent (CH, fig. 4):

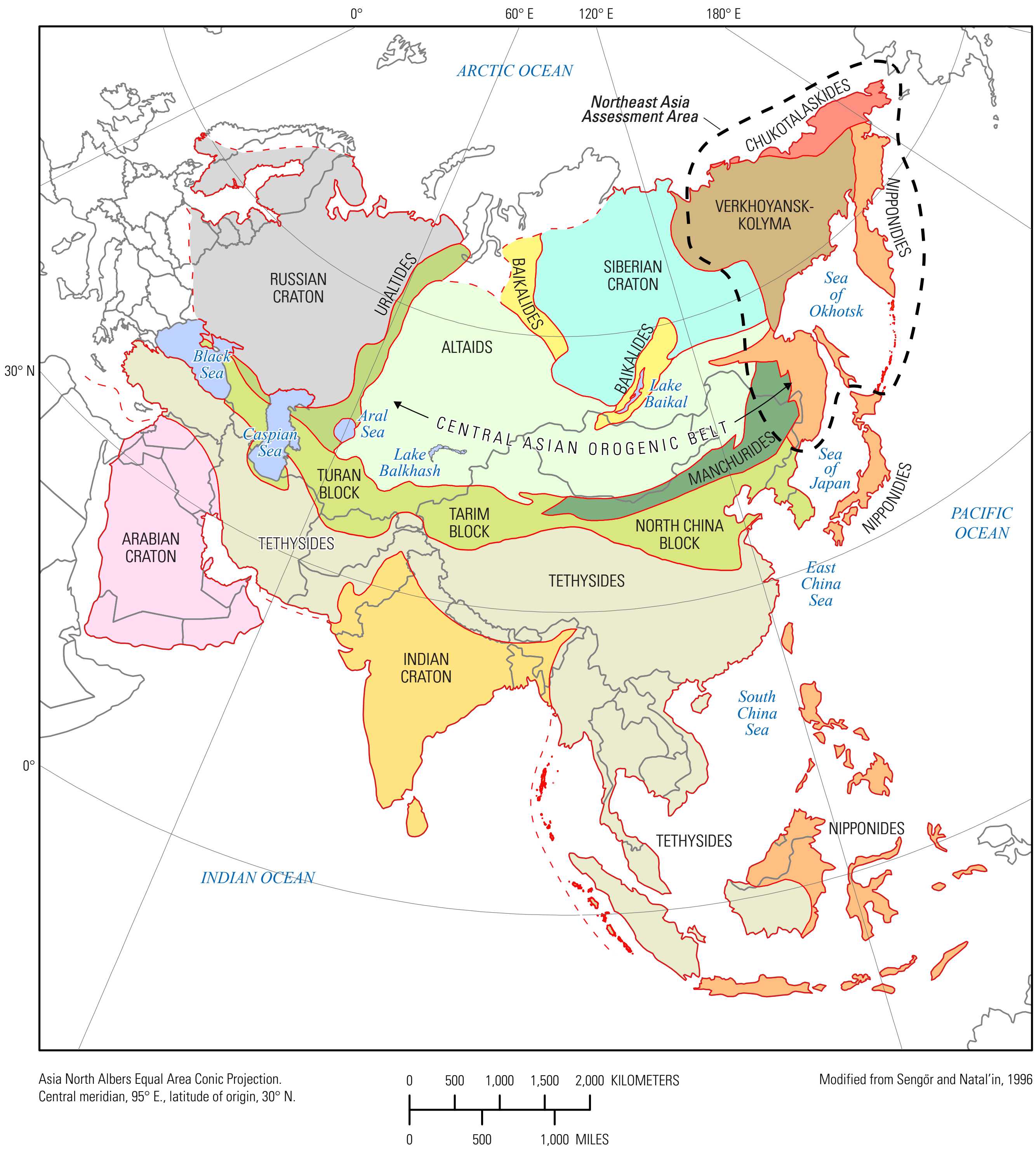
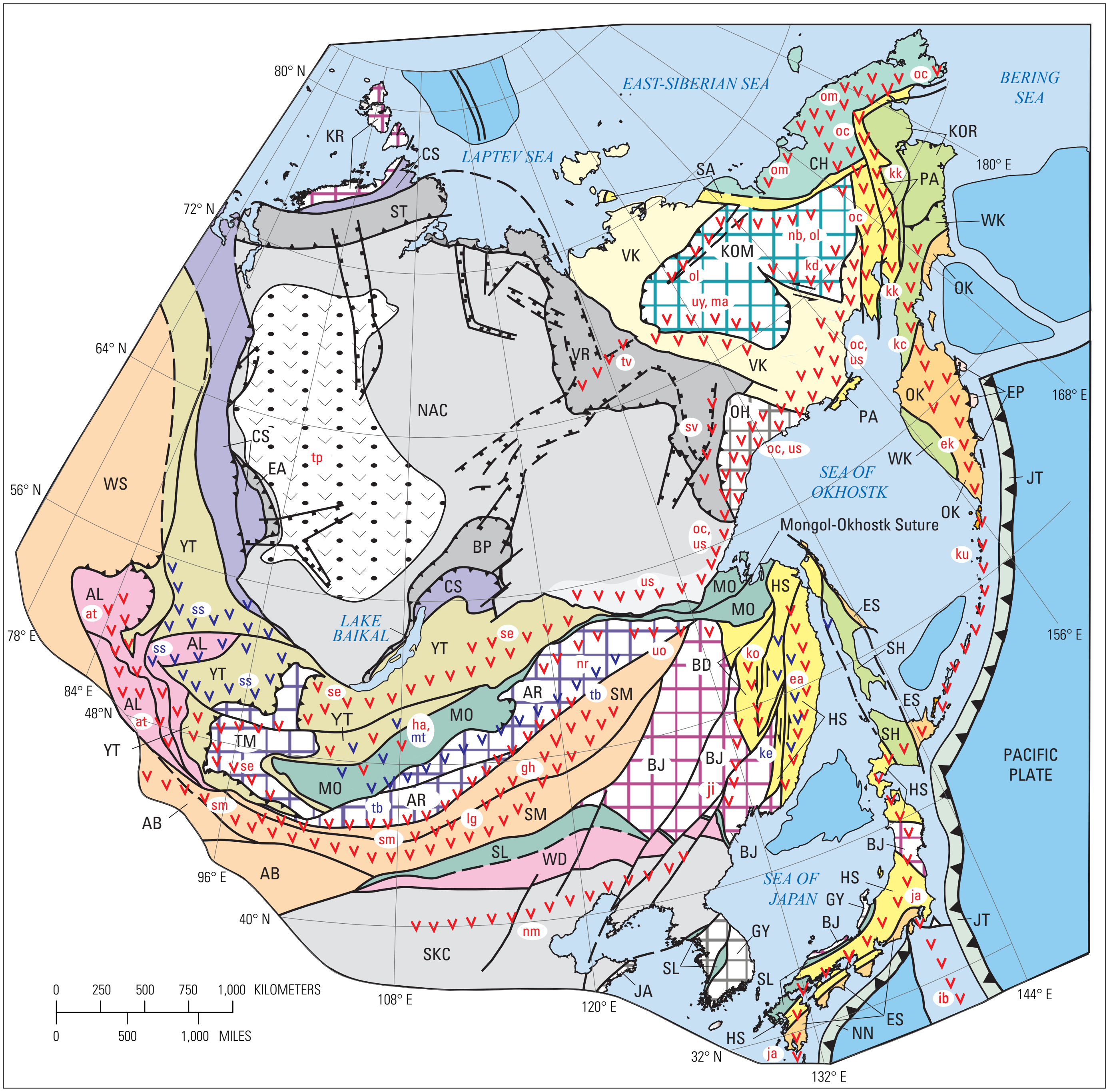


Figure 3. Tectonic framework of major orogenic systems in Asia showing the approximate region of the northeast Asia assessment area. Red lines are approximate boundaries between systems, dashed where uncertain or unknown.



Modified from Parfenov and others 2009, 2010

Figure 4. Northeast Asia summary geodynamics map (scale, approximately 1:34,000,000), showing locations of major geologic and tectonic units including cratons; cratonal margins; cratonal terranes and superterranes; tectonic collages; overlap and transform continental arcs; island arcs; and sea and ocean units. See Parfenov and others (2009, 2010) for full descriptions of map units and the data sources from which the map was built. (Modified from Parfenov and others 2009, 2010)

EXPLANATION

Cratons and Cratonal Margins

Cratons: NAC - North Asian (Archean and Proterozoic), also known as the Siberian craton; SKC - Sino-Korean (Archean and Proterozoic)

Cratonal Margin: BP - Baikal-Patom (Riphean through Cambrian and older basement); EA - East Angara (Riphean and older basement); ST - South Taimyr (Ordovician through Jurassic); VR - Verkhoyansk (Devonian through Jurassic)

Tectonic Collages Between the North Asian and Sino-Korean Cratons

CS - Circum-Siberia (Proterozoic)

YT - Yenisey-Transbaikal (Vendian through Early Ordovician)

AL - Altay (Vendian to Ordovician)
WD - Wundurmiao (Riphean through Ordovician)

AB - Atasbogd (Ordovician through Permian); SM - South Mongolia-Khingan (Ordovician through Carboniferous); WS - West Siberian (Ordovician through Carboniferous)

MO - Mongol-Okhotsk (Devonian through Late Jurassic); SL - Solon (Carboniferous and Permian)

Tectonic Collages Along the Northern and Eastern Margins of North Asian and Sino-Korean Cratons

CH - Chukotka (Paleozoic and Triassic); considered part of the Arctic Alaska-Chukotka microcontinent

VK - Verkhoyansk-Kolyma (Paleozoic through Early Jurassic)

BD - Badzhal (Triassic through Early Cretaceous); PA - Penzhina-Anadyr (Late Jurassic and Cretaceous); HS - Honshu-Sikhote-Alin (Jurassic and Early Cretaceous); SA - South Anyui (Permian through Jurassic)

KOR - Koryak (Late Jurassic through Paleocene); SH - Sakhalin-Hokkaido (Cretaceous); WK - West Kamchatka (Middle-Cretaceous through early Tertiary)

ES - East Sakhalin (Late Cretaceous and Early Tertiary); OK - Olyutorka-Kamchatka (Late Cretaceous to Paleocene)

EP - East Kamchatka Peninsular (Mainly Paleocene)

Active Subduction Zones

JT- Japan Trench (including Kuril-Kamchatka trench) (Miocene through Holocene); NN - Nankai (Miocene through Holocene)

Cratonal Terranes and Superterranes

Cratonal terranes (Archean and Proterozoic): GY - Gyeonggi-Yeongnam; JA - Jiaonan; OH - Okhotsk

Late Proterozoic and Cambrian superterranes: AR - Argun-Idermeg; TM - Tuva-Mongolia

Archean through Permian superterranes: BJ - Bureya-Jiamusi; KR - Kara

Jurassic superterrane: KOM - Kolyma-Omolon (Archean through Jurassic); Omolon is considered a microcontinent

Pelagic and Oceanic Rocks

Surficial deposits

Oceanic crust

Active Arcs, Overlap Continental-Margin Arcs, and Igneous Belts

at - Altay Arc (Devonian and early Carboniferous, 381 to 290 Ma)
ea - East Sikhote-Alin Arc (Late Cretaceous through early Tertiary, 96 to 65 Ma)
ek - East-Kamchatka (Pliocene to present)
gh - Gobi-Khankaisk-Daxing'anling Arc (Permian, 295 to 250 Ma)
ha - Hangay Arc (late Carboniferous and Early Permian, 320 to 272 Ma)
ja - Japan (late Cenozoic, 23 to 0 Ma)
ib - Izu-Bonin (late Cenozoic, 20 to 0 Ma)
ji - Jihei Arc (Permian, 295 to 250 Ma)
kc - Central-Kamchatka (Oligocene to Miocene, and Pliocene)
kd - Kedon continental margin arc (Devonian and early Carboniferous)
kk - Koryak-Kamchatka (middle to late Eocene)
ko - Khingan-Okhotsk continental arc (middle to late Cretaceous)
ku - Kuril-Kamchatka (middle-Neogene to present)
lg - Lugyngol arc (Permian and Triassic, 295 to 250 Ma)
ma - Main granite belt (Late Jurassic, 144 to 134 Ma)
nb - Northern granite belt (Early Cretaceous, 138 to 120 Ma)
nm - North Margin (late Carboniferous and Permian, 320 to 272 Ma)
nr - Norovlin Arc (Devonian and early Carboniferous, 410 to 255 Ma)
oc - Okhotsk-Chukotka Arc (Late Cretaceous and early Tertiary, 96 to 53 Ma)
ol - Oloy Arc (Late Jurassic, 154 to135 Ma)
om - Omineca - Selwyn collisional granite belt (Early and middle Cretaceous)
se - Selenga Arc (Permian through Jurassic, 295 to135 Ma)
sm - South Mongolian Arc (Carboniferous through Triassic, 320 to 203 Ma)
ss - South Siberian Arc (Devonian)
sv - South Verkhoyansk granite belt (Late Jurassic through middle Cretaceous, 157 to 93 Ma)
tv - Transverse granite belt (Early Cretaceous, 134 to 124 Ma)
uo - Umlekan-Ogodzhin (Cretaceous, 135 to 65 Ma)
us - Uda-Murgal and Stanovoy Arc (Jurassic and Early Cretaceous, 203 to 96 Ma)
uy - Uyandina-Yasachnaya Arc (Late Jurassic and Early Cretaceous, 154 to 120 Ma)

Plume-Related Igneous Province

tp Tungus Plateau igneous province - (late Permian and Early Triassic, 245 Ma)

Transpressional Arcs

ke - Kema (middle Cretaceous)
mt - Mongol-Transbaikal (Late Triassic through Early Cretaceous, 320 to 96 Ma)
ss - South Siberian (Early Devonian, 415 to 400 Ma)
tb - Transbaikalian-Daxinganling (Middle Jurassic through Early Cretaceous,175 to 96 Ma)

Symbols, Faults, and Contacts

Overlap continental margin or island-arcs and collisional magmatic belts
Transform-continental-margin arc
Active subduction zone
Thrust
Strike-slip fault
Fault
Contact
Riphean aulacogen
Devonian aulacogen
Modern rift system (Gakkel Ridge)

Modified from Parfenov and others 2009, 2010

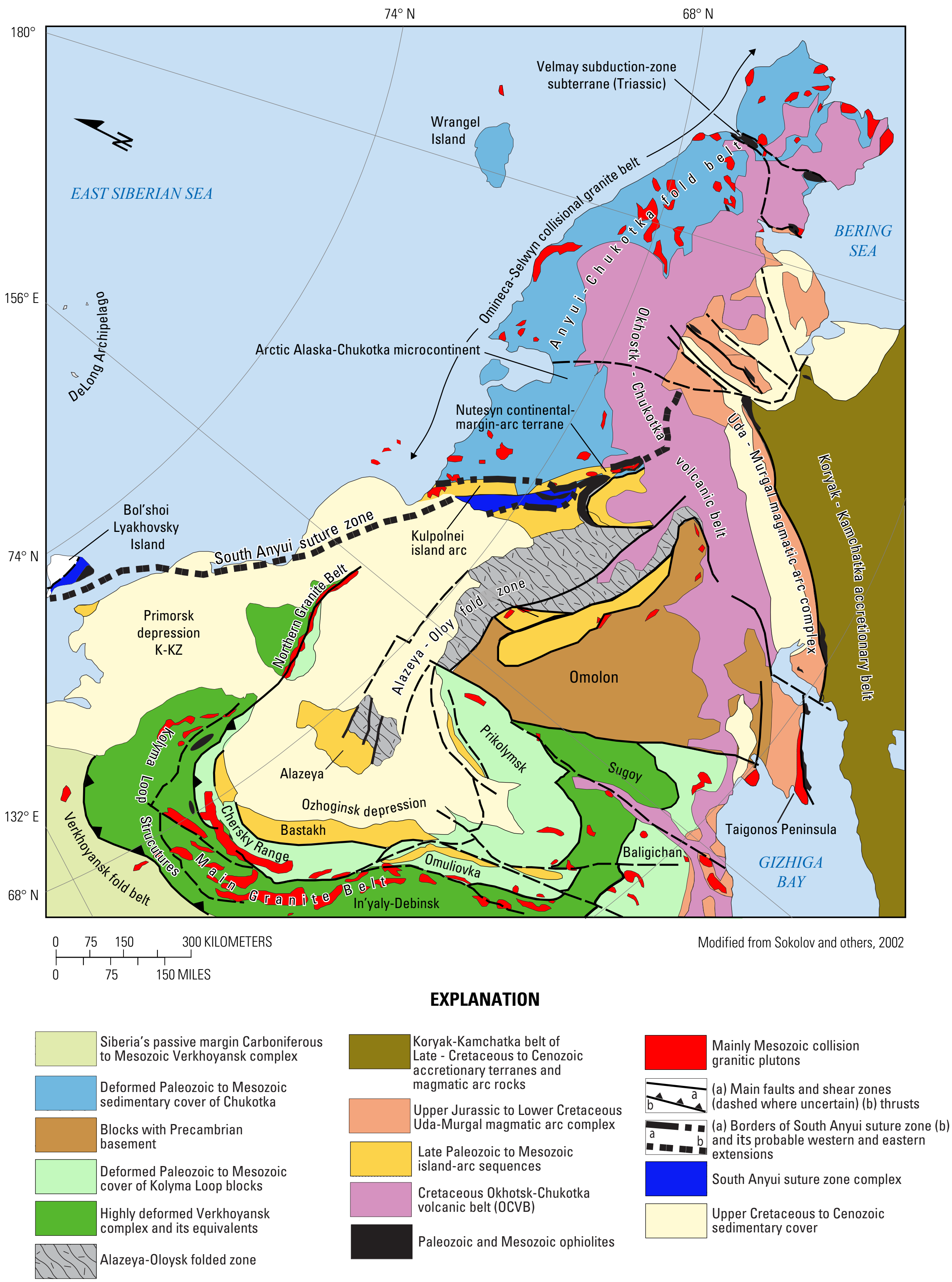


Figure 5. Geologic framework of northeastern Russia and adjacent regions. See Sokolov and others (2002) for the data sources from which the map was built.

- The Early to middle Cretaceous magmatic rocks of the Anyui-Chukotka fold belt, referred to as the Omineca-Selwyn collisional granite belt (om, fig. 4; also see the red Mainly Mesozoic collision granite plutons on fig. 5).

(c) Arcs that formed along the paleo-Pacific Ocean margin:

- The Jurassic and Early Cretaceous Uda-Murgal Arc, a continental- and island-arc complex (us, fig. 4; also see fig. 5).
- The Late Cretaceous and early Tertiary Okhotsk-Chukotka continental arc (oc, fig. 4; also see fig. 5).

The magmatic arc- and belt-related features of the Russian northeast mainland are shown on figures 4 and 5, and discussed in greater detail in appendixes A, B, and C of this report. A brief timeline of their development follows below.

The Kedon Arc, a continental margin arc, was formed along the margin of the then-offshore Omolon microcontinent (or cratonal block; kd in the eastern part of KOM in fig. 4). The Kedon Arc was amalgamated with other outboard terranes and accreted to the eastern margin (present-day geography) of the Siberian craton in the Middle to Late Jurassic as the Kolyma-Omolon superterrane (Kolesov and Stone, 2002; Lawver and others, 2002; Khudoley and Prokopiev, 2007). The Verkhoyansk fold belt, Uyandina-Yasachnaya Arc, and Main and Northern granite belts formed as the Kolyma-Omolon superterrane accreted and collided with the Siberian craton. Shortly after the addition of the Kolyma-Omolon superterrane to the Siberian margin, the Oloy Arc developed along the outboard northeastern margin of the Kolyma-Omolon superterrane in response to the approach and accretion of the Arctic Alaska–Chukotka microcontinent. This accretionary event resulted in the South Anyui suture zone (fig. 5), as well as the accretion and development of island- and continental arcs northeast of the suture, along the southwestern margin of the Arctic Alaska–Chukotka microcontinent (Sokolov and others, 2002, fig. 6c; Nokleberg, 2010; Parfenov and others, 2011, Time Stage 9—Late Jurassic (145 Ma)). In the Cretaceous, after accretion of the Arctic Alaska–Chukotka microcontinent, a regionally extensive period of thrusting and crustal thickening related to convergence affected the circum-north Pacific, including the northeastern part of the Russian northeast, forming the Omineca-Selwyn collisional granite belt in the Anyui-Chukotka fold belt (fig. 5; Zonenshain and others, 1988; Nokleberg and others, 1994; Nokleberg and others, 2000, and references therein). Contemporaneous and subsequent to the assembly and amalgamation of the Kolyma-Omolon superterrane and Arctic Alaska–Chukotka microcontinent to the Siberian craton during Jurassic and Early Cretaceous time, orogenic activity shifted southeast forming two elongate, overlapping continental arcs. The older Uda-Murgal magmatic arc complex (fig. 5) is fragmented along its length, representing multiple continental- and island- arc segments accreted to one another (Zonenshain and others, 1990). The Uda-Murgal magmatic arc complex is broadly overlapped, intruded, and deformed by younger magmatic rocks of the Okhotsk-Chukotka volcanic belt (fig. 5), which is considered to be an Andean-style arc, and is the largest part of an arc complex that spans the entire eastern margin of the Asian continent (Zonenshain and others, 1990; Hourigan and Akinin, 2004; Akinin and Miller, 2011).

Russian Southeast

The important magmatic arcs and belts of the Russian southeast (that is, the Nipponides region of Sikhote-Alin Mountains, south of the Mongol-Okhotsk Suture; see figs. 1, 3, and 4) include:

- The middle to Late Cretaceous Khingan-Okhotsk Arc (ko, fig. 4; also see fig. 6).
- The Late Cretaceous through early Tertiary East Sikhote-Alin Arc, a continental- and island-arc complex (ea, fig. 4; also see Cretaceous to Tertiary arc on fig. 6).

The magmatic arc- and belt-related features of the Russian southeast are shown on figures 4 and 6, and discussed in greater detail in appendixes D and E of this report. A brief timeline of their development follows below.

During the Jurassic through Early Cretaceous—contemporaneous with the Uda-Murgal magmatic arc complex and the Okhotsk-Chukotka arc complexes—the Mongol-Okhotsk Ocean was closing as the North China Block and accretionary collages to the north (the Manchurides and Altaids of Inner and Outer Mongolia (fig. 3), also known as the Amuria block; Zonenshain and others, 1990; Cogné and others, 2005) converged with the southern and southeastern margin of the Siberian craton, culminating in the formation of the Mongol-Okhotsk Suture in Late Jurassic–Early Cretaceous time (Cogné and others, 2005; see also Bussien and others, 2011). This feature extends nearly 3,000 km from northwest Mongolia to the Sea of Okhotsk (see figs. 4 and 6). The Khingan-Okhotsk continental arc developed to the south of the Mongol-Okhotsk Suture, and is considered by some (for example, Khanchuk and others, 2006) to be the southern extension of the Okhotsk-Chukotka volcanic belt (Faure and Natal'in, 1992; Kirillova, 2003; Natal'in, 2007; Parfenov and others, 2009). Magmatism ceased in the Khingan-Okhotsk Arc and shifted further east to the East Sikhote-Alin Arc (fig. 6) in response to outboard-stepping of subduction related to the accretion of central and southern Sikhote-Alin tectonic units at the end of the Late Cretaceous (Zonenshain and others, 1990; Faure and others, 1995; Parfenov and others, 2011).

Russian Far East

The important magmatic arcs and belts of the Russian Far East (the Nipponides region of Kamchatka and the present-day

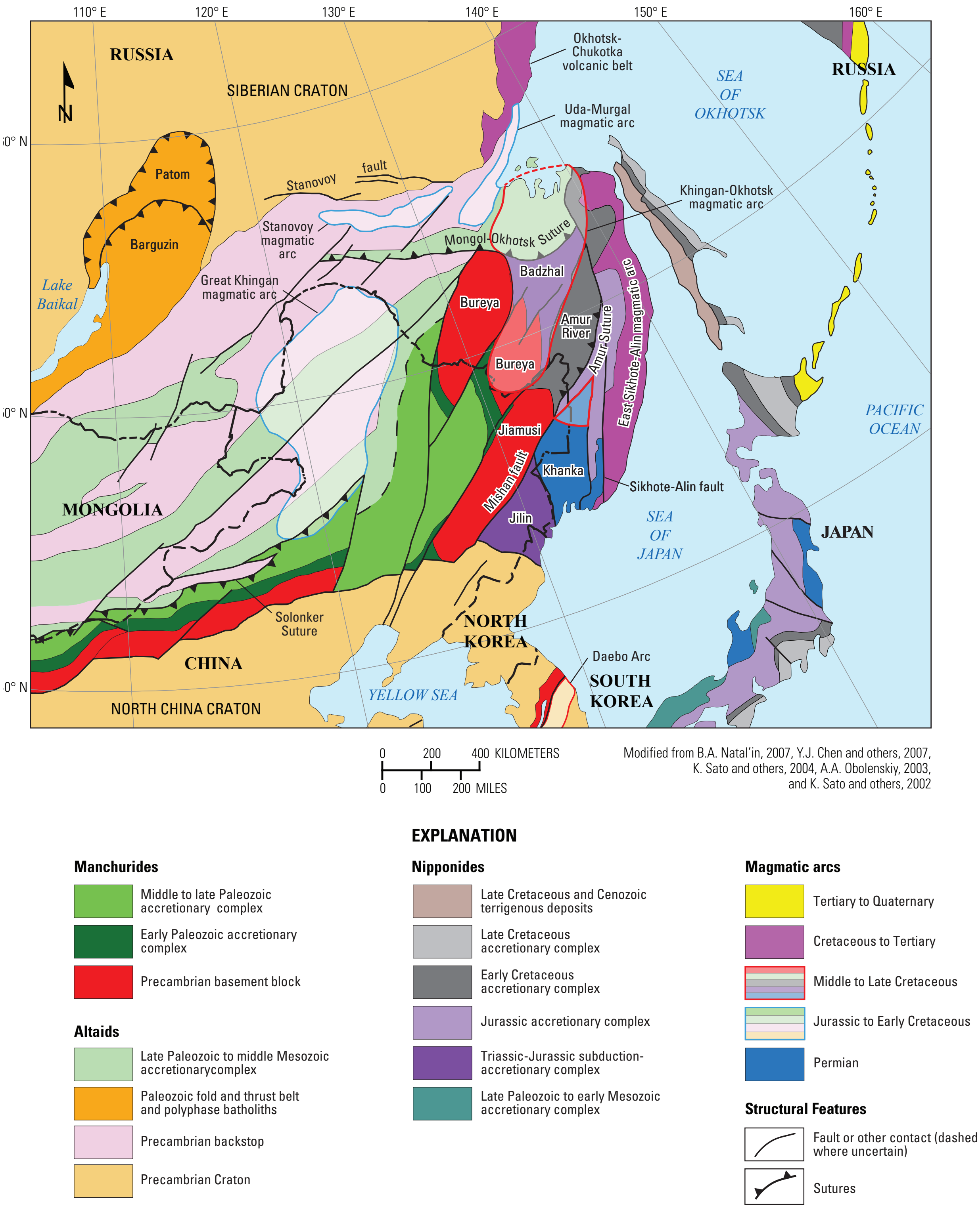


Figure 6. Geologic framework of southeastern Russia and adjacent regions. See Natal'in (2007) and Chen and others (2007) for data sources from which the map was built.

northwestern margin of the Pacific Plate; see figs. 1, 3, and 4) include the following:

- The Late Cretaceous to Paleocene Olyutorka-Kamchatka island arc (contained within OK on fig. 4; also referred to as Achaivayam-Valaginsky terrane, paleo-island-arc as indicated on fig. 7).
- The middle to late Eocene Koryak-Kamchatka continental arc (kk, fig. 4; also see fig. 7).
- The middle to late Eocene (early phase) and Pliocene to present (later phase) Kuril-Kamchatka island arc (ku, fig. 4; also see East Kamchtka and Kuril belt on fig. 7).
- The Oligocene to Miocene Central Kamchatka continental arc (kc, fig. 4; also see central Kamchatka subaerial volcanic belt on fig. 7).
- The Pliocene to present East Kamchatka continental arc (ek, fig. 4; also see East Kamchtka and Kuril belt on fig. 7).

The magmatic arc- and belt-related features of the Russian Far East are shown on figures 4 and 7, and discussed in greater detail in appendix E of this report. A brief timeline of their development follows below.

In the Late Cretaceous, continental- and island-arc magmatism along the paleomargin of northeast Asia shut down and shifted eastward to an oceanic tectonic setting in the present-day region of the Koryak Mountains and Kamchatka Peninsula (fig. 1) (Akinin and Miller, 2011; also see Hourigan and others, 2009, and references therein; Konstantinovskaya, 2011, and references therein). In the early to middle Eocene, after long distance transport from the southeast, the Late Cretaceous to Paleocene Olyutorka-Kamchatka island arc (OK on fig. 4) accreted to a submerged, offshore part of the northeast Asian margin (Harbert and others, 2003; Avdeiko and others, 2007; Hourigan and others, 2009; Shapiro and Solov’ev, 2009; Konstantinovskaya, 2011, and references therein). During the latter phase of this accretionary event, the Koryak-Kamchatka continental arc (KOR on fig. 4) developed in the northwestern Kamchatka-Koryak region in response to the initiation of a short-lived (?) subduction zone (Zonenshain and others, 1990; Nokleberg and others, 2000, 2005a; Hourigan and others, 2009, and references therein). The Koryak-Kamchatka Arc extends parallel to the northern part of the Okhotsk-Chukotka volcanic belt for about 800 km, lying mainly to its east (Nokleberg and others, 2005a). After the Olyutorka-Kamchatka island arc accreted, magmatic activity shifted southeastward with the development of the Central Kamchatka continental arc, located along the central-axis of the Kamchatka Peninsula and isthmus (Avdeiko and others, 2007; Parfenov and others, 2011). Contemporaneously to the south, as the Central Kamchatka Arc enlarged, Kuril-Kamchatka island-arc magmatism developed while magmatism to the west in the Koryak-Kamchatka Arc waned (Nokleberg and others, 2000; Parfenov and others, 2011). Kuril-Kamchatka magmatism can be considered the southern island-arc extension of northern Central Kamchatka continental-arc magmatism. With the onset of subduction of the present-day Pacific Plate in the Miocene (Parfenov and others, 2011), magmatism shifted again to the southeast forming the East Kamchatka continental arc (ek on fig. 4) and the Kuril-Kamchatka trench and subduction zone (Nokleberg, 2010). East Kamchatka magmatism can be considered the northern continental-arc extension of southern Kuril-Kamchatka island-arc magmatism.

Assessment Data

Availability and Quality

The geology and metallogeny of northeast Asia is not as well-known as that of other parts of the world, at least as can be qualified based on information available in English-language geoscientific literature. Although much of the region has been mapped at appropriate scales, the understanding of the geologic and tectonic history continues to evolve rapidly. Hundreds, if not thousands of igneous map units remain uncharacterized and undated (many of which are in regions that are difficult to access).

Although there has been a dramatic increase of English-language literature in the last decade, a significant amount of relevant information remains only in the Russian- and Chinese-language literature, much of which was not readily accessible by the assessment team. In addition, mineral exploration companies and government geologic institutions in Russia and China do not necessarily make detailed earth science information available to the public.

As a result, the assessment team relied primarily on generalized regional-scale compilations (see table 1), on academic papers in the scientific literature (including non-English-language publications), and on promotional material from the Web sites of mineral exploration companies. These materials cover large geographical areas and rocks formed over long time spans therefore complicating discrimination of permissive host rocks for porphyry copper deposits within larger magmatic arcs or provinces. Thus, it was difficult to avoid including many rocks that were strongly suspected of being nonpermissive, whether because of unknown (unmapped) locations or because the map units were undifferentiated (for example, I-, A-, and S-type granites grouped into single granitoid units that contain leucogranite, plagiogranite, granite, granodiorite, diorite, or other mixes of permissive and nonpermissive or marginally permissive lithologic types).

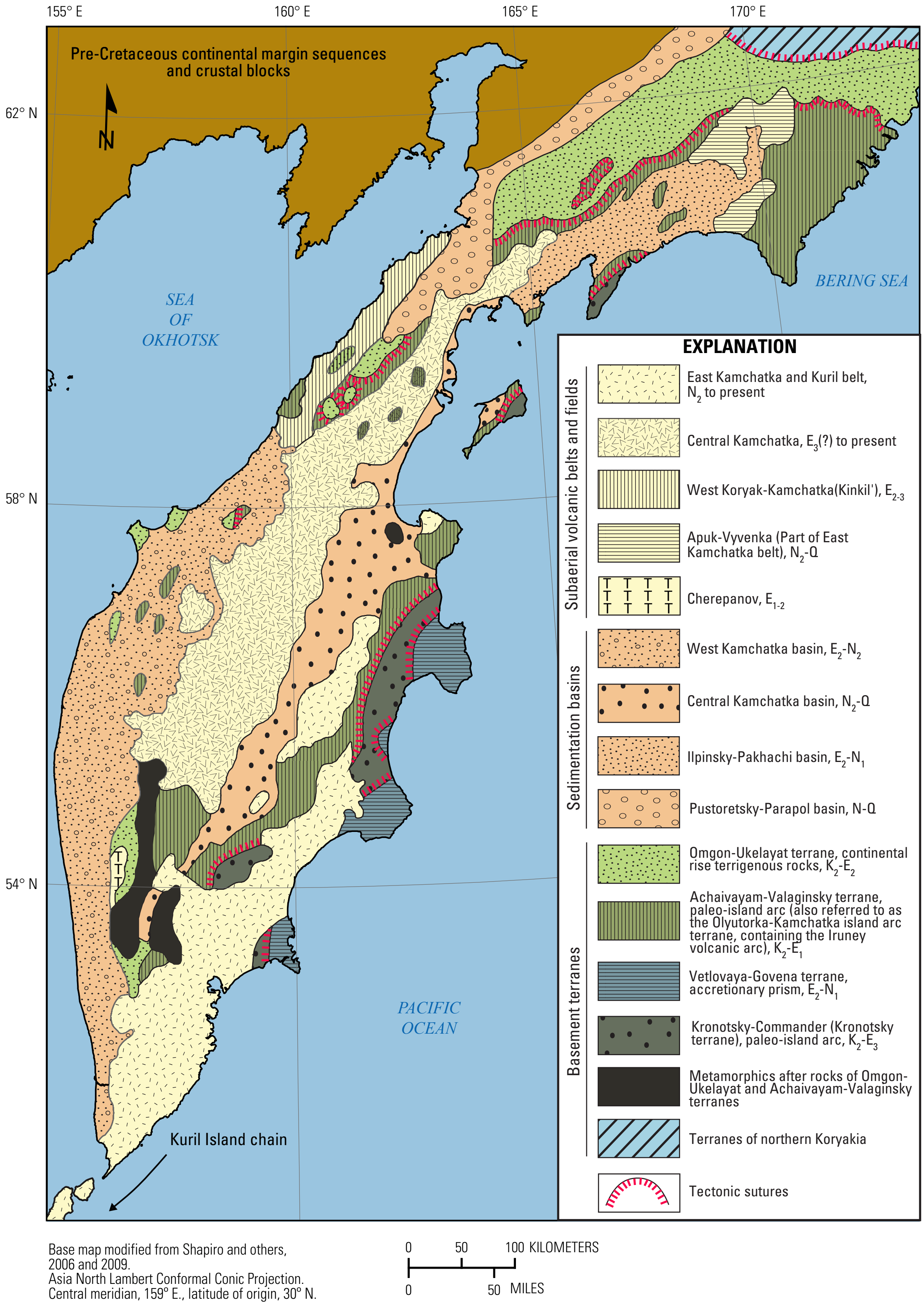


Figure 7. Geologic framework of easternmost Russia and adjacent regions. See appendix H for key to age terms. See Shapiro and others (2006, 2009) for data sources from which the map was built.

Table 1. Principal sources of information used in the assessment of undiscovered porphyry copper deposits in magmatic arcs and belts of northeast Asia.

[n.a., not applicable; GIS, geographic information system; CIS, Commonwealth of Independent States; ~, approximate]

Theme	Name or Title	Scale	Citation
Geology	Map of mineral resources of Kamchatka region	1:500,000	Litvinov and others (1999)
	Map of pre-Quaternary formations, sheet R-(55)-57 (Nizhnekolymsk)	1:1,000,000	Aulov and others (2000)
	Map of pre-Quaternary formations, sheet P-60 (Cape Navarin)	1:1,000,000	Emel'yanova (2001)
	Map of pre-Quaternary formations, sheets O-56 (Magadan); P-56,57 (Seymchan)	1:1,000,000	Korolkov (1992)
	Map of pre-Quaternary formations, sheet P-58,59 (Kamenskoe)	1:1,000,000	Kovaleva and others (1986)
	Map of pre-Quaternary formations, sheet O-57,(58) (Palano)	1:1,000,000	Markovskiy and others (1989)
	Map of pre-Quaternary formations, sheet Q-56,57 (Srednekolymsk)	1:1,000,000	Shul'gina and others (1990)
	Map of pre-Quaternary formations, sheet Q-60,1 (Anadyr')	1:1,000,000	Surmiloa and others (2001)
	Map of pre-Quaternary formations, sheet Q-54,55 (Khonuu)	1:1,000,000	Surmilova and others (1986)
	Map of pre-Quaternary formations, sheet Q-58,59 (Markovo)	1:1,000,000	Malyshev (1999)
	Map of pre-Quaternary formations, sheet Q-2 (Uelen)	1:1,000,000	Zhukovym (1959)
	Map of pre-Quaternary formations, sheet P-54 (Oymyakon)	1:1,000,000	Domokhotovym (1962)
	Map of pre-Quaternary formations, sheet P-55 (Kolyma River)	1:1,000,000	Lariym (1962)
	Map of pre-Quaternary formations, sheet O-50,51 (Aldan)	1:1,000,000	Lagzdina and others (1978)
	Map of pre-Quaternary formations, sheet O-49,50 (Bodaibo)	1:1,000,000	Konnikov and others (1984)
	Map of pre-Quaternary formations, sheet N-49,50 (Chita)	1:1,000,000	Efimov and others (1990)
	Map of pre-Quaternary formations, sheet N-47,48 (Irkutsk)	1:1,000,000	Dodin and others (1986)
	Map of pre-Quaternary formations, sheet M-53,54,55 (Khabarovsk)	1:1,000,000	Bezverhny and others (1993)
	Map of pre-Quaternary formations, sheet L-53,54 (Kavalerovo)	1:1,000,000	Sokolov and others (1993)
	Map of pre-Quaternary formations, sheet L-52,53 (Pogranichnyy)	1:1,000,000	Sokolovym and others (1976)
	Map of pre-Quaternary formations, sheet K-52,53 (Vladivostok)	1:1,000,000	Bykovskaya and others (1991)
	Geological map of the Altai-Sayan folded area	1:1,500,000	Seamen (1995)
	Geological map of Russia and CIS countries	1:2,500,000	Petrov and Streinikov (2008)
	Geodynamic map of the USSR and adjacent seas	1:2,500,000	Zonenshain and others (1988)
	Mineragenetic map of Russian Federation and adjacent states	1:2,500,000	Rodnov and others (2001)
	Geological map of the People's Republic of China	1:2,500,000	China Geological Survey (2004a)
	Tectonic map of China and adjacent regions	1:5,000,000	Ren (1999)
	Tectonic map of Northeast Asia	1:5,000,000	Tilman and others (1992)
	Metallogenic map of Kamchatka, Sakhalin and Kuril Islands	1:1,500,000	Rotman (1982)
	Tectonic map of the Central Asian - Pacific Belt junction area	1:1,500,000	Karsakov and Chunjing (2001)
	Tectonic map of the Russian Far East	~1:5,000,000	Khanchuk and others (2006)
	Tectonic map of Central Asia and adjacent areas	1:2,500,000	Petrov and others (2007)
	Geological map of Central Asia and adjacent areas	1:2,500,000	Li and others (2004)
	Tectonic map of Asia	1:8,000,000	Research Institute of Geology (1982)

Table 1. Principal sources of information used in the assessment of undiscovered porphyry copper deposits in magmatic arcs and belts of northeast Asia.—Continued

[n.a., not applicable; GIS, geographic information system; CIS, Commonwealth of Independent States; ~, approximate]

Theme	Name or Title	Scale	Citation
Mineral occurrences and metallogeny	Porphyry copper deposits of the world	n.a.	Singer and others (2008)
	Large mineral deposits of Siberia	n.a.	Seltmann and others (2010)
	Natural resources GIS of Russia	n.a.	GlavNIVC (Head Research Information Computer Center of the Russian Ministry of Natural Resources) (1998)
	World minerals geosciencedatabase	n.a.	Kirkham and Dunne (2000)
	Super deposits (Largest mineral deposits of the world database)	n.a.	Volkov and others (1999 [2006])
	Porphyry deposits	n.a.	Andrey Chitalin, written comm. (2009)
	Mineral Resources Data System (MRDS)	n.a.	U.S. Geological Survey (2005)
	Terrane, mineral deposit, and metallogenic belt maps of the Russian Far East, Alaska, and the Canadian Cordillera	n.a.	Nokleberg and others (1998)
	Mineral resources, metallogenesis, and tectonics of Northeast Asia	n.a.	Nokleberg and others (1999)
	Significant metalliferous and selected non-metalliferous lode deposits, and selected placer districts of Northeast Asia	n.a.	Nokleberg and others (2003)
	Geodynamic, tectonic, metallogenic, mineral deposit, and geophysical maps and associated descriptive data for Northeast Asia	n.a.	Nokleberg and others (2006)
	Northeast Asia metallogenic belts	1:15,000,000	Rodionov and others (2004)
	Metallogenic belts and terranes of the Russian Far East	1:10,000,000	Nokleberg and others (2005b)
	Major metallogenic belts	1:15,000,000	Nokleberg and others (2007)
	Mineragenetic map of Russian Federation and adjacent states	n.a.	Rodnov and others (2001)
	Non-ferrous metal deposits of CIS countries and Mongolia	n.a.	Metal Mining Agency of Japan (1997)
	Mineral deposit data of mineral resources map of East Asia	1:3,000,000	Kamitani and others (2007)
	Mineral resources map of Asia	1:10,000,000	Kamitani and Naito (1998)
Geophysical	EMAG2- Earth Magnetic Anomaly Grid	2 arc-minute resolution	National Geophysical Data Center (2009)
	Magnetic anomaly data in the Former Soviet Union	1:2,500,000	Racey and others (1996)
	Magnetic anomaly map of the People's Republic of China and its adjacent waters	1:5,000,000	China Geological Survey (2004b)

Similarly, reliable data and descriptions for prospects and occurrences are difficult to find and verify. In the Russian- and Chinese-language literature (and often in the Russian- and Chinese-originated English-language literature), geographic coordinate locations for deposits and prospects are not typically provided, and when they are, often prove to be inaccurate, sometimes by hundreds of kilometers. When the locations of deposits and prospects or other metallogenic features are shown on page-size maps, geographic coordinates commonly are not provided.

In some regions, prospects under investigation by mineral exploration companies, as well as by the various government-owned provincial geologic bureaus with no public presence, are not included on publically available maps or tabular compilations. As such, there are likely many more prospects than identified in this assessment.

Comprehensive deposit descriptions are sparse, and few deposits and prospects have been dated with isotopic methods. Polymetallic vein, mantos, or massive copper-rich forms of mineralization are commonly classified as porphyry-related, or sometimes referred to as porphyry-style, primarily because they are large and can be open-pit mined, not because they have geologic characteristics that correspond to porphyry copper mineral deposit models.

Furthermore, the reporting of mineral resources is typically scant and inconsistent, or contained metal values and average grades are not well defined. The difficulty of correlating the Soviet classification system for quantifying mineral resources with other international classification systems, such as the Committee for Mineral Reserves International Reporting Standards (CRIRSCO), presents challenges for the characterization of data for porphyry copper deposits and prospects (for more detailed discussions, see Diatchkov, 1994; Jakubiak and Smakowski, 1994; Kotlyar, 1996; Henley, 2004; Weatherstone, 2008; and Sutphin and others, 2011).

Geologic Maps

Geologic maps ranging in scale from 1:500,000 to 1:8,000,000 were used for tract delineation during the assessment (table 1). For Russia, the assessment primarily relied on the published 1:2,500,000 scale geologic map of Russia and surrounding Commonwealth of Independent States (CIS) countries, compiled by Petrov and Streinikov (2008), distributed through A.P. Karpinsky Russian Geological Research Institute (VSEGEI), Ministry of Natural Resources and Ecology of the Russian Federation. The compilation is based on 1:1,000,000 scale maps published mainly in the mid-1970s through mid-2000s, as well as some dating back to the late 1950s and early 1960s (see table 1 for references of 1:1,000,000 scale maps). This geologic map shows at least 62 different plutonic and volcanic map units, mainly composed of multiple lithologies, and 10 categories of acid, basic, intermediate, mixed, and ultrabasic volcanogenic formations. Visual inspection of the linework between the 1:2,500,000 and the various 1:1,000,000 maps included in the compilation indicates that the smaller scale maps closely match the larger scale map in many areas, and in some instances they are the identical. According to our Russian collaborators, the descriptive information and attributes for the 1:2,500,000 scale map have been updated and enhanced compared to the 1:1,000,000 source maps, particularly with respect to map unit age designations. Therefore, the assessment team's consensus was that the 1:2,500,000 scale map represented information that was compatible with the 1:1,000,000 scale maps. The challenge that this map posed for assessment work, however, was that approximately 70 percent of the plutonic and volcanic map units have undifferentiated igneous lithology descriptions, consisting of three to five compositions, which in many cases include mixtures of permissive and nonpermissive units. Larger-scale maps were consulted for some areas (see table 1).

For the small region assessed in northeastern China (see fig. 1), the team used geologic maps that were published as part of a collection of Geologic Memoirs by the Chinese Ministry of Geology and Mineral Resources from 1984 through 1993. 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 isotopic age data gathered in the 1990s.

The digital geologic maps used for the assessment do not always reflect the most recent isotopic age determinations or petrologic studies on the rocks in the tract (in many cases, ages of the igneous rocks are not accurately known). In addition, many of the small plutons that host porphyry copper deposits in the assessment region are too small to be depicted. In some instances, the locations of plutons were digitized from large-scale maps or detailed figures in journal articles.

Mineral Deposits and Prospects

A global database of porphyry copper deposits and prospects published by Singer and others (2008) was used as a starting point for this assessment, then supplemented with other global- and regional-scale mineral occurrence databases, including that of the Geological Survey of Canada (Kirkham and Dunne, 2000; Natural Resources Canada, 2010) and databases prepared by the Metal Mining Agency of Japan and the Geological Survey of Japan (Metal Mining Agency of Japan, 1997; Kamitani and Naito, 1998; Kamitani and others, 2007). In addition to the geologic literature, commercially available databases, technical reports, and company Web sites were consulted. 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, 2005). See table 1 for a full listing of data sources.

Sites were categorized as deposits or prospects on the basis of available publications. Deposits and prospects that could be further classified with some certainty as porphyry copper or porphyry copper-related are included in the database used in this assessment (appendix F). The deposit-type classification of some sites is ambiguous due to insufficient information. 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 generally were not included. Some skarns were included if it seemed likely that an associated porphyry system could be inferred.

Where possible, the locations of deposits and prospects were verified or revised using satellite or aerial imagery data served by Esri, Google Earth, or other online services (for example, open pits, headframes, trenching, drill pads, and related features). These verifications and revisions are noted in the deposits and prospects database (appendix F) and geographic information system (GIS) database (appendix G).

Other Data

Global and regional-scale aeromagnetic anomaly data covers most of the assessment area (see table 1). Magnetic anomaly data in the Former Soviet Union (Racey and others, 1996), the aeromagnetic map of China (China Geological Survey, 2004b), and the EMAG2 dataset (Maus and others, 2009) display primarily broad, relatively deep magnetic features that do not correlate well with mapped outcrops of permissive rocks. 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.

Geographic Features and Political Boundaries

The political boundaries used in this report are the 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.

Assessment Methods

The assessment of undiscovered porphyry copper deposits in northeast Asia was completed using the USGS three-part form of mineral resource assessment based on descriptive mineral deposit and tonnage-grade models (Singer, 1993, 2007a,b; Singer and Menzie, 2010). This form of mineral resource assessment provides internally consistent estimates of undiscovered resources that can be evaluated using tools for economic, environmental, and policy analysis. Assessments are based on analogy, that is, that undiscovered resources will be like those that have already been discovered. The three-part assessment involves (1) delineation of permissive tracts according to the types of deposits permitted by the geology, (2) estimation of the amount of metal in typical deposits by using grade and tonnage models, and (3) estimation of the number of undiscovered deposits of each type using a variety of methods (Singer, 2007a). Probabilistic estimates of numbers of undiscovered deposits for each permissive tract are combined with grade and tonnage models in a Monte Carlo simulation to estimate amounts of metal that could be contained in undiscovered deposits.

Permissive Tracts

A mineral resource assessment permissive tract is defined as a geographic area (a tract of land) which is determined to possess certain characteristics and attributes that permit the occurrence of a particular type of mineral deposit. Permissive boundaries are delineated such that the probability of undiscovered deposits of the type being assessed occurring outside the boundary are negligible (specifically, tracts are drawn such that the probability of a deposit occurring outside the boundary is less than 1 in 100,000 to 1,000,000) (Singer, 2007a).

Descriptive mineral deposit models provide criteria for delineating permissive tracts by highlighting geologic features associated with a given deposit type that are obtained readily from geologic maps, such as tectonic setting and host-rock lithology (Singer, 2007a; Singer and Berger, 2007). Permissive tracts outline geologic features that represent appropriate settings for the deposit type, such as subduction-related magmatic arcs for porphyry copper deposits. In addition, mineral occurrence databases are used to plot the spatial distribution of known deposits and prospects, which further serve to refine and constrain permissive tract boundaries. Similarly, local- and regional-scale structures (faults, sutures, and other tectonic boundaries), isopachs, geochemical anomalies, geophysical anomalies, and other relevant geoscientific datasets can be used to guide delineation of permissive tracts.

Permissive tract for porphyry copper deposits include volcanic and intrusive rocks of a specified age range and composition that are part of a magmatic arc or belt related to a convergent plate margin. The tract generally is bounded by the outline of the magmatic arc, as depicted on the scale of the maps available, and also should include known porphyry copper deposits and prospects of that age range. The tract also incorporates areas suspected to include similar geology that are covered by younger or structurally overlying materials that are less than 1 km thick.

Permissive Tract Delineation

A geology-based approach was used to delineate mineral resource assessment tracts permissive for the occurrence of porphyry copper deposits. Lithologic descriptions from regional-scale geologic maps and geologic literature were used to identify and categorize map units as permissive or nonpermissive. Overall, permissive rocks for porphyry copper mineralization include intermediate to felsic composition calc-alkaline and alkaline plutonic and volcanic rocks, while nonpermissive rocks include ultramafic and mafic assemblages (for example, ophiolitic sequences), or highly-evolved peraluminous granites. Excluded units include coeval mafic, ultramafic, and feldspathoid-rich rocks (foiditoids and foidolites; Le Maitre, 2002), units in very deeply eroded areas, and when possible, widespread areas of dominantly silicic volcanism and granitoids of suspected A- or S-type origin or strongly peraluminous composition, such as units labeled as two-mica granites, leucogranite, alaskite and leucocratic granites. Because of overly generalized map unit descriptions and (or) limited attribute descriptions of rock types or alteration, it was not possible to unequivocally discriminate or subdivide permissive from nonpermissive units. Many areas within tracts may not be permissive for the occurrence of porphyry copper because of metamorphism, deep erosion, and mafic submarine volcanism. Undifferentiated map units precluded more thorough differentiation of permissive and nonpermissive host rocks for porphyry copper deposits; larger-scale geologic maps would likely permit delineation of a smaller, more restricted tract. Overall, the team chose to err on the side of inclusion.

Permissive map units were grouped into time slices to define magmatic arcs or belts of a given age, or related to specific orogenic events associated with porphyry copper formation. The resulting groups of permissive map units form the geologic framework of the tract. Appendixes A–E describe the map units used to define individual tracts. The framework permissive map units were then used to delineate preliminary tracts by applying a 10-km buffer zone around intrusive units and a 2-km buffer zone around volcanic units. The buffer effectively expands the permissive units to include all porphyry copper deposits and significant prospects, as well as unexposed permissive rocks that could host undiscovered porphyry copper mineralization proximal to mapped permissive units. The buffers allow for possible downward expansion of intrusions below their surface expressions (subsurface satellite cupolas of intrusions and unmapped parts of plutons), and for extensions of intrusive and volcanic units beneath overlapping cover materials (mineral occurrences that are covered by younger materials, such as basalt flows, glacial till, colluvium, alluvium, or basin-fill sediments less than 1 km thick).

The rationale for buffering, and in particular for choosing 10-km and 2-km buffers, is derived from previous assessment experience (listed below in no particular order):

- Uncertainty related to the true, on-the-ground location of the mapped igneous rock contacts, as represented on geologic maps compiled from a number of scales from a number of sources.
- Intrusion contacts commonly slope outwards, beneath surrounding cover, and porphyry copper deposits, which can form peripherally to intrusive bodies, can have alteration areas as extensive as 10 km (Singer and others, 2008).
- Bodies of permissive volcanic rocks can have relatively thin edges, which might be discontinuous, covered, or otherwise not mapped at the scale of the source geologic maps used for the assessment.
- Proximity analysis of volcanic rock-hosted epithermal gold and silver deposits in Nevada indicate that most significant intrusion-related occurrences lie within 10 km of a plutonic body, as mapped at 1:500,000 scale (for additional details, see Mihalasky, 2001, p. 75–76).
- Ten kilometers is a subjective, expert-based estimate representing the nominal extent of a mining lease, which may or may not include peripheral backyard claims, prospects, or other exploration areas.
- A radius of 10 km around a pluton is a fair approximation for the hypothetical extent of (or at least includes) a potentially mineralizing system (that is, the extent of district or local-scale hydrothermal circulation; see Nesbitt and Muehlenbachs, 1989; Sillitoe and Bonham, 1990).
- Distal signatures of porphyry copper deposits, such as dispersion of pathfinder elements and thermal effects, sometimes extend 10 km or more away from the center of mineralization along structures (John and others, 2010).
- A radius of 2 km around volcanic map units (as opposed to 10 km around plutonic map units) represents an expert-based judgment that intrusive bodies associated with these map units are likely to be much smaller and limited in extent (Hammarstrom and others, 2010).
- Possible lateral offset of the ore zone away from the surface projection of the causative intrusion, caused by hydraulic gradients at shallow depths around a volcanic edifice, as exemplified by the Lepanto high sulfidation epithermal Cu-Au ore body in the Mankayan mineral district of northern Luzon, Philippines, which is laterally offset approximately 5 km from the associated Far Southeast porphyry Cu-Au deposit (see Hedenquist, 2010; Chang and others, 2011).
- Accepted precedent for the use of buffers around igneous map units to delineate permissive tracts in previous USGS mineral resource assessments, including Singer (1996) and Wallace and others (2004).

Although buffers are not always appropriate—10 km may be an overstatement with regard to small igneous bodies or an understatement for extensive, long-lived bodies—they are considered reasonable for ensuring that permissive areas of interest within the tectonic environment being assessed are included (for more detailed discussion, see Wallace and others, 2004, p. 105, 125–126, 131).

Preliminary draft tracts, termed prototracts, were produced by applying a polygon aggregation and smoothing process to the buffered permissive geologic map units and any other permissive features (such as geochemical or geophysical anomalies). The processing approximates manual delineation of the tract, but is rapid and reproducible. The processing procedure consists of four primary steps:

1. Unioning of all permissive geologic map unit buffers and other polygon features to form the framework of the tract.
2. Aggregation of unioned polygons using an aggregation distance of 20 km and a minimum hole size of 2,000 km^2.
3. Simplifying of the aggregated polygons using a bend-simplify algorithm with a simplification tolerance of 5 km.
4. Line-smoothing of the simplified polygons using a polynomial approximation with exponential kernel (PAEK) algorithm with a tolerance of 20 km.

The parameter settings were empirically determined by delineation trials where computer-generated prototracts were compared to manually delineated tracts. Because of necking, thinning, and contraction of the polygons related to geospatial processing, the prototracts were manually cleaned (for example, polygon necks removed), re-buffered to 2 km, and unioned with all permissive polygon features to ensure that original permissive boundaries were honored. Prototracts were further revised by the following:

- Clipping prototract polygon boundaries using terrane-bounding structures if appropriate (such as for tracts in pre-accretionary terranes).
- Removal of younger nonpermissive intrusive rocks by applying a 250-meter buffer to the polygons representing these intrusions and performing an erase overlay operation.

Additional manual refinements produced the final permissive tracts delineated in this assessment. All operations were carried out in ArcGIS 9.X using a combination of the standard tools available in Arc Toolbox.

Although the tracts are delineated so as to include all areas considered to have potential for undiscovered porphyry copper deposits, the following caveats should be noted. The tracts were drawn on the basis of geologic maps at scales no larger than 1:1,000,000, and small intrusions, such as dikes, are not represented. Similarly, areas of hydrothermally altered rocks are not indicated on most geologic maps. Some important deposits have been discovered in areas where mineralized rocks are covered by basalt flows or unconsolidated surficial materials. These cover materials may be opaque to most currently available (and affordable) geophysical exploration methods, even where cover material is much less than 1 km thick.

Estimating Numbers of Undiscovered Deposits

Numbers of undiscovered deposits within each permissive tract were estimated at multiple quantiles (intervals that subdivide a frequency into equal groups) by an assessment team using a variety of strategies, including knowledge of permissive tract geology, porphyry copper geologic settings, deposit occurrence density models from around the world, or counting and assigning probabilities to geologic anomalies indicative of porphyry copper mineralization (Singer, 2007b). Estimates of the number of undiscovered deposits explicitly represent the subjective probability (at a given level of confidence, or degree of belief) that some fixed, but unknown, number of undiscovered deposits exists within the delineated permissive tract (Singer, 1993).

The thoroughness of exploration in a region, the repetition of examination by different exploration companies or other concerns, the level of detail (regional- or local-scale), and the variety of exploration techniques used all provided additional insight for making estimates of undiscovered deposits. The rationales for individual tract estimates are discussed in the appendixes.

The assessment team evaluated the available data and made individual, subjective, initially blind estimates of the numbers of undiscovered porphyry copper deposits. Estimators were asked for the smallest number of deposits consistent with the porphyry copper model that could be present in a given tract at three specified quantiles, represented by three levels of certainty: 90 percent, 50 percent, and 10 percent. For example, on the basis of available data, a team member might estimate that there is a 90-percent chance of 1 or more; a 50-percent chance of 5 or more; and a 10-percent chance of 10 or more undiscovered deposits within a permissive tract.

After the first blind estimates were made, they were shared and differences between individual estimates were discussed and evaluated before a single team estimate was agreed on for each tract. The estimates are converted to a mean number of deposits and standard deviation based on an algorithm developed by Singer and Menzie (2005). The algorithm can be described by the following general equations to calculate an expected (mean) number of deposits (λ) and a standard deviation (s_x) based on estimates of numbers of undiscovered deposits predicted at different quantile levels[6] (N_{90} = 90 percent level, N_{50} = 50 percent level, and so on):

$$\lambda = 0.233N_{90} + 0.4N_{50} + 0.225N_{10} + 0.045N_{05} + 0.04N_{01} \quad (1)$$

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

where N_z is the estimated number of deposits associated with the Zth probability level, expressed in terms of percent.

These equations were programmed in a simple spreadsheet to allow the team to quickly evaluate estimates. The spread in the number of deposits associated with the 90th percentile to the 10th percentile or 1 percentile reflects uncertainty; large differences in number suggest great uncertainty. The expected number of deposits for the permissive tract, or the numbers associated with a given probability level, reflect favorability.

Another useful parameter for reporting uncertainty associated with an estimate is the coefficient of variation (C_v), defined as follows:

$$C_v = s_x \div \lambda \quad (3)$$

The coefficient of variation is commonly reported as percent relative variation:

$$\%C_v = 100 \times C_v \quad (4)$$

Team estimates reflect both the uncertainty in what potentially exists and the favorability of the tract (Singer, 1993). In poorly explored areas with little to no data about mineral occurrences, there was less information to constrain estimates of undiscovered numbers of deposits. In these cases, the wide spread in estimates among the various team members reflect their uncertainty.

The calculated mean expected number of deposits and measured tract areas were compared with numbers of deposits predicted by deposit density models developed for control areas from around the world (Singer and Menzie, 2005; Singer and others, 2007b).

[6]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}.

Undiscovered Resource Endowment

Estimates of numbers of undiscovered deposits for each permissive tract are combined with the selected grade and tonnage models in a Monte Carlo simulation using the EMINERS computer program (Duval, 2012; Bawiec and Spanski, 2012). EMINERS is based on the original Mark3 computer program that was developed to provide a probabilistic estimate of amounts of resources that could be contained in undiscovered deposits (Root and others, 1992). Probability distributions based on known grades and tonnages and the estimates of numbers of undiscovered deposits at different quantiles are used to predict the metal endowment. Results of 4,999 Monte Carlo simulations are sorted and ranked, and estimates of contained metal are reported at selected quantile levels and as a mean for each commodity (copper, molybdenum, gold, and silver) and for the total amount of mineralized rock.

The EMINERS simulation results are expressed as probability distributions of quantities of contained metals and ore tonnages for each permissive tract. The contained metals and ore tonnages are reported at selected quantile levels (0.95, 0.9, 0.5, 0.1, and 0.05 confidence levels), along with the mean expected amount of metal, the probability of the mean, and the probability of no metal, including associated standard deviations and variances. The amount of metal reported at each quantile represents the least amount of metal expected. The quantiles are linked to each tract simulation and, therefore, should not be added. Mean estimates, however, can be added to obtain total amounts of metal and mineralized rock in undiscovered deposits.

Porphyry Copper Deposits and Prospects in Northeast Asia

Russia possesses a large variety of metallic and industrial mineral commodities and types of mineral deposits (for review, see Nokleberg and others 2005a,b). According to Petrov and others (2009), Russia is host to 139 copper deposits of various deposit-types and sizes. In contrast to the rest of the world, where most of the copper production is derived from large, open-pit, relatively low-grade porphyry copper deposits, copper in Russia is produced primarily from Cu-Ni-PGE magmatic, volcanogenic massive sulfide, and sediment-hosted copper deposit types (Nokleberg and others, 2005a; Petrov and others, 2009). The majority of the copper reserves are in Cu-Ni-PGE magmatic sulfide ores at Norilsk (43.4 percent), followed by volcanogenic massive sulfide deposits (27.9 percent), sediment-hosted deposits (23.8 percent), and other deposit types (about 5 percent) (Levine and Wallace, 2004; Petrov and others, 2009).

In the Russian Far East and along the northwest Pacific Ocean margin, Petrov and others (2009) showed that most of the copper for this region occurs in the form of prognostic resources (P1+P2), and that, including P3 resources, most of the copper may be contained in potentially large copper-molybdenum porphyry-type deposits. Copper-bearing deposits are scattered throughout the region, but few have been positively identified as porphyry-copper or porphyry Cu-Mo deposits. Figure 8 shows the distribution of known porphyry copper deposits and prospects across the assessment region (see table 2 for a listing of deposits, and the individual appendixes for a listing of the prospects in each tract). Numerous prospects are present, but relative to the region's size and extent, the density of known copper porphyry deposits appears to be low, particularly when compared to other Pacific margin regions such as the cordillera of North, Central, and South American (see U.S. Geological Survey National Mineral Resource Assessment Team, 2000, 1998; Cunningham and others, 2008; Hammarstrom and others, 2010; John and others, 2010, and Mihalasky and others, 2011). None of the identified porphyry copper deposits or prospects are being mined, although there are many aggressive drilling programs and some pre-feasibility-level studies underway (for example, the Peschanka deposit; Chitalin, 2009). According to Volkov and others (2006), under the economic conditions prevailing at the time, the development of most of these porphyry systems remained uncertain.

Grade and Ore Tonnage of Known Porphyry Copper Deposits in Northeast Asia

Only two known porphyry copper deposits are present in northeast Asia: Peschanka and Lora (fig. 8, table 2).

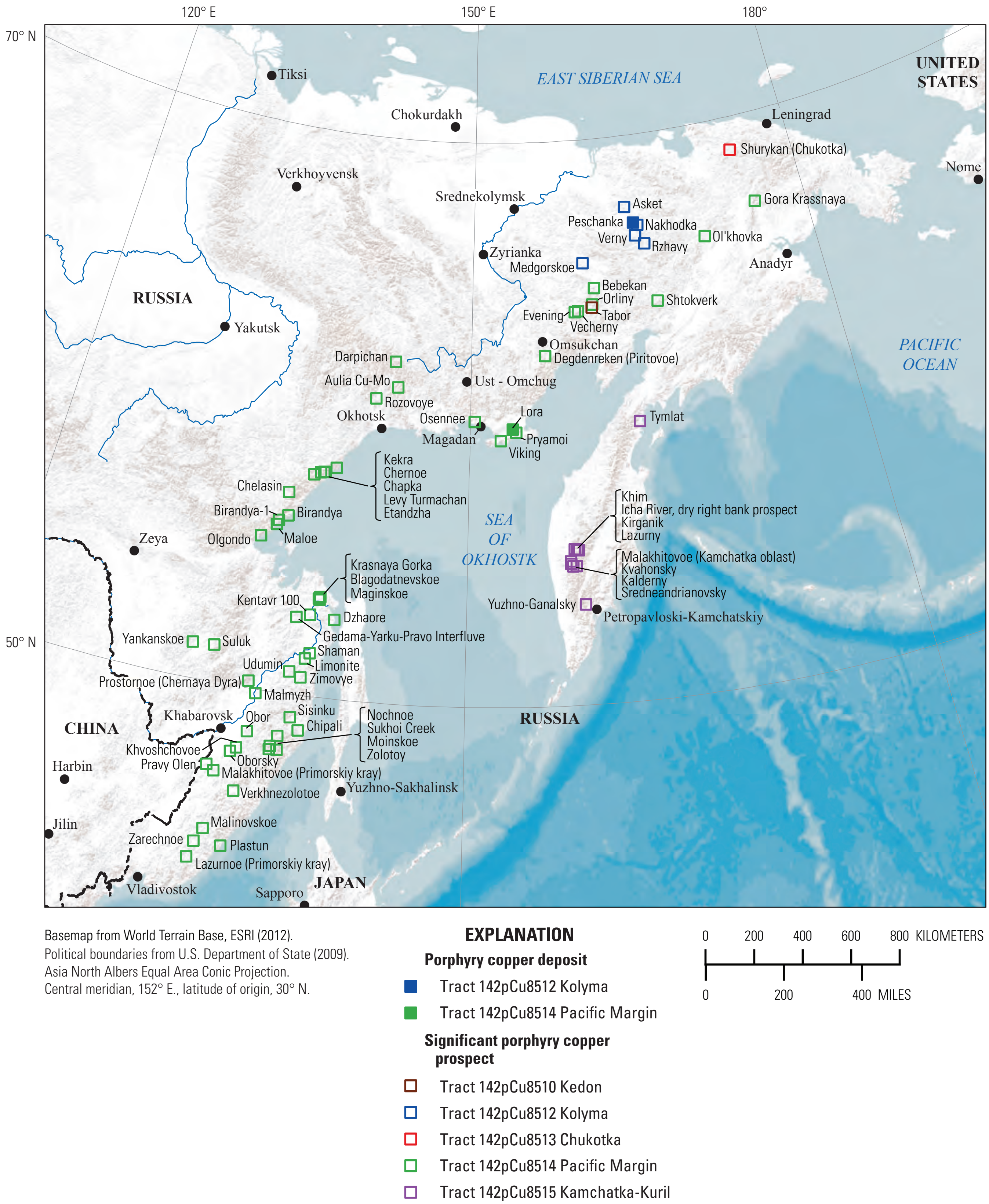
Peschanka is a world-class porphyry deposit comparable to Oyu Tolgoi in Mongolia and Pebble or Bingham in the United States. The reserve at Peschanka is 1,517 Mt at a copper grade of 0.52 percent and a gold grade of 0.3 g/t, calculated at a cutoff grade of 0.4 percent copper equivalent. This yields a contained copper resource of nearly 8 Mt. The molybdenum grade is relatively low, at 0.009 percent (Chitalin and others, 2011).

The Lora deposit is a medium- to small-size deposit compared to deposits world-wide. The resource at Lora is 178 Mt, with a copper grade of 0.5 percent, molybdenum of 0.025 percent, and silver of 2.1 g/t (there is no information about gold), yielding a contained copper resource of almost 0.9 Mt.

Although sparse, the available data from the Peschanka and Lora deposits suggest that the overall size distribution of the known porphyry copper deposits in northeast Asia is comparable (fig. 9) to that in the global general model of Singer and others (2008). Therefore, the general global grade and tonnage model was used for assessing all permissive tracts delineated in this study.

Age of Porphyry Copper Deposits and Prospects in Northeast Asia

The age of known porphyry copper deposits and prospects in the region of the Russian Far East and northwest Pacific Ocean margin ranges from the late Paleozoic through the Cenozoic. The distribution of isotopic and stratigraphically inferred age dates for 160 deposits and prospects is shown in figure 10 (also see appendix F). The distribution is dominated by Cretaceous and early



Basemap from World Terrain Base, ESRI (2012).
Political boundaries from U.S. Department of State (2009).
Asia North Albers Equal Area Conic Projection.
Central meridian, 152° E., latitude of origin, 30° N.

Figure 8. Porphyry copper deposits and significant prospects in northeast Asia.

Table 2. Summary of identified resources in porphyry copper deposits in the magmatic arcs and belts of northeast Asia.

[Ma, million years; Mt, million metric tons; Cu, copper; Mo, molybdenum; Au, gold; Ag, silver; t, metric ton; %, percent; g/t, grams per metric ton; n.d., no data; n.a., not applicable]

Tract	Tract name	Deposit name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Mo (t)	Contained Au (t)
142pCu8512	Kolyma	Peschanka	142	1,517	0.52	0.0092	0.3	1.4	7,900,000	139,600	460
142pCu8514	Pacific Margin	Lora	95.4	178	0.5	0.025	n.d.	2.1	890,000	44,500	n.d.
Totals	n.a.	n.a.	n.a.	1,695	n.a.	n.a.	n.a.	n.a.	8,790,000	184,100	460

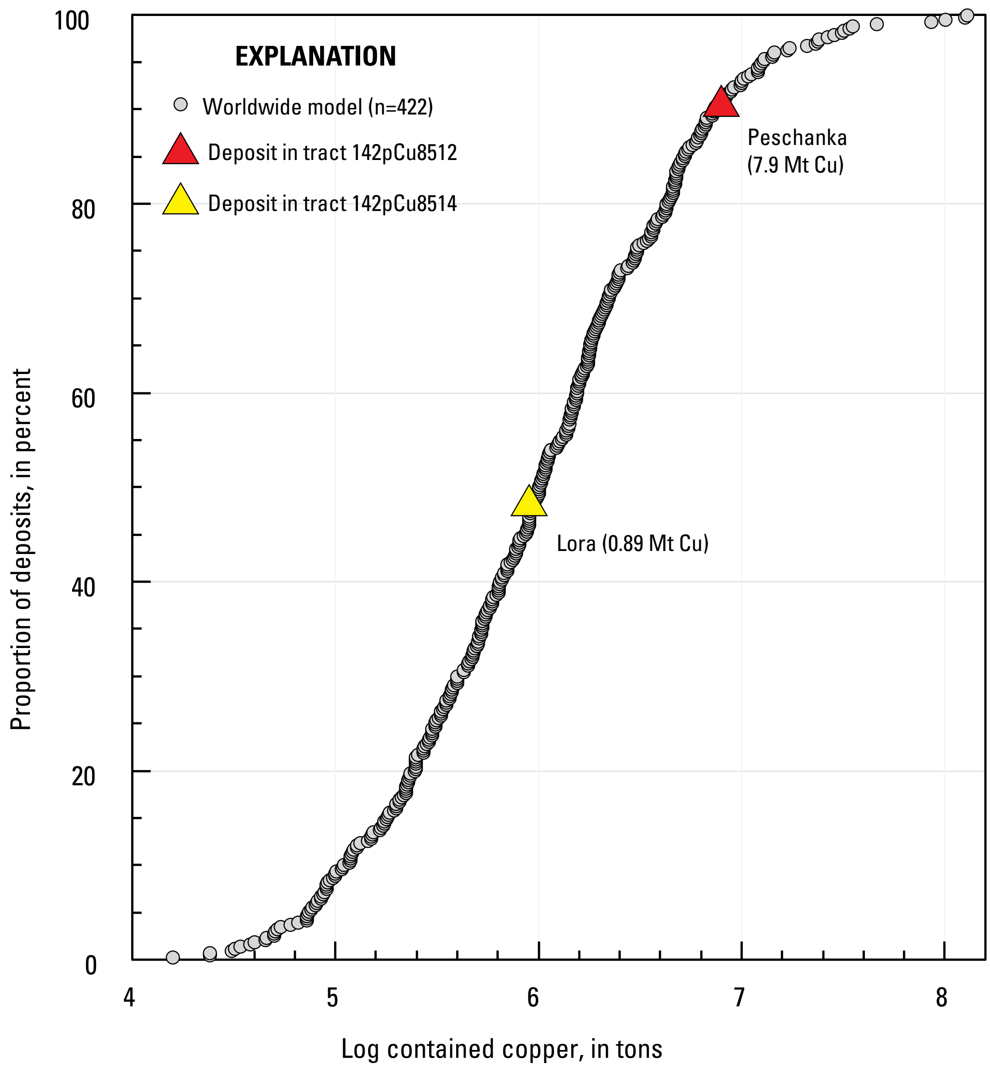


Figure 9. Cumulative frequency plot showing the contained copper of northeast Asia porphyry copper deposits compared to world-wide deposits from the Singer and others (2008) global general model. n, number of porphyrycopper deposits in the global model; Cu, copper; Mt, million metric tons.

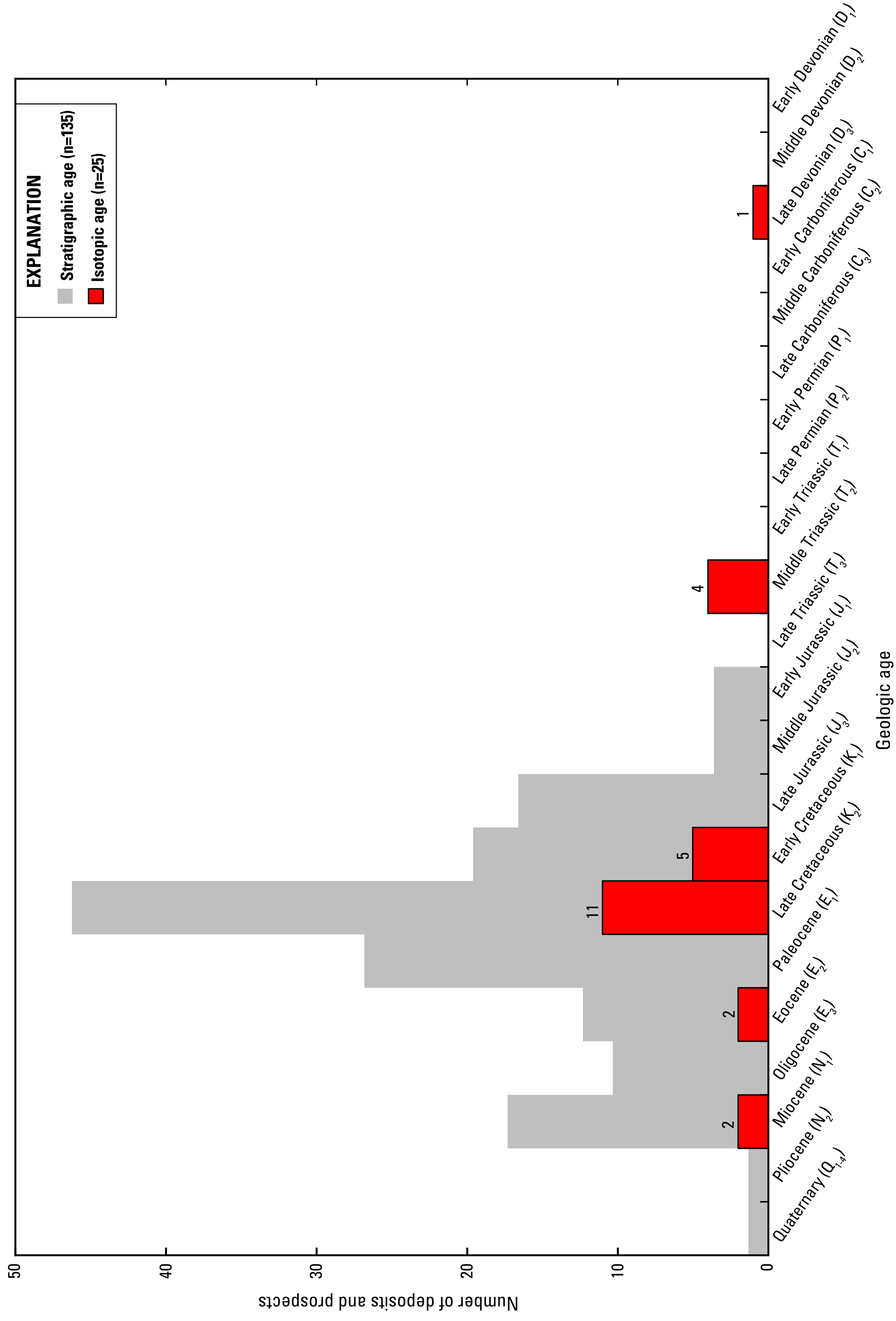


Figure 10. Age distribution of porphyry copper deposits and prospects in northeast Asia. Stratigraphic ages are from published sources or inferred from this assessment. The radioisotope systems used for 17 of the 25 isotopic age determinations are unknown; the rest are K-Ar, Rb-Sr, and U-Pb dates. Material dated (whole-rock or mineral) is unspecified. See appendixes F and H for additional age information and sources.

Tertiary isotopic age dates associated with deposits and prospects occurring along the present-day and paleo-Pacific Ocean margin of Russia and China, and on the Kamchatka Peninsula. Although the data are sparse, the age distribution peaks are consistent with porphyry copper and molybdenum deposit belts, metallogenic epochs, and magmatic pulses in the (1) Late Devonian to early Carboniferous, (2) Middle Triassic to Jurassic, (3) Late Jurassic to Late Cretaceous, (4) Late Cretaceous to Paleogene, and (5) Neogene-Quaternary (see Zvezdov and others, 1993; Yakubchuk, 2002, 2009; Sato and others, 2004; Sotnikov and others, 2004; Goryachev and others, 2006; Volkov and others, 2006; and Akinin and Miller, 2011).

Other Deposit Types

Gold deposits are extensively distributed throughout the study area. Lead, tin, tungsten, and silver deposits occur in the northern (Russian Far East) part of the region, and tin, tungsten, molybdenum, iron, and PGE deposits occur in the southeastern (Sikhote-Alin) part of the region (see Nokleberg and others, 2005a, maps on figure 7).

Permissive Tracts

Five mineral resource assessment tracts permissive for porphyry copper deposits were delineated (table 3, fig. 11). The age range of the tracts and the resources in known porphyry copper deposits are presented in figure 12 and table 3. Brief summaries of the tracts are included here, but detailed tract descriptions and rationales for delineation and estimates for numbers of undiscovered deposits are given in appendixes A–E. Descriptions of deposits and prospects are in appendix F. Tract boundaries and the deposits and prospects database are included as Esri ArcGIS files in appendix G.

Kedon Tract

Located in northeastern Russia, the Kedon tract (142pCu8510), with an area of about 31,000 km^2 (representing approximately 1.5 percent of the total assessment tract area), is defined by a small arcuate belt of Middle Devonian through Early Carboniferous igneous rocks that were formed in a continental-arc setting along an offshore microcontinental terrane. Permissive rocks in this tract include mainly calc-alkaline, intermediate-composition plutonic and volcanic units, such as granodiorite, granite, quartz diorite, diorite, dacite and rhyolite. The tract includes one significant porphyry copper prospect (table 3; fig. 8). Because of metamorphism, deep erosion, and mafic submarine volcanism, this tract was not deemed particularly favorable for porphyry copper formation or preservation.

Kolyma Tract

Located in northeastern Russia, the Kolyma tract (142pCu8512), with an area of about 555,000 km^2 (representing approximately 26 percent of the total assessment tract area), is defined by a large arcuate region to the west and a roughly circular region to the east of Late Jurassic to Early Cretaceous igneous rocks formed in island-arc, continental-arc, and collisional magmatic settings that developed along the margins of a superterrane accreted to the Siberian craton. Permissive rocks in this tract include mainly calc-alkaline, intermediate-composition plutonic and volcanic units, such as granite and granodiorite (including porphyries), plagiogranite, diorite, quartz diorite porphyries, rhyolite and dacite. The tract includes one world-class porphyry copper deposit (Peschanka; see fig. 9), as well as five significant porphyry copper prospects and at least 19 other smaller prospects (table 3; fig. 8). Based upon the presence of the Peschanka deposit, as well as a number of significant prospects that form a deposit trend which includes Peschanka, the circular eastern part of the tract is considered to be highly favorable for porphyry copper deposit formation and preservation, significantly more so than the western part. Fewer prospects are known in the arcuate western part of the tract that represents the 1,100-km long, northwest-trending Late Jurassic Main Granite Belt of northeast Asia (fig. 5) that formed in a collisional setting.

Chukotka Tract

Located in northeastern Russia, the Chukotka tract (142pCu8513), with an area of about 210,000 km^2 (representing approximately 10 percent of the total assessment tract area), is defined by a semi-continuous linear belt of Early to Late Cretaceous igneous rocks formed in island-arc, continental-arc, and collisional magmatic settings developed along the margins of a microcontinent accreted to the superterrane previously accreted to the Siberian craton (see Kolyma tract above). Permissive rocks in this tract include mainly calc-alkaline, intermediate-composition plutonic and volcanic units, such as granite and granodiorite (including porphyries), quartz diorite, diorite, plagiogranite, tonalite, rhyolite and dacite. The tract includes one significant porphyry copper prospect, Shurykan (table 3, fig. 8). The regional metallogenic environment, dominated by Mo-, W-, Sn-, and polymetallic-vein and hot-spring Hg prospects and deposits, however, does not appear to be particularly favorable for porphyry copper mineralization.

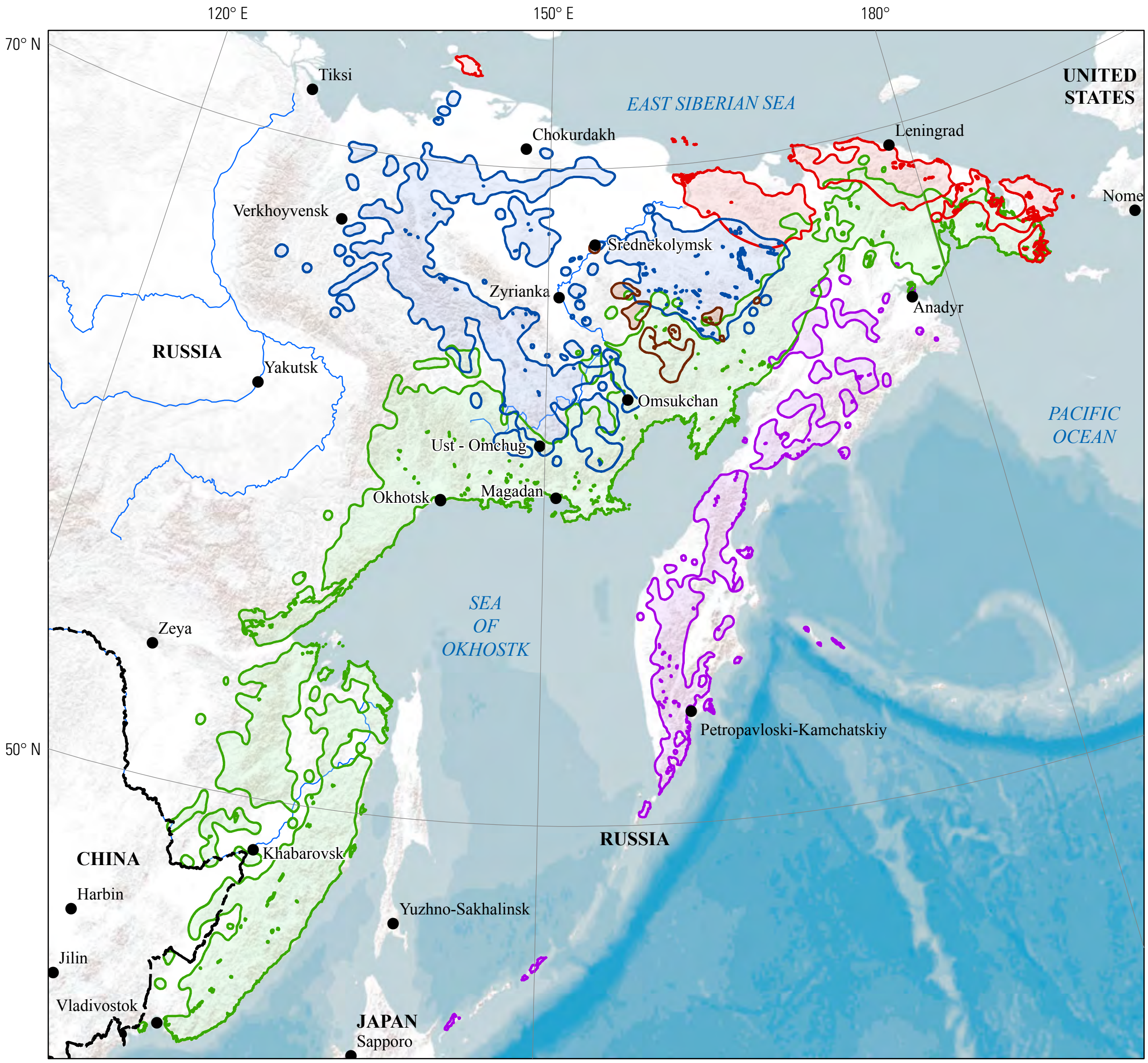
Pacific Margin Tract

Located along the margins of northeastern and southeastern Russia, the Pacific Margin tract (142pCu8514), with an area of about 1,140,000 km^2 (representing approximately 53.5 percent of the total assessment tract area), is defined by continuous narrow belt of Cretaceous through middle Tertiary igneous rocks in a series of continental- and island-arc complexes that were

Table 3. Permissive tracts for porphyry copper deposits in northeast Asia.

[km^2, square kilometers; n.a., not applicable]

Tract	Tract Name	Countries	Area (km^2)	Geologic feature assessed	Deposits	Significant prospects	Prospects	Total occurrences
142pCu8510	Kedon	Russia	30,720	Middle Devonian through early Carboniferous volcanic and intrusive rocks that compose a discontinuous continental margin arc formed along the Omolon microcontinent	0	1	0	1
142pCu8512	Kolyma	Russia	555,280	Late Jurassic to Early Cretaceous volcanic and intrusive rocks that compose island-arc, continental margin arc, and collisional magmatic belts accreted to and formed along the Kolyma-Omolon superterrane	1	5	19	25
142pCu8513	Chukotka	Russia	210,360	Early to Late Cretaceous volcanic and intrusive rocks that compose island-arc, continental-arc, and collisional magmatic belts formed along and accreted to the Arctic Alaska-Chukotka microcontinent	0	1	0	1
142pCu8514	Pacific Margin	Russia, China	1,138,430	Cretaceous through middle Tertiary volcanic and intrusive rocks that compose a series of continental- and island-arc systems formed along and accreted to the paleomargin of northeast Asia	1	53	50	104
142pCu8515	Kamchatka-Kuril	Russia	195,150	Latest Cretaceous through Quaternary volcanic and intrusive rocks that compose a series of continental- and island-arc systems formed along and accreted to the margin of northeast Asia	0	10	17	27
Totals	n.a.	n.a.	2,129,940	n.a.	2	70	86	158



Base map from World Terrain Base, Esri (2012).
Political boundaries from U.S. Department of State (2009).
Asia North Albers Equal Area Conic Projection.
Central meridian, 152° E., latitude of origin, 30° N.

EXPLANATION

Assessed porphyry copper tract

- 142pCu8510 Kedon
- 142pCu8512 Kolyma
- 142pCu8513 Chukotka
- 142pCu8514 Pacific Margin
- 142pCu8515 Kamchatka-Kuril

0 200 400 600 800 KILOMETERS

0 200 400 MILES

Figure 11. Map showing permissive tracts for porphyry copper deposits in northeast Asia.

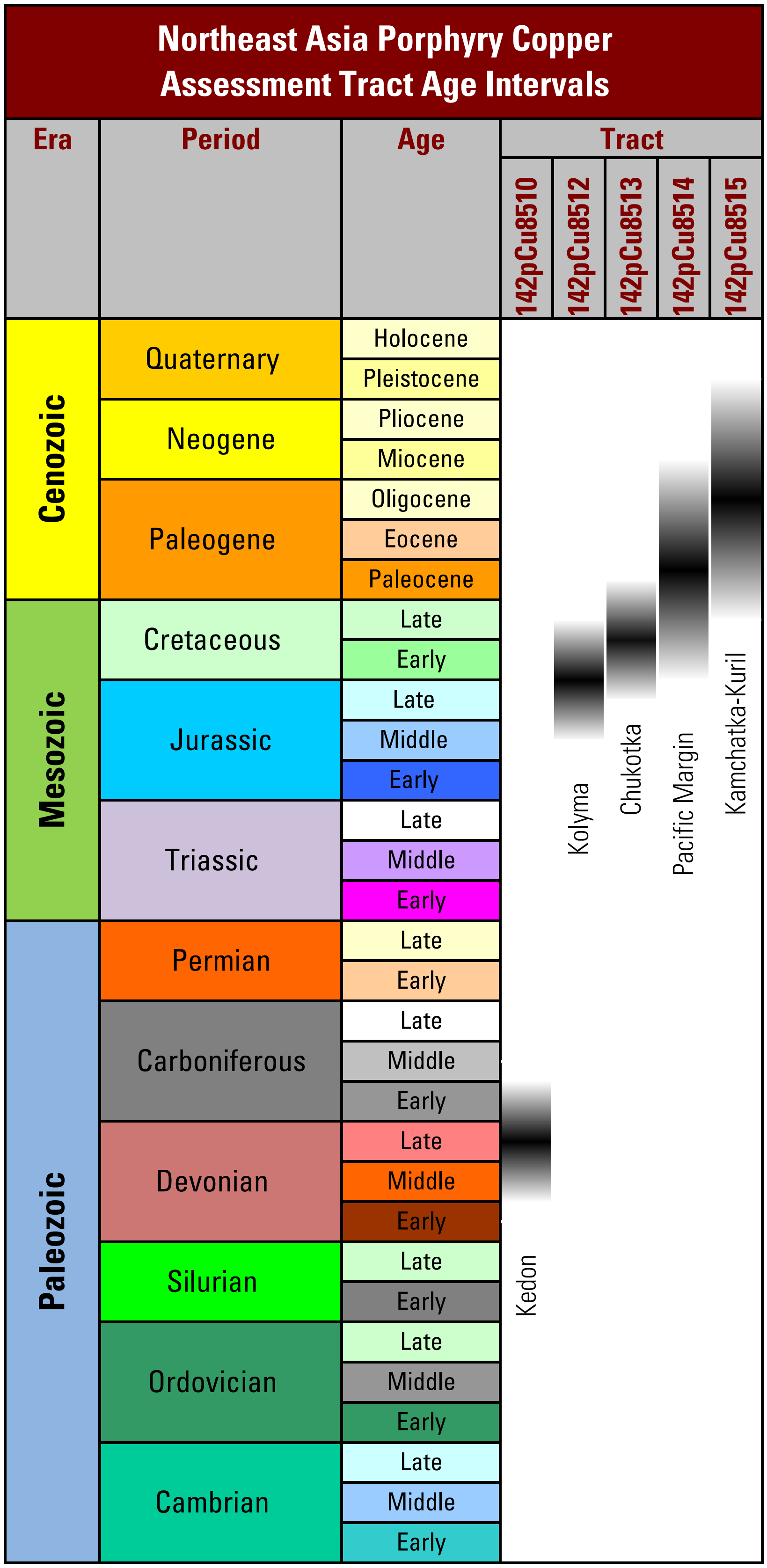


Figure 12. Geologic time scale showing the relative age ranges and temporal overlap among permissive tracts for porphyry copper deposits in the northeast Asia.

developed on and successively accreted to the paleomargin of northeast Asia in response to subduction of the ancestral Pacific Ocean plate. Permissive rocks in this tract include mainly calc-alkaline, intermediate-composition plutonic and volcanic units, such as granite and granodiorite (including porphyries), quartz diorite, diorite, plagiogranite, granosyenite, quartz monzonite, rhyolite, rhyodacite, and dacite. The tract includes one medium-sized porphyry copper deposit (Lora; see fig. 9), as well as 53 significant porphyry copper prospects, and at least 50 other smaller prospects (table 3; fig. 8). The tract as whole is comparable in tectonic setting, dimensions, and geologic age-range to the North American Cordillera of the United States and Canada. It includes a wide variety of magmatic systems and rock types that are permissive for the occurrence of porphyry copper deposits. The northern and southern Pacific Ocean margin extents of the tract are considered highly favorable for the formation and preservation of porphyry copper deposits, while the in-land southern part of the tract appears less favorable.

Kamchatka-Kuril Tract

Located in the Russian Far East, the Kamchatka-Kuril tract (142pCu8515), with an area of about 195,000 km^2 (representing approximately 9 percent of the total assessment tract area), is defined by semi-fragmented belt of latest Cretaceous through Quaternary igneous rocks formed in a series of continental- and island-arcs that were successively developed on and accreted to the outboard margin of northeast Asia in response to subduction of the ancestral and present-day Pacific Ocean plate. Permissive rocks in this tract include mainly calc-alkaline, intermediate-composition plutonic and volcanic units, such as diorite, granodiorite, quartz diorite, granite (including porphyries), andesite, dacite, and rhyolite. The tract includes 10 significant porphyry copper prospects, and at least 17 other smaller prospects (table 3; fig. 8). With significant prospects present within the central region of the tract, and thick recent volcanic cover present in the southern part of the tract, the central part of the tract is considered more favorable for copper porphyry deposit formation and exposure than the northern and southern parts.

Assignment of Deposits and Prospects to Permissive Tracts

Assignment of each deposit and prospect to a mineral resource assessment tract was based on age information available in databases used for this assessment (see table 1), and further evaluated and constrained by mineralization and host-rock age information compiled from recent geologic literature. Of the 158 deposits and prospects compiled for this assessment, only 25 had isotopic age determinations (see appendix F and fig. 10). Deposits and prospects lacking isotopic age determinations were given a provisional tract assignment based on descriptions in the geologic literature and their proximity to geologic map units that could be associated with them. The tract assignment of some deposits and prospects remains ambiguous because of insufficient information.

Exploration History and Status

In many parts of the world, porphyry copper exploration has been cyclic in response to changing global economic trends and the evolution of local infrastructure. Some important factors affecting exploration cycles include level of risk, demand-and-supply related commodity price fluctuations, availability and application of new geoscience information and technologies, and government policies and regulations (see Nokleberg and others, 2005a). The dissolution of the Soviet Union in 1991, following political liberalization (glasnost/perestroika) and the reforms and policies introduced by Soviet General Secretary (and later President) Mikhail Gorbachev in the 1980s (1986), marked a major change in the nature of mineral exploration in Russia and other former Soviet republics.

During the 1990s and into the 2000s, Russia transitioned from a state-controlled, centrally planned economy to a more market-oriented economy. Before the introduction of Western free-market economic concepts, mineral exploration and development was driven by commodities required for the Soviet industrial base and, in the case of gold, for foreign currency exchange (Miller and others, 2002; Nokleberg and others, 2005a; Busch, 2010). Exploration and exploitation of minerals was not affected by commodity market supply and demand economics. As a result, mineral production was frequently subsidized by government-planned development programs (Miller and others, 2002), and deposits were commonly mined and developed in remote areas regardless of economic viability (Nokleberg and others, 2005a).

Mineral exploration and development in the Russian Far East predates the 20th century (Miller and others, 2002). Early accounts indicate that, by the 16th and 17th centuries, mineral exploration and mining in the Russian territory was already flourishing (Nalivkin, 1973) and systematic work was already being carried out during the time of Czar Peter the Great (1680s–1720s; see Mavor, 1925). When the Soviet Union emerged in 1922, following the Bolshevik Revolution (1917) and the Russian Civil War (1918–1923), very little of its vast territory had undergone detailed or systematic geologic exploration and research (Mavor, 1925; Nove, 1992), as indicated in figure 13*A*. The Russian Far East had received only cursory study in regions easily accessible, such as along major rivers and coastal areas. By the late 1930s, likely in response to the Soviet General Secretary Joseph Stalin's series of national "five-year" centralized economic plans (Nove, 1992), the purpose of which was to develop heavy industry and technology, much of the Russian northeast and some of the southeast had undergone some level of geologic scrutiny (fig. 13*B*). During this time and into the 1940s, a significant part of mineral prospecting was probably carried out by exiled geologists and labor camp prisoners, who discovered deposits of gold, tin, tungsten, and other mineral resources (Rubinstein and Barsky, 2002).

Regional-scale geologic mapping (1:500,000 to 1:200,000 scale) was carried out during the 1960s and

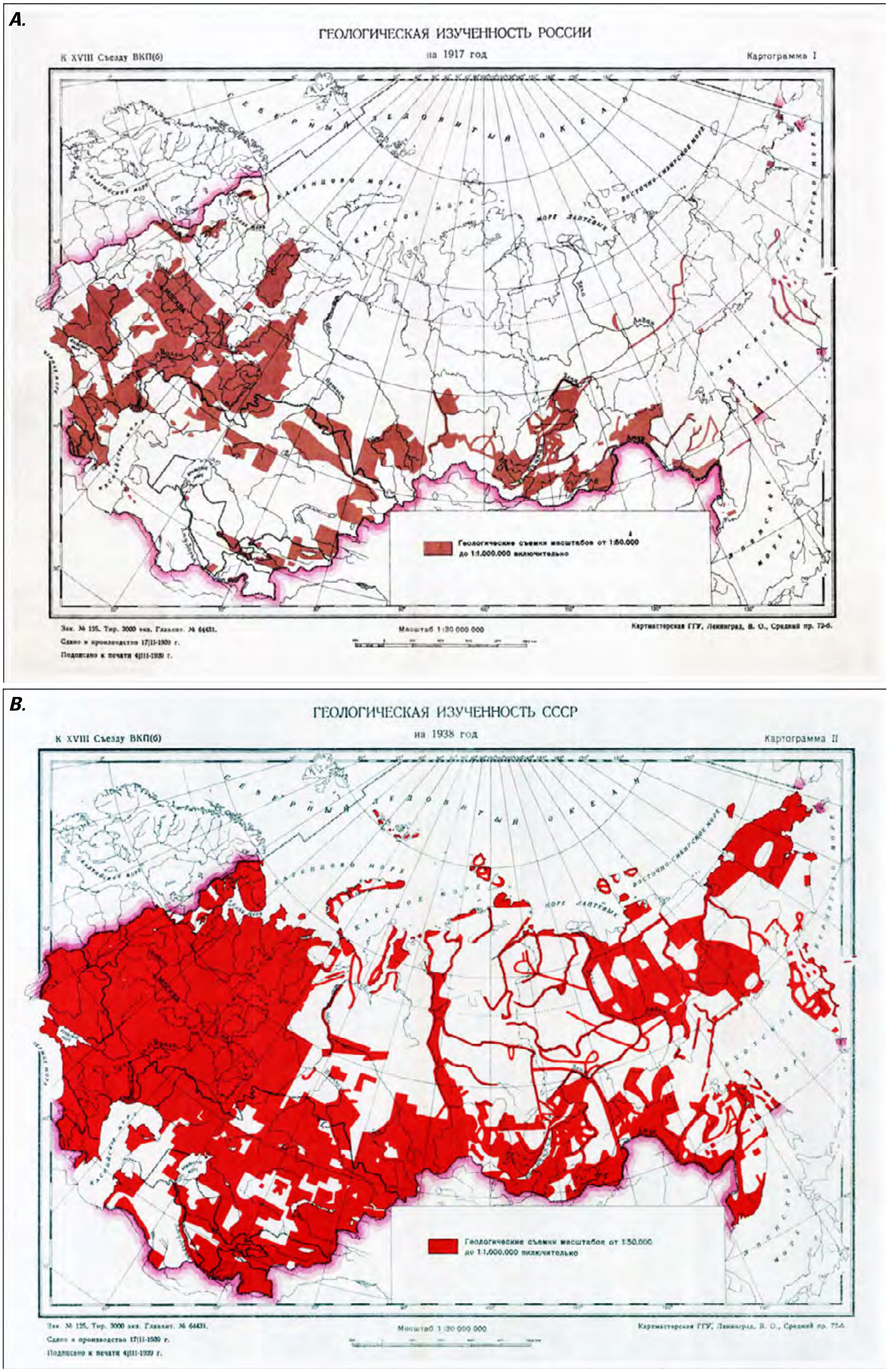


Figure 13. Historical maps showing regions of geologic mapping at scales of 1:50,000 to 1:1,000,000. *A*, Geologic Study of the Russia, 1917 (1:30,000,000 scale). *B*, Geologic Study of the USSR, 1938 (1:30,000,000 scale). Published by Kartmasterskaya Glavnoe Geologicheskoe Upravlenie, Leningrad, 1938. Obtained from S.R. Tikhomirova (written commun., 2011).

1970s, followed by more detailed local-scale mapping (1:50,000 to 1:25,000 scale) during the 1980s and continuing today (Kotlyar, 1996). Geochemical surveys commonly accompanied geologic exploration since the 1930s, including early copper surveys. Stream sediment and rock samples were routinely collected during the regional-scale surveys of the 1960s and 1970s. Reconnaissance regional-scale surveys discovered only subeconomic, low-grade deposits, such as molybdenum-copper deposits in central Kamchatka; many more exposed, economic mineral deposits were discovered during subsequent local-scale surveys (Kotlyar, 1996).

After the dissolution of the Soviet Union in 1991, geologic exploration dramatically decreased (Kotlyar, 1996). Nokleberg and others (2005a) noted that Russia, Belarus, and Ukraine had extensive exploration until their independence in the early 1990s (D.R. Wilburn, USGS, written commun., 2003; Wilburn, 2004). Since their independence, the countries of the former Soviet Union have been trying to attract foreign investment, but weak and unstable governments, economies, and metal markets have slowed these efforts (Nokleberg and others, 2005a). Exploration in Russia during the early 2000s demonstrated potential for the development of deposits of nonferrous, precious, and rare metals ores and industrial minerals, such as antimony, arsenic, barite, gold, lead, and zinc (Levine and Wallace, 2004). Since about 1998, the principal exploration targets in Russia have been gold, diamonds, and platinum group metals (Wilburn, 2005). Copper exploration activity in the Commonwealth of Independent States for the period 1995 through 2004 showed an increase until 2000, after which activity decreased slightly then stabilized through 2004 (Wilburn, 2005). During the middle and latter 2000s, the total budgets of companies doing mineral exploration in Russia was relatively steady, and as of 2011, Russia and other countries of the former Soviet Union were considered among the top destinations for nonferrous exploration based on world exploration trend reports prepared by the former Metals Economics Group for 2009 through 2012.[7] The Fraser Institute 2011/2012 Annual Survey of Mining Companies, however, indicates that Russia consistently ranks in the lower quarter for attractiveness for mining investment because of factors related to land, legal, and regulatory issues, infrastructure availability and reliability, political stability, taxation and trade barriers, geologic information quality and accessibility, and security (McMahon and Cervantes, 2012).

Russia today is an emerging free-market economy. Nokleberg and others (2005a) observed that, although few actual discoveries were made during the mid-1990s to mid-2000s, several significant areas of previously known mineralization were reevaluated in light of improved exploration concepts, state-of-the-art geologic and tectonic analysis, and refined mineral deposit models. Given reforms in the mining regulatory framework and the involvement of western exploration companies, new discoveries can be expected.

[7]Acquired by SNL Metals and Mining; current reports are available for download at http://go.snl.com/MEG-MS-FreeReport.html.

Summary of Assessment Results and Undiscovered Resources

Two of the permissive tracts (Kolyma and Pacific Margin) contain identified resources in the Peschanka and Lora deposits, respectively (see table 2). All of the tracts contain copper-bearing porphyry prospects that have undergone some level of examination, from grab-sampling to more thorough trenching and drilling, but for which only exploration-quality, incomplete, and unreliable grades (and in some cases tonnage) estimates are available. These partially explored prospects are not included as identified resources.

Probabilistic estimates of numbers of undiscovered deposits are summarized in table 4, along with statistics that describe mean expected numbers of undiscovered deposits, the standard deviation and coefficient of variation associated with the estimate, the number of known deposits, and the known and undiscovered deposit density calculated for each tract. The assessment predicts a mean expected total (N_{und}) of about 67 undiscovered porphyry copper deposits in the assessment region (see table 4), many more than the two deposits that have already been discovered (table 2; fig. 8). Mineral resource simulation results are summarized in table 5 and figure 14. The estimates of undiscovered resources in the table refer to metal potentially contained in undiscovered porphyry copper deposits.

Discussion of Assessment Results

The results of this assessment indicate that significant amounts of additional resources are likely to be present in undiscovered porphyry copper deposits in northeast Asia (table 5; fig. 14). However, a substantial part of these resources, if they are indeed present, may be inaccessible or uneconomic. Results of this assessment should be interpreted with due caution, as no economic filters have been applied to these results to evaluate whether the estimated undiscovered resources might be economic, and if so, under what conditions. For each permissive tract, identified resources are compared with mean and median estimates of undiscovered copper resources in figure 14.

The mean estimate of undiscovered copper resources in the assessment area (about 256,500,000 t) is nearly 30 times the amount of copper present in identified resources (about 8,800,000 t). Although this amount of undiscovered copper resources is large and perhaps overly optimistic, the following points should be considered:

- The Pacific Margin tract—with its marked paucity of porphyry copper deposits—is comparable in tectonic setting, dimensions, geologic age-range, and variety of permissive rock compositions to the North American Cordillera of the United States and Canada, which hosts numerous porphyry copper deposits, including

Table 4. Estimates of numbers of undiscovered porphyry copper deposits in northeast Asia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*,standard deviation; *Cv*%, 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, square kilometers; area, area of permissive tract in square kilometers; density, deposit density reported as the total number of deposits per 100,000 km². N_{und}, *s*, and *Cv*% are calculated using a regression equation (Singer and Menzie, 2005)]

Tract	Tract name	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km²)	Deposit density (N_{total}/100k km²)
		N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
142pCu8510	Kedon	0	1	2	4	4	1.2	1.2	100	0	1.2	30,720	3.9
142pCu8512	Kolyma	2	8	36	36	36	14.0	13.0	87	1	15.0	555,280	2.7
142pCu8513	Chukotka	0	2	6	12	12	3.1	3.4	110	0	3.1	210,360	1.5
142pCu8514	Pacific Margin	10	20	100	100	100	40.0	34.0	84	1	41.0	1,138,430	3.6
142pCu8515	Kamchatka-Kuril	2	6	20	20	20	8.9	6.7	75	0	8.9	195,150	4.6

Table 5. Summary of simulations of undiscovered resources in porphyry copper deposits and comparison with identified copper and gold resources in porphyry copper deposits in the magmatic arcs and belts of northeast Asia.

[t, metric tons; Mt, million metric tons, n.a., not applicable (only means are additive); -, unknown]

Tract	Tract name	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)	Identified gold resources (t)	Mean estimate of undiscovered gold resources (t)	Median estimate of undiscovered gold resources (t)	Mean estimate of undiscovered molybdenum resources (t)	Mean estimate of undiscovered silver resources (t)	Mean estimate of rock (Mt)
142pCu8510	Kedon	-	4,500,000	810,000	-	120	1	120,000	1,500	890
142pCu8512	Kolyma	7,900,000	56,000,000	30,000,000	460	1,400	780	1,500,000	18,000	11,000
142pCu8513	Chukotka	-	12,000,000	3,500,000	-	290	68	320,000	3,700	2,400
142pCu8514	Pacific Margin	890,000	150,000,000	95,000,000	-	3,800	2,400	4,100,000	49,000	31,000
142pCu8515	Kamchatka-Kuril	-	34,000,000	20,000,000	-	860	500	920,000	11,000	6,900
Totals	n.a.	8,790,000	256,500,000	n.a.	460	6,470	n.a.	6,960,000	83,200	52,190

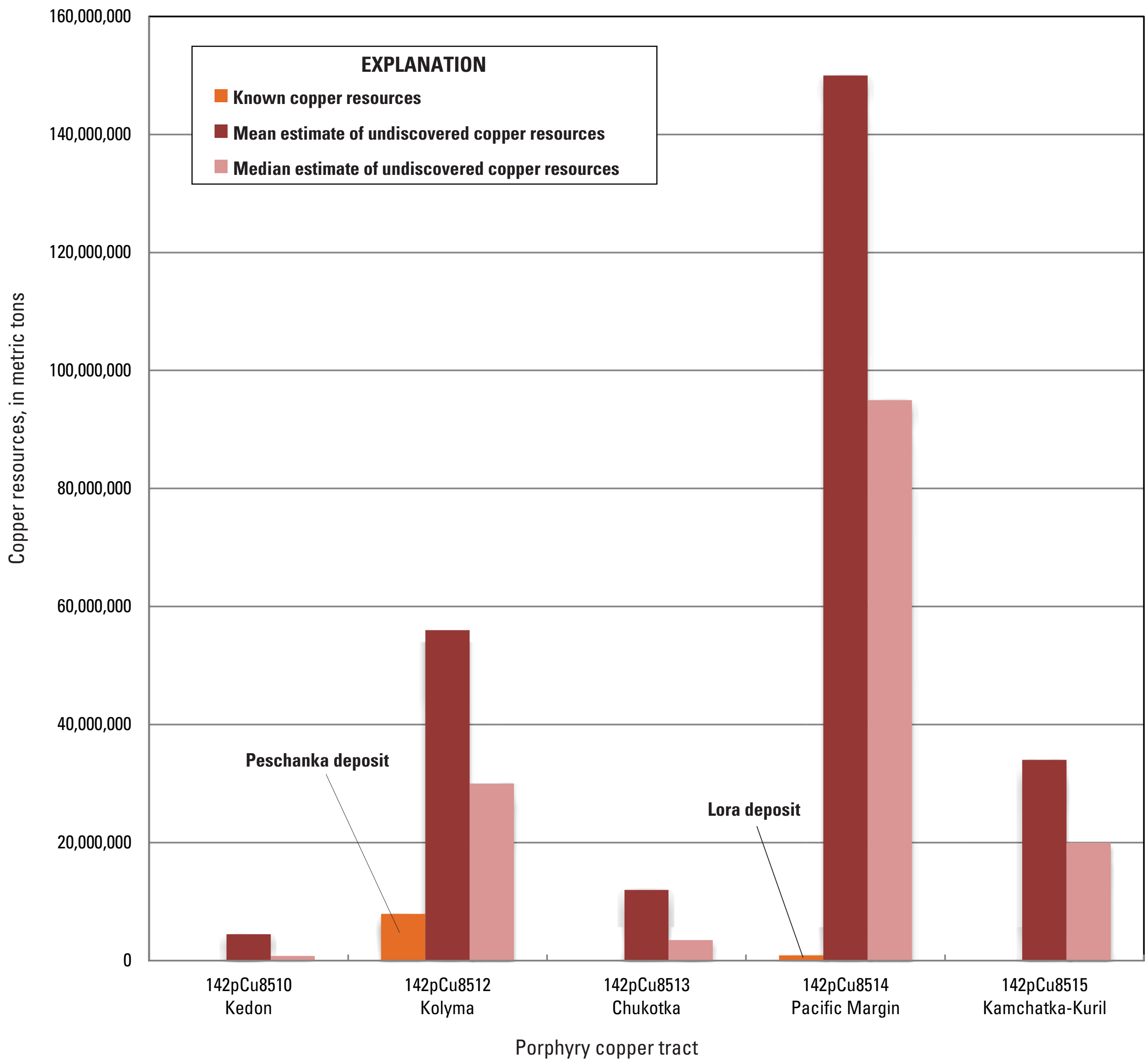


Figure 14. Bar chart showing identified and undiscovered copper resources for permissive tracts in northeast Asia.

world-class deposits such as Pebble (Alaska, United States), Highland Valley and Gibraltar (British Columbia, Canada), Yerington (Nevada, United States), Bingham (Utah, United States), and a host of deposits in the porphyry copper province of Arizona, in the continental United States (see Mutschler and others, 2000; U.S. Geological Survey National Mineral Resource Assessment Team, 2000; Cooke and others, 2005; Singer and others, 2008; Mihalasky and others, 2011).

- Exploration in the region is immature in comparison to the circum-Pacific porphyry copper belts of South, Central, and North America. For example, in the Russian Far East, because of its strategic military importance, much of the Kamchatka Peninsula was not open to systematic mineral exploration work by Soviet geologists until the 1970s, and it was not until 1992 that Western mineral exploration companies were given permission to enter the region (Nally, 2003; see also Lattanzi and others, 1995, and references therein).
- The current model for porphyry copper deposit alteration, mineralization, and formation, which has been widely accepted throughout most of the world since the 1970s, was not actively applied to mineral exploration in the former Soviet Union until the early 1990s.

To date, no modern, large-scale porphyry copper deposit mining operations have been developed in the assessed region. The Peschanka deposit, which will likely be the first large-scale porphyry copper mining operation in the region, was discovered in the late 1960s to early 1970s, explored during 1972–86, and is undergoing an aggressive drilling program that started in 2010 (Chitalin and others, 2011; Nikolaev and others, 2012). Compared to the historical discovery rate and evolution in understanding of porphyry copper deposits, Peschanka has a relatively short history. For example, the Bingham Canyon deposit, which was the first large-scale porphyry copper mining operation in the world, has a history dating back about 150 years to its discovery in 1863, geologic studies beginning in the 1870s, and open-pit exploitation starting in 1906 (James, 1978; Rio Tinto, 2009; John and others, 2010). The possibility exists that northeast Asia, in general, could just be entering its initial phase of understanding and discovery. For a more detailed discussion about the historical context of porphyry deposits, see John and others (2010) and figure 4 in Seedorff and others (2005), which graphically illustrates the historical context of porphyry deposits in relation to political and economic conditions, copper and molybdenum metal prices and production, mining and processing technologies, discovery and development of deposits, and trends in industry and scientific approaches.

If exploration considerations and comparisons with other similar porphyry copper provinces and deposits around the circum-Pacific are proven to be true, northeast Asia probably hosts many undiscovered porphyry copper deposits. Kotlyar (1996) commented, for example, that, "…there is another factor that affects the discovery of ore-bearing plutons in the Russian Far East. Ore-bearing and altered plutons, which commonly have areas less than 1.5 square km, are typically characterized by relatively high porosity. These rocks generally are confined to small depressions, small valleys, or to the lowest parts of slopes in the present landscape. The rocks do not crop out well and could not have been discovered without geochemical surveys and drilling because of the permafrost. All these data suggest that previous negative evaluations of the copper potential in the Russian Far East could result from a lack of adequate geochemical surveys and drilling."

Acknowledgments

The assessment of porphyry copper deposits in the Russian Far East and northeasternmost China has a long history, and many different people have been involved. Klaus J. Schulz and Joseph A. Briskey initiated the project and participated in the first workshop, in Kunming, Yunnan, in 2002. Drs. Stephen G. Peters and Warren J. Nokleberg coordinated and led the initial assessment activities, prepared preliminary reports, and represented the U.S. Geological Survey (USGS) to our Russian and Chinese counterparts at several meetings. Jack H. Medlin, USGS international specialist for Asia and the Pacific, facilitated joint project activities. Kathleen M. Johnson, in her role as former USGS Mineral Resources Program Coordinator, provided spirited and constant support over the life of the project. Jane M. Hammarstrom and Michael L. Zientek, project chiefs of the USGS Global Mineral Resource Assessment Project (GMRAP), gave generously of their time to render guidance and support. Pamela M. Cossette and Connie L. Dicken provided technical support and reviews for GIS databases and metadata. USGS colleagues David M. Sutphin, Peter G. Vikre, and Michael L. Zientek served on an assessment oversight committee to evaluate the assessment results prior to publication. Technical reviews of the manuscript and GIS were provided by Alison B. Till and Lukas Zürcher, which greatly improved the manuscript. Further revisions of the manuscript for the Global Mineral Resource Assessment publication series were completed by Jane M. Hammarstrom.

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Appendix A. Porphyry Copper Assessment for Tract 142pCu8510, Kedon—Russia

By Mark J. Mihalasky[1], Steve Ludington[2], Dmitriy V. Alexeiev[3], Thomas P. Frost[1], Thomas D. Light[1], Deborah A. Briggs[1], and John C. Wallis[1], with contributions by Arthur A. Bookstrom[1], and Andre Panteleyev[4]

Deposit Type Assessed: Porphyry Copper

Descriptive model: Porphyry copper (Cox, 1986; John and others, 2010)
Grade and tonnage model: General porphyry copper (Singer and others, 2008)
Table A1 summarizes selected assessment results.

Location

The Kedon tract is an arcuate belt about 850 km long and 50 to 150 km wide in the Eastern Siberian Highlands of far eastern Russia (fig. A1; see also fig. 1[5]). Most of the tract lies within the northern part of the Magadan Oblast.

Table A1. Summary of selected resource assessment results for tract 142pCu8510, Kedon—Russia.

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

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2011	1	30,720	-	4,500,000	810,000

Geologic Feature Assessed

The Kedon tract is an assemblage of Middle Devonian through early Carboniferous volcanic and intrusive rocks in the Russian northeast associated with the Kedon magmatic belt, a discontinuous continental-arc that formed by subduction of oceanic crust beneath the Omolon microcontinent and which presently forms the core of the larger Kolyma-Omolon superterrane (figs. 4 and 5).

[1]U.S. Geological Survey, Spokane, Washington, United States.

[2]U.S. Geological Survey, Menlo Park, California, United States.

[3]Geological Institute, Russian Academy of Sciences, Moscow, Russia.

[4]XDM Geological Consultants, Victoria, British Columbia, Canada.

[5]Refers to figures in the main text.

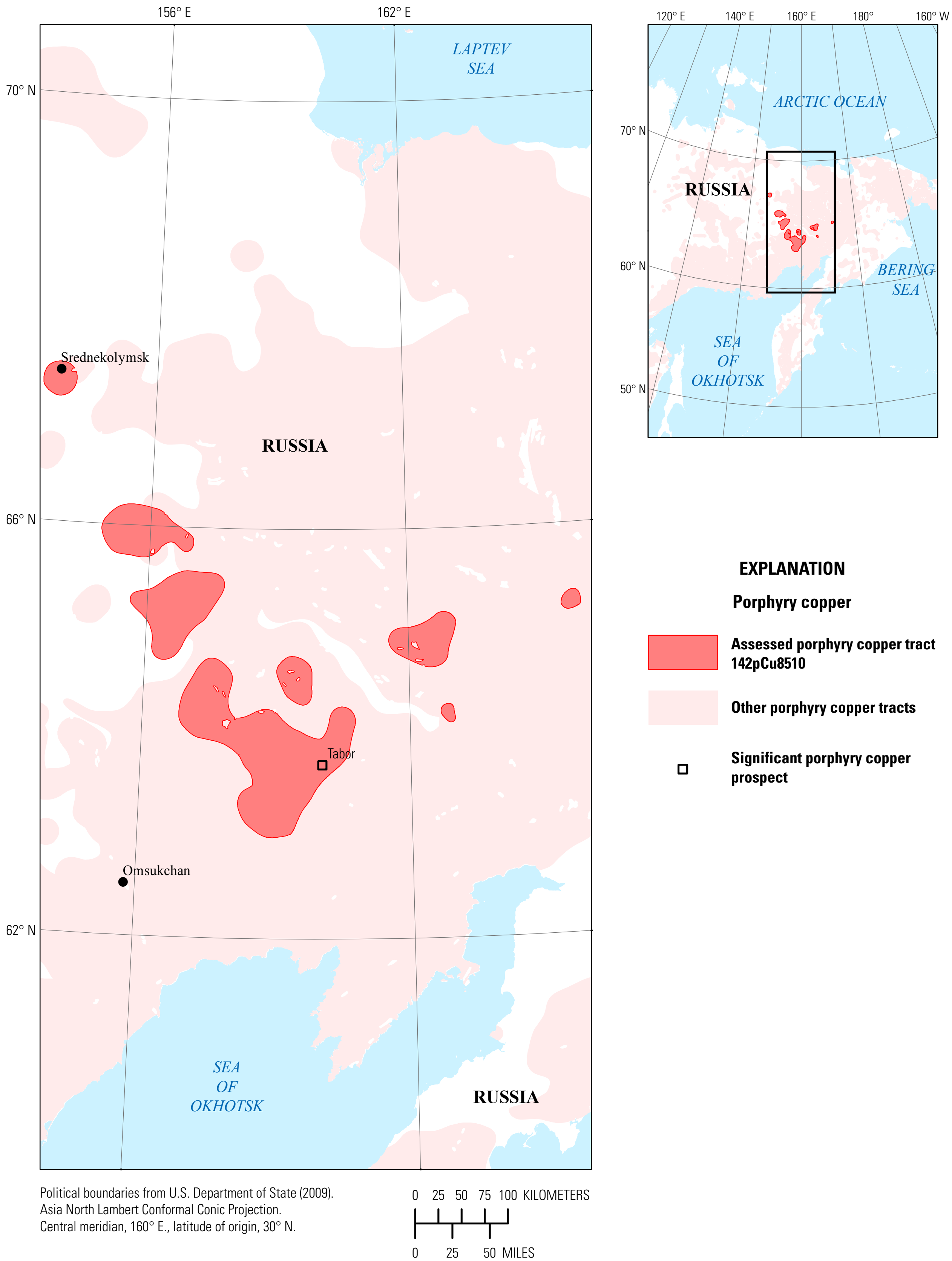

Figure A1. Map showing tract location and known porphyry copper occurrences for tract 142pCu8510, Kedon—Russia.

Delineation of the Permissive Tract

Geologic Criteria

The Kedon tract was delineated on the basis of igneous rock lithology, tectonomagmatic and metallogenic features, and the distribution of known mineral deposits and prospects. It is constrained where possible by regional-scale structural boundaries and the distribution of other related and unrelated deposit types.

The Kedon tract outlines a short-lived, discontinuously preserved continental margin magmatic arc that developed during the Middle to Late Devonian through the early Carboniferous on Archean to early Proterozoic crystalline basement rocks and the middle Proterozoic through middle Paleozoic miogeoclinal sedimentary cover sequences of the Omolon microcontinent (kd, fig. 4, also see Omolon, fig. 5; Zonenshain and others, 1990; Nokleberg and others, 2000, 2005, and references therein; Volkov and others, 2006; Sidorov and others, 2008; Parfenov and others, 2011). Accreted to the Siberian craton in the Middle to Late Jurassic (Kolesov and Stone, 2002; Lawver and others, 2002; Khudoley and Prokopiev, 2007), the Omolon microcontinent is now a cratonal block bound on all sides by strike-slip, shear, or transpressional structures (Zonenshain and others, 1990; Didenko and others, 2002), and forms the core of the Kolyma-Omolon superterrane (KOM, fig. 4; Kolesov and Stone, 2002).

Igneous rocks of the Kedon magmatic belt are associated with a convergent subduction setting. Zonenshain and others (1990) indicated that the Kedon calc-alkaline volcanic and plutonic arc rocks are characteristic of Andean-type active margins. Nokleberg and others (2005) interpreted felsic magmatism in the region as forming in a subduction-related continental arc.

The Kedon tract was defined using primarily calc-alkaline, intermediate-composition igneous map units with ages D, D2-3, and appropriate PZ1, and PZ2 rock units (fig. A2; see appendix H for explanation of ages). Intrusive units include granodiorite, granite, quartz diorite, diorite, plagiogranite, granosyenite, alkaline granite, and alkaline syenite. Volcanic units include primarily dacite and rhyolite closely associated with permissive intrusive units, with lesser amounts of trachyrhyolite and alkaline trachyte.

The Kedon tract is bound on all sides by Late Jurassic to Early Cretaceous faults (see fig. 4). No consensus exists on the nature, location, orientation, extent, and component parts of these structural features, and the regions they enclose. When aligned with aeromagnetic anomalies, many of these features, as mapped, coincide only in a general way. Because these bounding features are not well constrained, the tract boundaries were not truncated or clipped to any specific tectonic contact. The extent of the tract is primarily constrained by permissive map units and the distribution of mineral occurrences.

The Middle to Late Devonian through early Carboniferous age range of the tract is consistent with metallogenic epochs and provinces (or belts) identified by Yakubchuk (2002), Volkov and others (2006), Goryachev and others (2006), Nokleberg and others (1993, 2000, 2005), and Nokleberg (2010) (also see figs. 10 and 12).

In an analysis of lithotectonic schemes and metallogeny of the North Pacific orogenic collage, Yakubchuk (2002) noted that the Devonian to Carboniferous felsic and intermediate units associated with the Omolon block included in the Kedon tract are among the oldest magmatic arc rocks of the Kolyma-Omolon superterrane. Yakubchuk (2002, fig. 3) also described middle Paleozoic (Devonian-Carboniferous) porphyry Cu-(Au-Mo) metallogenesis in this region. The Kedon metallogenic belt of Volkov and others (2006, figs. 1 and 2, table 2) is defined on the basis of the Devonian–Lower Carboniferous Kedon Group and coeval subvolcanic intrusive and volcanic rocks, and formed in a continental margin setting. Goryachev and others (2006, fig. 8.4) delineate the Kedonsky metallogenic belt, a middle Paleozoic (416–318 Ma) feature that is very similar in extent to the Kedon tract. The Kedon tract corresponds generally to the Kedon metallogenic belt of Nokleberg and others (1993, 2000, 2005) and Nokleberg (2010), a pre-accretionary belt consisting of epithermal Au-Ag vein, porphyry Mo, Fe-skarn and associated deposits that occur in early and middle Paleozoic felsic igneous rocks (Nokleberg and others, 1993; Nokleberg, 2010, fig. 19; Parfenov and others, 2011, plate “Time Stage 6 – Late Devonian (370 Ma)”; and Nokleberg and others, 2005, figs. 16 and 18, tables 3 and 4).

Known Deposits

There are no porphyry copper deposits known in the tract.

Prospects, Mineral Occurrences, and Related Deposit Types

The Tabor prospect (table A2; figs. 8 and A1) associated with the Orliny granodiorite pluton, is the only well-described porphyry copper prospect in the tract. At Tabor, trench samples from a 3,200 by 500 m mineralized zone yielded assays of 0.7 percent copper and 0.015 percent molybdenum as well as gold and silver. Mineralization at Tabor occurs in propylitically altered Devonian granodiorites intruded by quartz diorite porphyry dikes.

Volkov and others (2006) sketch map of the southern Omolon Massif shows two other porphyry Cu-Mo occurrences, Vecherny and Krustal’ny, located about 75 km southwest of Tabor. They also noted that epithermal gold-silver occurrences such as Orliny, north of Tabor, and Dubl, some 25 km to the southwest along the Upper Omolon fault zone are likely porphyry-related.

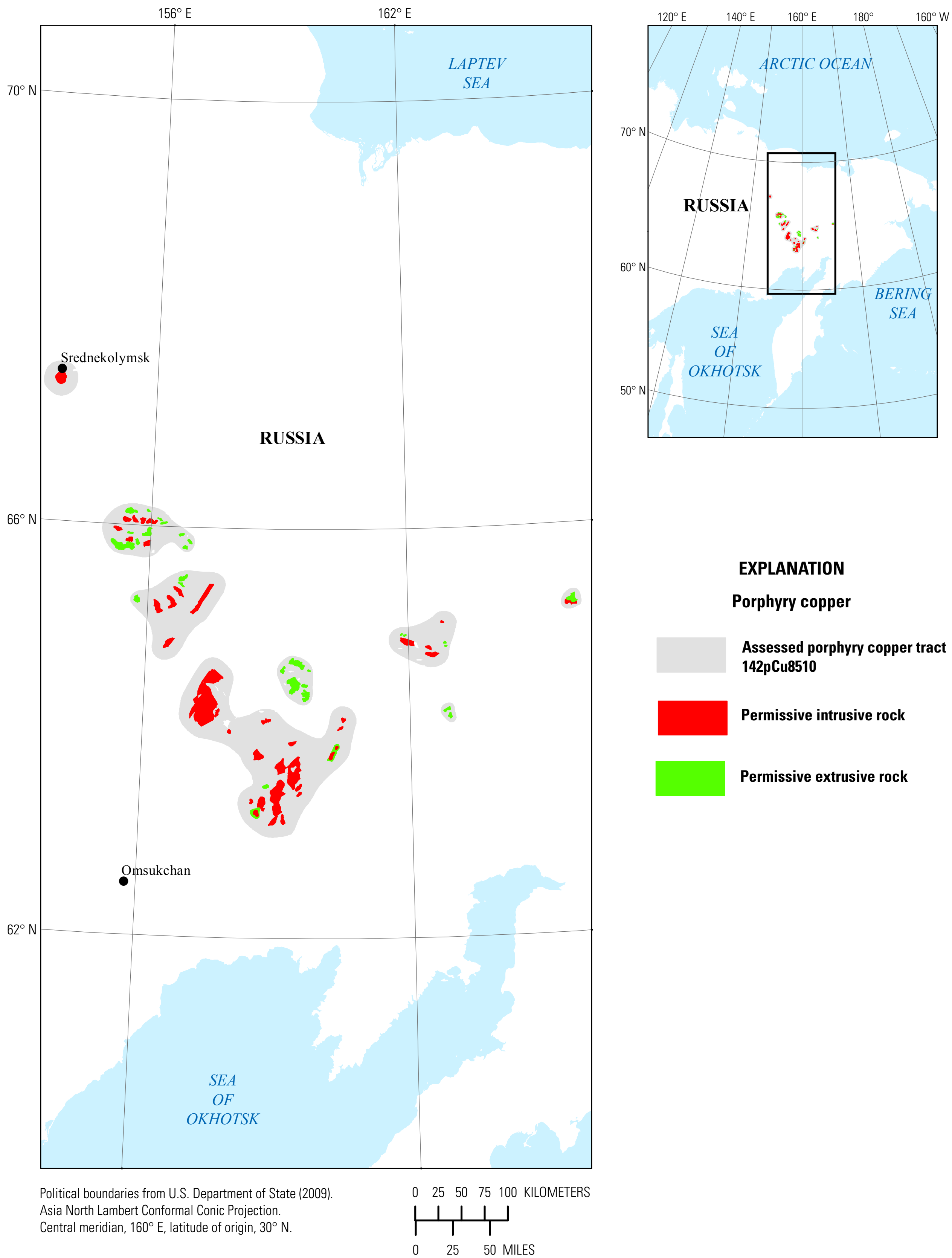

Figure A2. Map showing permissive rocks used to delineate tract 142pCu8510, Kedon—Russia.

Table A2. Significant prospects in tract 142pCu8510, Kedon—Russia.

[Ma, million years; %, percent; g/t, grams per metric ton. See deposits and prospects database, appendix F, for sources of information]

Name	Latitude	Longitude	Age (Ma)	Comments
Tabor	63.717	160.033	367	Trench samples from the mineralized zone yielded 0.7% Cu and 0.015% Mo; highest grades of 1% Cu and 0.5% Mo observed in veins with visible molybdenite; >0.1 g/t Au and 1–4 g/t Ag also detected

Sources of Information

The assessment team relied primarily on (1) smaller-scale compilations (see table 1 for map scales) that do not include sufficient information to adequately resolve geologic and metallogenic features in more detail, (2) the experience and knowledge of our assessment team's international collaborators, and (3) academic publications in the scientific literature. Most useful to this assessment were the expertise and insights about existing research and data provided by our international collaborators, as well as regional- and local-scale metallogenic studies and maps from scientific papers and exploration company materials. In addition, Google Earth imagery and user-uploaded personal photographs often provided a means by which to verify the locations of deposits and prospects.

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. Given the varied magmatic environments present, the general model was deemed the most appropriate to represent the types of porphyry copper deposits that could possibly form in this tract.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The Kedon tract is the smallest of the five northeast Asia tracts, making up a little less than 1.5 percent of the total area of all the tracts combined. Only one significant prospect is known in this tract, Tabor (see table A2, appendix F and G). At least two other porphyry Mo-Cu occurrences (Vecherny and Khrustal'ny; also possibly Orliny) are known in the region of the southern Omolon Massif, but these are probably Late Cretaceous in age (Volkov and others, 2006). There are, however, two epithermal Au-Ag occurrences within the tract that are probably Late Devonian to early Carboniferous in age (see Volkov and others, 2006, fig. 2 and table 2; Sidorov and others, 2008, fig. 2).

The assessment team concluded that the geologic framework of the region is not well understood, and the Devonian age ascribed to many of the plutonic units may not be accurate. Many may actually be associated with the younger Okhotsk-Chukotka (Early Cretaceous, Late Cretaceous, and locally Paleocene age continental-arc rocks) or Uda Murgal (Early Cretaceous arc and Triassic–Jurassic island-arc rocks) arc complexes to the southeast (Nokleberg and others, 2005; Volkov and others, 2006; see figs. 3 and 4). The team also noted that permissive map units portray a somewhat fragmented and discontinuous arcuate belt of arc rocks, but that the overall ratio of intrusive to volcanic rocks in the tract suggests that the region is exposed at an appropriate erosion level to preserve porphyry copper deposits.

Based upon available information, the assessment team concluded that the level of mineral exploration was moderate to low with respect to porphyry copper deposits. Index maps showing geologic mapping conducted in the 1910s and 1930s (fig. 13; S.R. Tikhomirova, written commun., 2011) suggest that exploration, before the late 1930s, was minimal. By 1938, a minor amount of research took place along waterways. Most of this area has not been mapped at large-scales (for example, 1:50,000 scale); however, more recent (1996–2004) geologic research and mapping at 1:200,000 scale has been carried out by VSEGEI (A.P. Karpinsky Russian Geological Research Institute) in the southern region of the tract.

The assessment team estimated a 50-percent chance of 1 or more deposits, a 10-percent chance of 2 or more deposits, and a 5-percent chance of 4 or more deposits, for a mean of 1.2 undiscovered deposits (table A3). Ambiguity related to age and setting of the permissive units, and the presence of only one known significant prospect, is reflected by the large uncertainty associated with the estimate (C_v% = 100) relative to the other tracts in this assessment.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table A4. Results of the Monte Carlo simulation are also presented as a cumulative frequency plot (fig. A3), which shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table A3. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu8510, Kedon—Russia.

[N_{XX}, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; *s*,standard deviation; *Cv*%, 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, square kilometers; area, area of permissive tract in square kilometers; density, deposit density reported as the total number of deposits per 100,000 km². N_{und}, *s*, and *Cv*% 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	1	2	4	4	1.2	1.2	100	0	1.2	30,720	3.9

Table A4. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu8510, Kedon—Russia.

[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	810,000	11,000,000	18,000,000	4,500,000	0.22	0.31
Mo	0	0	0	230,000	510,000	120,000	0.16	0.54
Au	0	0	1	280	550	120	0.20	0.50
Ag	0	0	0	3,200	6,800	1,500	0.16	0.63
Rock	0	0	200	2,200	3,700	890	0.23	0.31

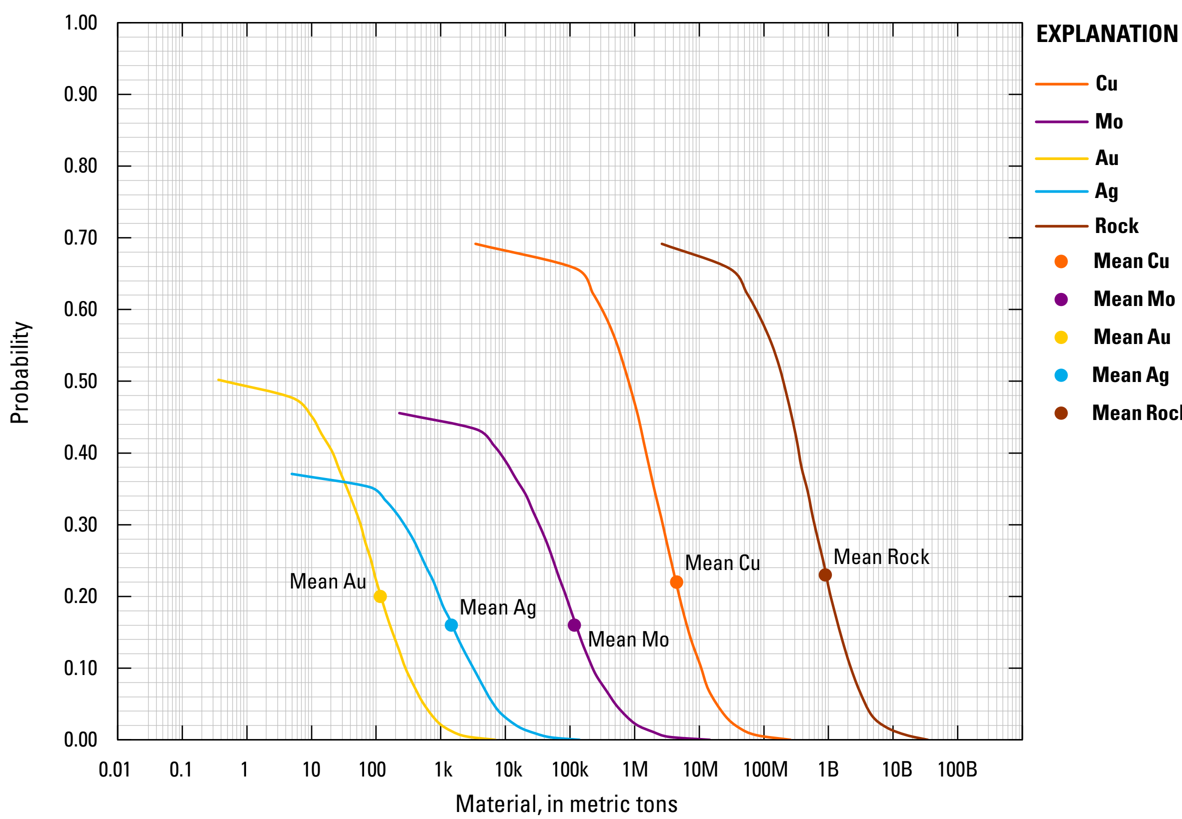

Figure A3. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 142pCu8510, Kedon—Russia. (k=thousands, M=millions, B=billions).

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Appendix B. Porphyry Copper Assessment for Tract 142pCu8512, Kolyma—Russia

By Mark J. Mihalasky[1], Steve Ludington[2], Dmitriy V. Alexeiev[3], Thomas P. Frost[1], Thomas D. Light[1], Deborah A. Briggs[1], and John C. Wallis[1], with contributions by Arthur A. Bookstrom[1], and Andre Panteleyev[4]

Deposit Type Assessed: Porphyry Copper

Descriptive model: Porphyry copper (Cox, 1986; John and others, 2010)
Grade and tonnage model: General porphyry copper (Singer and others, 2008)
Table B1 summarizes selected assessment results.

Location

The Kolyma tract consists of a large arcuate western region and a roughly circular eastern region. The western part is about 1,800 km in length and 1,100 km in width (fig. B1). The eastern part is about 500 km in diameter. The tract as a whole is about 1,600 km long from east to west and 1,400 km long from north to south. It extends from the Sea of Okhotsk in the south, north across far eastern Russia to the East Siberian Sea (see fig. 1[5]). The western part lies within the Sakha Republic and Magadan Oblast. The eastern part lies mainly in the Chukotka Autonomous Province, but also extends into the Sakha Republic and Magadan Oblast.

Table B1. Summary of selected resource assessment results for tract 142pCu8512, Kolyma—Russia.

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

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2011	1	555,280	7,900,000	56,000,000	30,000,000

Geologic Feature Assessed

An assemblage of Late Jurassic to Early Cretaceous volcanic and intrusive rocks in the Russian northeast associated with island-arc, continental-arc, and collisional magmatic belts that developed along the western, northern, and eastern margins of the Kolyma-Omolon superterrane (see KOM, fig. 4) were assessed. These magmatic rocks formed during accretion of the Kolyma-Omolon superterrane to the eastern margin of the Siberian craton and during subsequent collision of the Arctic Alaska–Chukotka microcontinent with the eastern margin of the Kolyma-Omolon superterrane (figs. 4 and 5).

[1]U.S. Geological Survey, Spokane, Washington, United States.

[2]U.S. Geological Survey, Menlo Park, California, United States.

[3]Geological Institute, Russian Academy of Sciences, Moscow, Russia.

[4]XDM Geological Consultants, Victoria, British Columbia, Canada.

[5]Refers to figures in the main text.

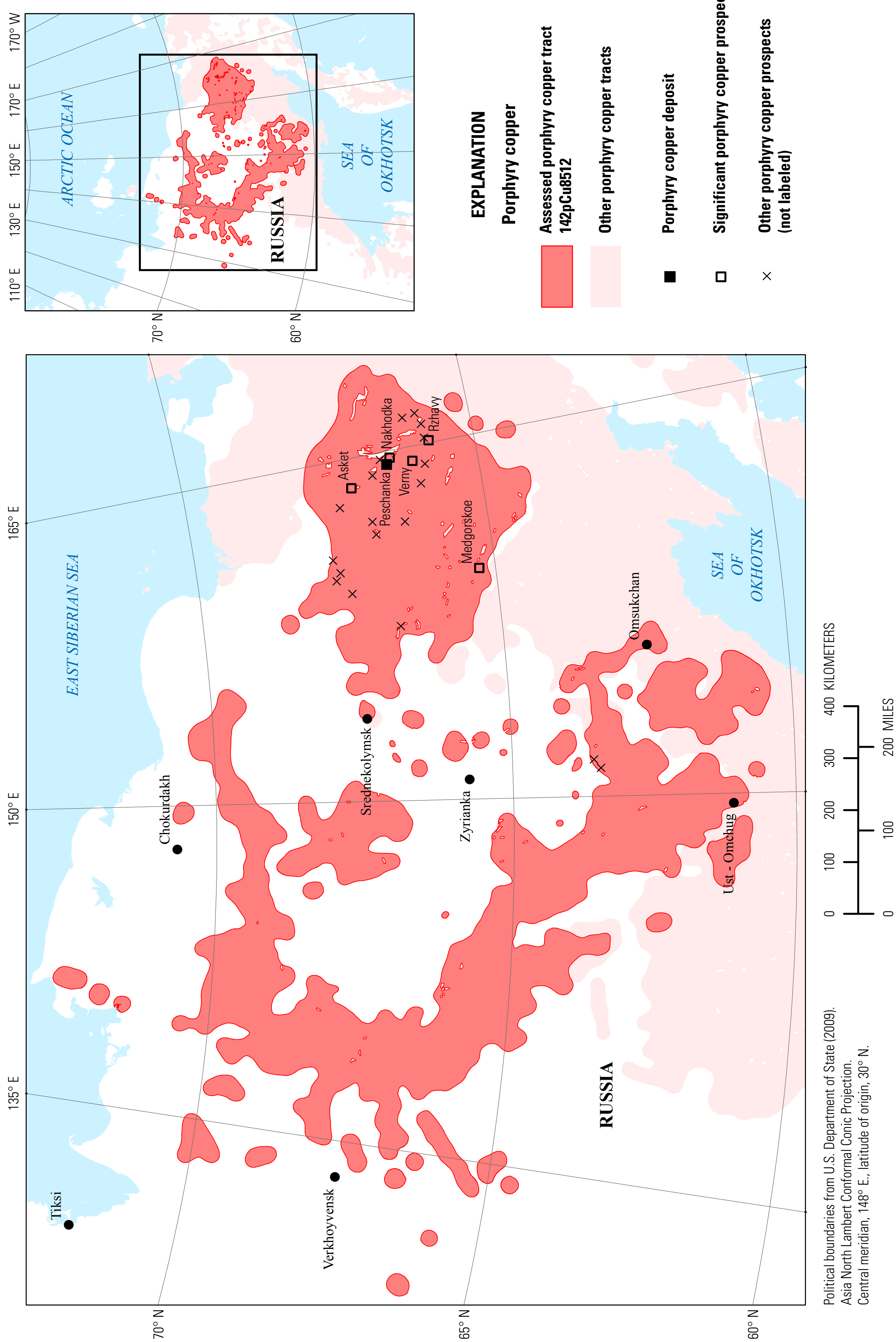

Figure B1. Map showing tract location and known porphyry copper occurrences for tract 142pCu8512, Kolyma—Russia.

Delineation of the Permissive Tract

Geologic Criteria

The Kolyma tract was delineated on the basis of igneous rock lithology, tectonomagmatic and metallogenic features, and known mineral deposits and prospects. It is constrained where possible by regional-scale structural boundaries and the distribution of other related and unrelated deposit types.

The Russian northeast consists of two major Mesozoic collisional orogens: The Verkhoyansk-Kolyma orocline (the Kolyma loop on fig. 5) and the Anyui-Chukotka fold belt (fig. 5; Zonenshain and others, 1990; Oxman and others, 2000; Soklov and others, 2005). The Verkhoyansk-Kolyma orocline formed during Late Jurassic to Early Cretaceous time when the Kolyma-Omolon superterrane was accreted to the northeastern margin of the Siberian craton (present-day coordinates). The Anyui-Chukotka fold belt formed in Early Cretaceous time when the Arctic Alaska–Chukotka microcontinent (variously delineated and referred to as the Novosibirsk-Chukotka or Chukotka terrane or tectonic collage; see Miller and others, 2009; Till and others, 2010) collided with the northeastern margin of the previously accreted Kolyma-Omolon superterrane (see figs. 4 and 5). These events represent the sequential closures of the Oimyakon Ocean basin, marked by the Kolyma loop collision suture (see Filatova and Khain, 2008; known also by other names, such as Cherskiy Suture, Adycha-Taryn or Yana-Indigirka structural zone) along the southwestern margin of the Kolyma-Omolon superterrane, and the Angayucham-South Anyui Ocean basin, marked by the South Anyui suture zone along the northeastern margin of the Kolyma-Omolon superterrane (see fig. 5; Fridovsky and Prokopiev, 2002; Lawver and others, 2002; Sokolov and others, 2002; Oxman, 2003; Hourigan and Akinin, 2004; Nokleberg and others, 2005; Parfenov and others, 2011).

This tract consists of island-arc, continental-arc, and collisional rock associations that formed along the western and eastern margins of the Kolyma-Omolon superterrane, southwest of the South Anyui suture zone (see fig. 5). Although nomenclature varies among authors, these magmatic rocks include several accreted Jurassic and Early Cretaceous island-arcs (Alezeya, Oloy, and Khetachan – the greater Alezeya-Oloy arc system) in the eastern and central parts of the tract (ol, fig. 4; also see Alazeya-Oloy folded zone, fig. 5), as well as some continental-arc rocks and collisional granitoid belts (Main and Northern—the Kolyma loop; ma and nb, fig. 4; also see fig. 5) in the western part of the tract. According to Layer and others (2001), the Main and Northern granitic belts are subduction-related (with the slab directed below the Kolyma-Omolon superterrane), and in the case of the Main belt, later overprinted by collisional magmatism (for additional details, see Nokleberg and others, 2000; Sokolov and others, 2002; Sidorov and others, 2008; Akinin and others, 2009). The Kolyma tract also includes Early to Late Cretaceous volcanic, subvolcanic, and plutonic rocks that radiate outward from the western margin of the Kolyma loop (the Transverse granite belt; tv, fig. 4; Nokleberg, 2010; Oxman, 2003, fig. 3) and various other units dispersed across the tract, all of which may represent residual pulses of magmatic activity related to regional extension (see Layer and others, 2001).

The tract was defined using primarily calc-alkaline, intermediate-composition igneous map units with ages mainly of K_1 and J_3, with less frequent ages of J_2, J_3-K_1, $K_{1\text{-}2}$, and K_2 (fig. B2; see appendix H for explanation of ages). Intrusive units include granite and granodiorite porphyries, plagiogranite, diorite and quartz diorite porphyries, with lesser amounts of granosyenite, monzodiorite, syenite, gabbro, diorite, alkaline granitoids. Volcanic units include primarily rhyolite and dacite closely associated with permissive intrusive units, with lesser amounts of rhyodacite and various trachytes.

The Kolyma tract, in the broadest sense, is bound to the north and northeast by the Early Cretaceous South Anyui suture zone, to the west and southwest by Late Jurassic collisional and accretionary structures along the eastern margin of the Verkhoyansk fold-thrust belt, and to the south and southeast by the Cretaceous to early Tertiary Okhotsk-Chukotka volcanic belt (fig. 5). The eastern part of the tract is further bound to the southwest by Late Jurassic to Early Cretaceous shear structures or sutures. The western, oroclinal loop part of the tract is controlled by Late Jurassic to Early Cretaceous plutonic rocks of the Main and Northern granite belts, and is flanked by collisional structures and suture zones that separate Jurassic age continent from Paleozoic and younger accreted terranes and arcs. No consensus exists on the nature, location, orientation, extent, and component parts of these structural features, and the regions they enclose. When aligned with aeromagnetic anomalies, many of these features, as mapped, coincide only in a general way. Because these bounding features are not well constrained, the tract boundaries were not truncated or clipped to any specific tectonic contact. The extent of the tract is primarily constrained by selected permissive map units and the distribution of mineral deposits.

The Late Jurassic-Early Cretaceous temporal (time-slice) rationale and criteria used for selecting the igneous rock map units that compose the framework of this tract are consistent with metallogenic epochs and provinces (or belts) identified by Yakubchuk (2002), Volkov and others (2006), Goryachev and others (2006), Nokleberg and others (1993, 1998, 2005), and Parfenov and others (2011) (also see figs. 10 and 12).

In an analysis of lithotectonic schemes and metallogeny of the North Pacific orogenic collage, Yakubchuk (2002, fig. 3) identified Jurassic and Cretaceous episodes of porphyry Cu-(Au-Mo) metallogenesis within the Alazeya-Oloy arc of the Verkhoyansk-Chukotka arc-backarc system, which corresponds with the Kolyma tract. The Oloy and Yasachnaya River metallogenic belts of Volkov and others (2006, fig. 1 and table 2; also see uy, fig. 4) are defined on the basis of Middle-Late Jurassic to Early Cretaceous intrusions in an island-arc setting. Goryachev and others (2006; fig. 8.7) delineate the Yasachnenskiy metallogenic belt, of Middle Jurassic to Early Cretaceous age (175–136 Ma), which is largely coincident with the southwestern portion of the western arcuate part of the Kolyma tract.

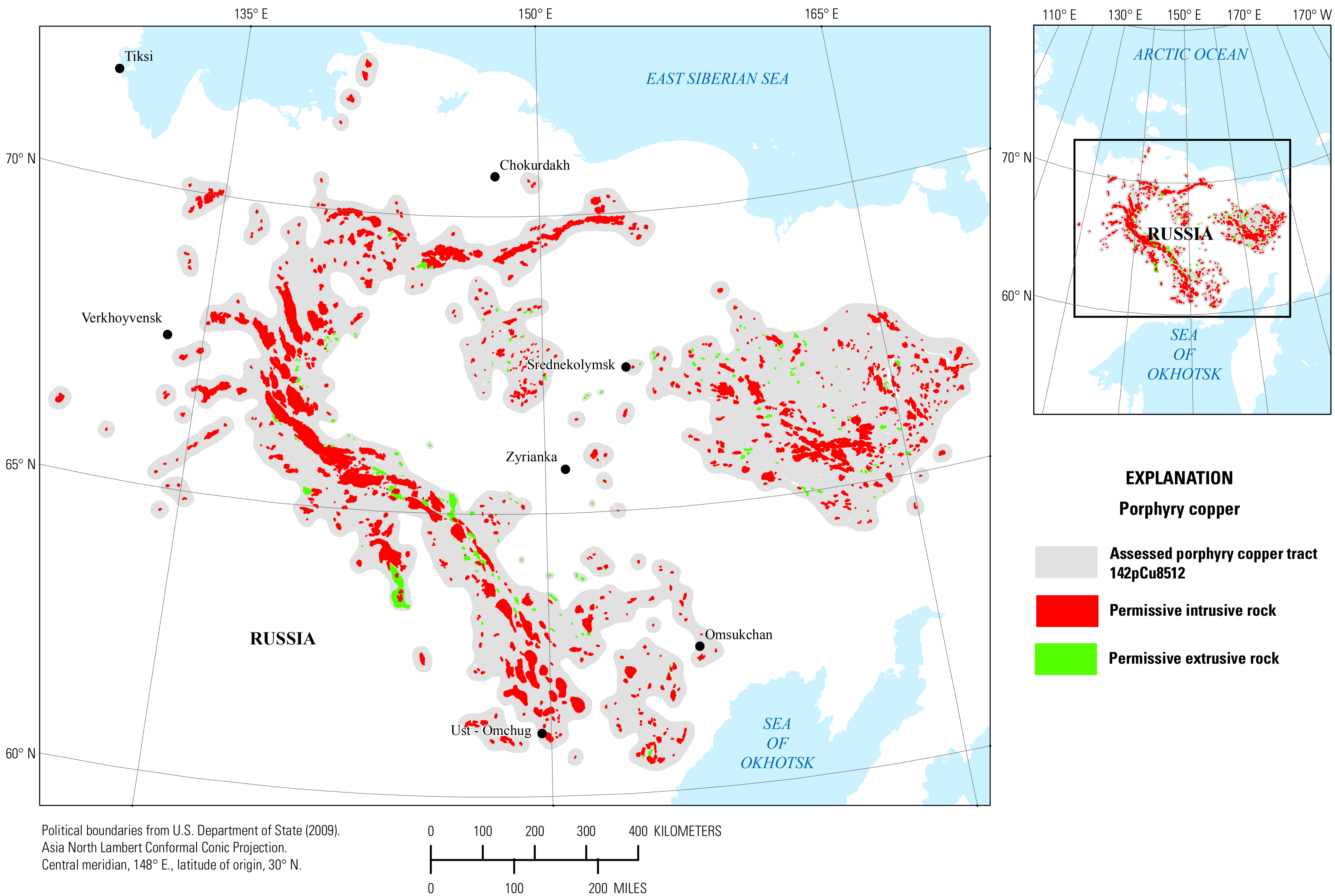

Figure B2. Map showing permissive rocks used to delineate tract 142pCu8512, Kolyma—Russia.

Goryachev and others (2006) note that copper porphyry deposits are associated with the Late Jurassic granitoids and subvolcanic bodies of the Uyandy-Yasacha island-arc terrane (which corresponds to the southern part of uy, fig. 4). The Kolyma tract also corresponds generally with Late Jurassic and (or) Early Cretaceous metallogenic belts identified by Nokleberg and others (1993, 1998, 2005, figs. 61 and 63, tables 3 and 4) and Parfenov and others (2011, plate “Time Stage 9 – Late Jurassic (145 Ma)”). The Yana-Kolyma, Yana-Polousnen, Darpir, Kular, and Shamanikha belts, which correspond to the arcuate, western part of the Kolyma tract, formed in a collisional setting and host some porphyry copper and copper-bearing quartz-vein mineralization, as well as numerous other deposit types. The Oloy and Left Omolon belts, which correspond to the central and southwestern margin of the eastern part of the Kolyma tract, formed in an island-arc setting and host porphyry Cu-Mo/Mo-Cu, Mo-Cu skarn, and Au-Ag epithermal vein deposits.

Known Deposits

There is one known porphyry copper deposit in the Kolyma tract (table B2, figs. 8 and B1, appendix F and G). The world-class Peschanka deposit, discovered in 1973 (see fig. 9) can be compared to giant porphyry deposits like Oyu Tolgoi in Mongolia and Pebble and Bingham in the United States. The resources at Peschanka are 1,517 Mt at 0.52 percent copper and 0.3 g/t gold, calculated for a cutoff grade of 0.4 percent copper equivalent. This yields a contained copper resource of nearly 8 Mt. The molybdenum grade is relatively low, at 0.009 percent (Chitalin and others, 2011). The deposit is exposed, and has been partially eroded. It is the subject of continued exploration and drilling, but has not reached feasibility status. For the purposes of this assessment, it is treated as a deposit because it has reported tonnage and grade data based on much exploration drilling.

Igneous rocks at Peschanka include a multiphase monzodiorite intrusion (142 Ma) that is cut by slightly younger stocks and dikes of monzodiorite porphyry, quartz monzodiorite porphyry, and syenite porphyry (Nokleberg and others, 1993, 2005; Chitalin and others, 2011). Copper porphyry mineralization is characterized by pervasive copper and molybdenite minerals in stockworks, veinlets, and disseminations. Potassic alteration characterizes the core of the deposit, with phyllic alteration in the periphery. The deposit has been partially dismembered by postmineral northwest-trending strike-slip faults.

Prospects, Mineral Occurrences, and Related Deposit Types

There are 5 significant porphyry copper prospects, and at least 19 other smaller prospects (only the significant prospects are listed in table B3; figs. 8 and B1 show significant prospects as well as other prospects; also see appendix F and G). Four of the significant prospects (Asket, Nakhodka, Verny, and Rzhavy) lie along the Baimka mineral trend, which includes Peschanka. These prospects are aligned along a northwest-trending strike-slip fault system (Chitalin and others, 2011).

Asket is located about 100 km to the northwest of Peschanka. It is associated with an Early Cretaceous diorite body that intrudes volcanic and sedimentary rocks. Mineralization occurs in the form of quartz-sulfide stockworks and veinlets, and as disseminations of pyrite, chalcopyrite, and subordinate molybdenum, within zones of propylitic alteration (Nokleberg, 1993, 2005).

Nakhodka is about 17 km south of Peschanka and consists of four mineralized stocks. Nakhodka is associated with a positive magnetic anomaly and copper-molybdenum geochemical halos (Volkov and others, 2006). The intrusive rocks are monzodiorite porphyry and monzonite-syenite. Mineralization is exposed and consists of stockworks and dense networks of quartz-chalcopyrite veinlets and sulfide disseminations. Supergene enrichment of copper ore is widespread (Volkov and others, 2006). Although no tonnage estimates are provided, Volkov and others (2006) suggest that Nakhodka has the potential to develop into a large deposit based upon its adequate level of exposure and widespread mineralization. Average grades reported are 0.4 percent copper and 0.15 g/t gold.

Verny and Rzhavy are 50 to 100 km southeast of Peschanka and are also associated with diorite porphyry and granodiorite porphyry stocks.

Sources of Information

The assessment team relied primarily on (1) smaller-scale compilations (see table 1 for map scales) that do not include sufficient information to adequately resolve geologic and metallogenic features in more detail, (2) the experience and knowledge of our assessment team’s international collaborators, (3) academic publications in the scientific literature, and (4) promotional materials from the Web sites of mineral exploration companies. Most useful to this assessment were the expertise and insights about existing research and data provided by our international collaborators, as well as regional- and local-scale metallogenic studies and maps from scientific papers and exploration company materials. In addition, Google Earth imagery and user-uploaded personal photographs often provided a means by which to verify the locations of deposits and prospects.

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used. There is only one known porphyry copper deposit in the tract (Peschanka, table B2) with available grade and tonnage. Peschanka is included in the general model and undiscovered deposits within the tract are expected to be like those in the model.

Table B2. Porphyry copper deposits in tract 142pCu8512, Kolyma—Russia.

[Ma, million years; Mt, million metric tons; t, metric ton; %, percent; g/t, grams per metric ton. Contained Cu in metric tons is calculated as tonnage (Mt*1,000,000) * Cu grade (percent)/100]

Name	Latitude	Longitude	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)
Peschanka	66.560	164.440	142	1,517	0.52	0.0092	0.3	1.4	7,900,000

Table B3. Significant prospects in tract 142pCu8512, Kolyma—Russia.

[Ma, million years; Mt, million metric tons; Kt, thousand metric tons; t, metric tons; %, percent; g/t, grams per metric ton; min, minimum; max, maximum; avg, average. See deposits and prospects database in appendix F for sources of information]

Name	Latitude	Longitude	Age (Ma) or age range	Comments
Asket	67.2239	163.7190	Jurassic through Cretaceous	Avg grades: 0.3–1.4% Cu, 0.03% Mo, 0.2–11.9 g/t Au, 0.5–30 g/t Ag
Medgorskoe	65.2800	159.5300	Jurassic through Cretaceous	Cu: 0.1% min, 2.94 % max, 0.3 % avg; Mo: 1.17% min, 0.6% max, 0.2 avg; Au: 0.1 g/t min, 0.6 g/t max, 0.2 g/t avg; total contained metals: 4Mt Cu, 80 Kt Mo, 20t Au
Nakhodka	66.4900	164.7000	142	Avg grades: 0.4% Cu, 0.015% Mo, and 0.15 g/t Au; ≤68.2 g/t Au (avg 3.6 g/t Au) and ≤277.4 g/t Ag (avg 35 g/t Ag) in the Vesenny main ore zone. Supergene enrichment widespread
Rzhavy	65.7783	165.1028	Jurassic through Cretaceous	May be Cu-Mo subtype
Verny	66.1167	164.3833	Jurassic through Cretaceous	Max grades: 3.6% Cu, 98.5 g/t Au,760 g/t Ag

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The Kolyma tract is the second largest of the five northeast Asia tracts, making up a little more than 26 percent of the total area of all the tracts combined. One world-class porphyry copper deposit, Peschanka, and at least five significant prospects are known in the eastern part of this tract (tables B2 and B3, and appendix F and G). With respect to contained copper, Peschanka is a large deposit compared to deposits world-wide (see fig. 9). In addition, there are at least 17 other prospects in the eastern part and 2 in the western part of the tract that have been identified on various maps and in related datasets (for example, Nokleberg and others, 1993, 1998, 2005; Rodnov and others, 2001; see appendixes F and G).

The assessment team recognized that the overall tectonomagmatic framework of the Kolyma-Omolon superterrane was reasonably well understood at the regional scale (particularly recently, for example, Parfenov and others, 2011; Nokleberg, 2010; Kuzmichev, 2009; Parfenov and others, 2009; Sokolov and others, 2009; and Yakubchuk, 2009). The geologic complexity of the region, however, has resulted in many conflicting interpretations, delineations, and tectonic reconstructions that made comprehensive and uniform assessment across the tract challenging.

In general, the assessment team concluded that there were many prospects, and with the Peschanka deposit and Nakhodka prospects along the Baimka mineral trend in the eastern part of the tract, the tract could be highly prospective for undiscovered porphyry copper deposits. The Peschanka ore system remains open to the sides and at depth. Chitalin and others (2011) reported that drilling and geophysical data suggest economic mineralization may extend more than 1 km in depth, and that further exploration may increase contained copper resources to at least 10 Mt. The Nakhodka prospect has the potential for becoming a large deposit according to an analysis and interpretation by Volkov and others (2006, p. 458). If prospects along this trend prove to be as rich as the Peschanka deposit, as suggested by the Nakhodka prospect, further exploration in the eastern part of the Kolyma tract could identify additional porphyry copper deposits.

By contrast, the western part of the tract hosts only two small Cu-Mo porphyry prospects, Datsitovy and Nevidimka (Volkov and others, 2006), which are located east of the Main granite belt units of the Kolyma loop (possibly associated with the Late Jurassic Uyandy-Yasacha Arc; figs. 4). The

Kolyma loop (see Kolyma Loop Structures on fig. 5) contains several subduction-related arcs and many of the permissive lithologies include units described as granodiorite porphyry, granite porphyry, diorite porphyry, monzodiorite porphyry, or syenite porphyry. In the Main belt of the loop, however, these rocks appear to be comingled with S-type granitoids (for example, see Hourigan and Akinin, 2004, fig. 3B), which are likely associated with an overprint of younger collisional magmatism that postdated active subduction (see Layer and others, 2001). Volkov and others (2008; see references therein) noted that the earliest intrusions emplaced along most of the southern extent of the Main granite belt during Early-Late Jurassic time are mantle derived, formed at depths of 2–3 km (no deeper than 5 km), whereas the younger Late Cretaceous granitoids are crustal in origin, emplaced at shallower depths of 0.5 to 1.5 km (no deeper than 3 km). The collisional setting shown schematically in figure 2*E* may apply to this area. This area corresponds to the Yana-Kolyma metallogenic province, described by Nokleberg and others (2005) as a belt of gold quartz-veins, sedimentary rock-hosted mercury, tin vein and greisen, and tungsten-vein deposits of Late Jurassic to Early Cretaceous age (also see Parfenov and others, 2009). This assemblage of deposit types may reflect vertical metallogenic zoning, from older, more deeply emplaced tin and tungsten systems (associated with S-type and I-type granitoids, respectively), to younger, more shallowly emplaced gold and mercury systems. Given these considerations, the assessment team concluded that the western part of the tract is permissive, but may not represent as favorable an environment for the formation of porphyry copper deposits as the eastern part of the tract.

The level of mineral exploration appears to vary across the tract. The eastern part of the tract is considered to be very prospective, and the region along the Baimka mineral trend and its northwest-southeast extensions are probably reasonably well explored. Conversely, the remote and difficult to access western part of the tract, in the region of the Main and Northern granite belts (see fig. 4), is likely not well explored (at least for porphyry copper mineralization). Index maps showing geologic mapping conducted in the 1910s and 1930s (fig. 13; S.R. Tikhomirova, written commun., 2011) suggest that mineral exploration before the late 1930s was minimal. By 1938, it appears that most of the western part of tract region had some research efforts (although specifically what that entailed is not defined), but that the eastern part of the tract (and the most prospective) remained mostly unstudied. Most of this area has not been mapped at large-scales (for example, 1:50,000 scale), with only some 1:200,000 geologic mapping carried out by VSEGEI (A.P. Karpinsky Russian Geological Research Institute) before 1979 and between 1980 and 1995. The southern end of the Main Granite Belt (fig. 5) has some recent 1:200,000 geologic mapping dating from 1996 through 2004. An important geochronologic study of Main Granite Belt intrusions was recently completed by Akinin and others (2009).

The assessment team estimated a 90-percent chance for 2 or more undiscovered deposits in the tract, a 50-percent chance of 8 or more deposits, and a 10-percent chance of 36 or more deposits, for a mean of 14.0 expected undiscovered deposits (table B4). The presence of a world-class deposit, along with a number of promising prospects in the eastern part of the tract, and the reasonably well understood tectonomagmatic framework of the region, is reflected by the smaller uncertainty in the number of undiscovered deposits estimated (C_v% = 87) relative to the other tract estimates in this assessment.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table B5. Results of the Monte Carlo simulation are also presented as a cumulative frequency plot (fig. B3), which shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table B4. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu8512, Kolyma—Russia.

[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, square kilometers; area of permissive tract in square kilometers; density, 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	8	36	36	36	14.0	13.0	87	1	15.0	555,280	2.7

Table B5. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu8512, Kolyma—Russia.

[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	220,000	2,000,000	30,000,000	140,000,000	190,000,000	56,000,000	0.37	0.04
Mo	0	7,200	660,000	4,000,000	5,700,000	1,500,000	0.32	0.08
Au	0	21	780	3,600	4,700	1,400	0.36	0.07
Ag	0	0	7,700	48,000	67,000	18,000	0.32	0.11
Rock	52	480	6,500	29,000	37,000	11,000	0.38	0.04

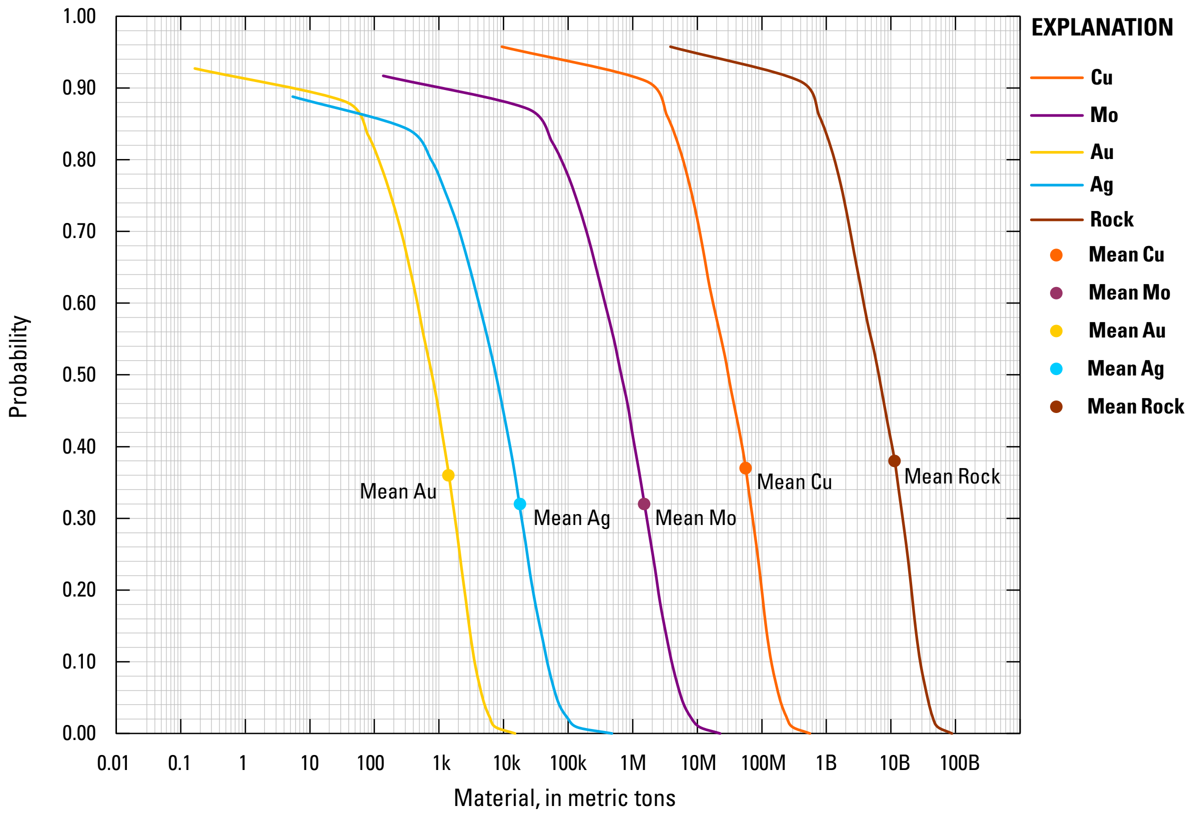

Figure B3. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract142pCu8512, Kolyma—Russia. (k=thousands, M=millions, B=billions).

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Appendix C. Porphyry Copper Assessment for Tract 142pCu8513, Chukotka—Russia

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Deposit Type Assessed: Porphyry Copper

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

Location

The Chukotka tract consists of an eastern belt and a small western region (fig. C1). The eastern part is a semicontinuous linear belt about 1,300 km in length and 450 km at its widest. It stretches from the Bering Strait northwest across the Chukchi Peninsula, over the Anadyr and Chersky ranges, to the Medvezhyi Islands in the East Siberian Sea (see fig. 1[5]). The western part is a roughly ovoid area about 70 km in diameter that covers most of Bol'shoi Lyakhovsky Island, which is the southernmost of the New Siberian Islands, in the East Siberian Sea. Most of the tract lies within the Chukot Autonomous Province, but a part extends into the Sakha Republic.

Table C1. Summary of selected resource assessment results for tract 142pCu8513, Chukotka—Russia.

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

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2011	1	210,360	-	12,000,000	3,500,000

Geologic Feature Assessed

The tract represents an assemblage of Early to Late Cretaceous volcanic and intrusive rocks in the Russian northeast associated with island-arc, continental-arc, and collisional magmatic belts. The arcs and belts developed adjacent to, and on, the southwestern margin of the Arctic Alaska–Chukotka microcontinent during its accretion to the eastern margin of the Kolyma-Omolon superterrane (figs. 4 and 5). This event followed the Late Jurassic to Early Cretaceous accretion of the latter to the Siberian craton.

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[3]Geological Institute, Russian Academy of Sciences, Moscow, Russia.

[4]XDM Geological Consultants, Victoria, British Columbia, Canada.

[5]Refers to figures in the main text.

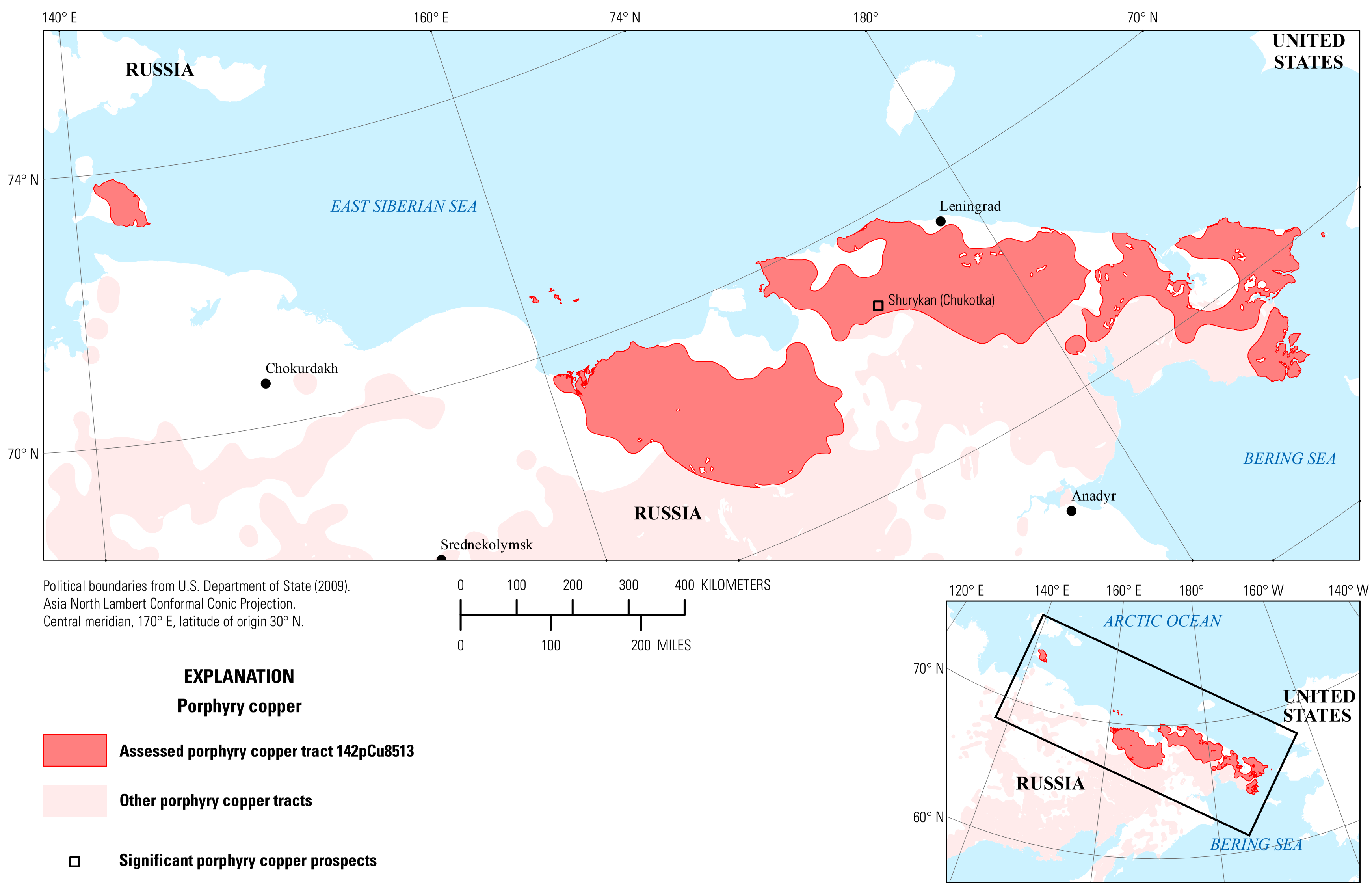

Figure C1. Map showing tract location and known porphyry copper occurrences for tract 142pCu8513, Chukotka—Russia.

Delineation of the Permissive Tract

Geologic Criteria

The Chukotka tract was delineated on the basis of igneous rock lithology, tectonomagmatic and metallogenic features, and known mineral deposits and prospects. It is constrained where possible by regional-scale structural boundaries and the distribution of other related and unrelated deposit types.

The Russian northeast consists of two major Mesozoic collisional zones: The Verkhoyansk-Kolyma orocline (the Kolyma loop) and the Anyui-Chukotka fold belt (Zonenshain and others, 1990; Oxman and others, 2000; Soklov and others, 2005; see Kolyma Loop structures and Anyui-Chukotka fold belt on fig. 5). The Verkhoyansk-Kolyma orocline (VK on fig. 4) formed during Late Jurassic to Early Cretaceous time when the Kolyma-Omolon superterrane was accreted to the northeastern margin of the Siberian craton (present-day coordinates). The Anyui-Chukotka fold belt formed in middle Mesozoic time when the Arctic Alaska–Chukotka microcontinent (variously delineated and referred to as the Novosibirsk-Chukotka or Chukotka terrane or tectonic collage; see Miller and others, 2009; Till and others, 2010) rifted away from North America and in Early Cretaceous time collided with the northeastern margin of the previously accreted Kolyma-Omolon superterrane (see figs. 4 and 5). This collision resulted from the closure of the Angayucham-South Anyui Ocean basin, marked by the South Anyui suture zone between the Arctic Alaska–Chukotka microcontinent and Kolyma-Omolon superterrane (see fig. 5; Fridovsky and Prokopiev, 2002; Lawver and others, 2002; Sokolov and others, 2002; Oxman, 2003; Hourigan and Akinin, 2004; Parfenov and others, 2011).

This tract consists of island-arc, continental-arc, and collisional magmatic rocks that formed near and on the southwestern margin of the Arctic Alaska–Chukotka microcontinent, northeast of the South Anyui suture zone (see fig. 5). Along the southwest margin of the tract, these include the Late Jurassic to Cretaceous magmatic rocks of the Kulpolnei island-arc and Nutesyn continental margin-arc terrane (see fig. 5). These rocks formed over northeast-dipping subduction zone settings along the southwestern margin of the Arctic Alaska–Chukotka microcontinent during the closure of the South Anyui Ocean (Nokleberg, 2010; Sokolov and others, 2002, fig. 6c; Parfenov and others, 2011, Time Stage 9 – Late Jurassic (145 Ma)). In the central and northeastern part of the tract, collisional granitoids of the middle Cretaceous Anyui-Chukotka fold belt (known as the Omineca-Selwyn collisional granitic belt) are widespread (Zonenshain and others, 1988; Nokleberg and others, 2000, and references therein; Tikhomirov and others, 2006; Miller and others, 2009; om, fig. 4; also see Granites of the Omineca-Selwyn collisional granite belt and Anyui-Chukotka fold belt, fig. 5). These granitic rocks are overlain and intruded by middle and Late Cretaceous volcanic and plutonic rocks of Okhotsk-Chukotka volcanic belt (Nokleberg and others, 2000, and references therein; Tikhomirov and others, 2006; Miller and others, 2009).

The tract was defined using primarily calc-alkaline, intermediate-composition igneous map units with age K_1 and minor amounts of K_2 (fig. C2). Intrusive units include granite and granodiorite (including porphyries), quartz diorite, diorite, plagiogranite, and tonalite, with lesser amounts of monzodiorite, monzonite, syenite, alkaline granite, and leucogranite. Volcanic units include primarily rhyolite and dacite closely associated with permissive intrusive units, with lesser amounts of andesite.

The Chukotka tract is bound to the southwest by the Early Cretaceous South-Anyui suture zone (see fig. 5). The Okhotsk-Chukotka volcanic belt rocks likely overlap the South Anyui suture zone and (or) structures related to Late Jurassic and Early Cretaceous accretionary tectonic collages along the southwest margin of the easternmost part of the tract. The northern boundary of the tract is not defined geologically, but terminates at the East Siberian Sea shoreline. The northern boundary of Arctic Alaska–Chukotka microcontinent is poorly known. It lies offshore, north of Wrangel Island, and appears to be a zone of extensional tectonism, the age of which is imprecisely known (Coakley and others, 2011). No consensus exists on the nature, location, orientation, extent, and component parts of these structural features and the regions they enclose. When aligned with aeromagnetic anomalies, many of these features, as mapped, coincide only in a general way. Because these bounding features are not well constrained, the tract boundaries were not truncated or clipped to any particular tectonic contact. The extent of the tract is primarily constrained by selected permissive map units and the distribution of mineral deposits.

The Early to Late Cretaceous temporal (time-slice) rationale and criteria used for selecting the igneous rock map units that compose the framework of this tract are consistent with metallogenic epochs and provinces (or belts) identified by Goryachev and others (2006), and Nokleberg and others (1993, 1998, and 2005) (also see figs. 10 and 12).

Goryachev and others (2006, figs. 8.8 and 8.9) delineate the Chukotka (Early Cretaceous, 136–99 Ma) and Chaunsky (Late Cretaceous, 99–70 Ma) metallogenic belts that are largely coincident with the main eastern part of the Chukotka tract. Goryachev and others (2006) indicate that these belts host Au-quartz vein and related deposits (Chukotka belt), and intrusion-related Sn- and Cu-Mo-porphyry mineralization (Chaunsky belt). The Chukotka tract also corresponds with the Late Cretaceous Chukotka and Eastern Asia-Arctic metallogenic belts of Nokleberg and others (2005, figs. 79 and 102, features CH, EACN, EACH, and the northwestern part of EAAB). The Chukotka belt formed in a collisional setting and hosts Au-quartz vein and Sn-polymetallic vein deposits in granitic plutons. The Eastern Asia-Arctic belt formed in a continental-arc setting and is host to Sn-polymetallic vein, Sn-greisen, Sn-skarn, Sn-porphyry, and granite-related Au. Farther inland and to the northwest, the Eastern Asia-Arctic belt (see features EAAB and EACH on figure 102 of

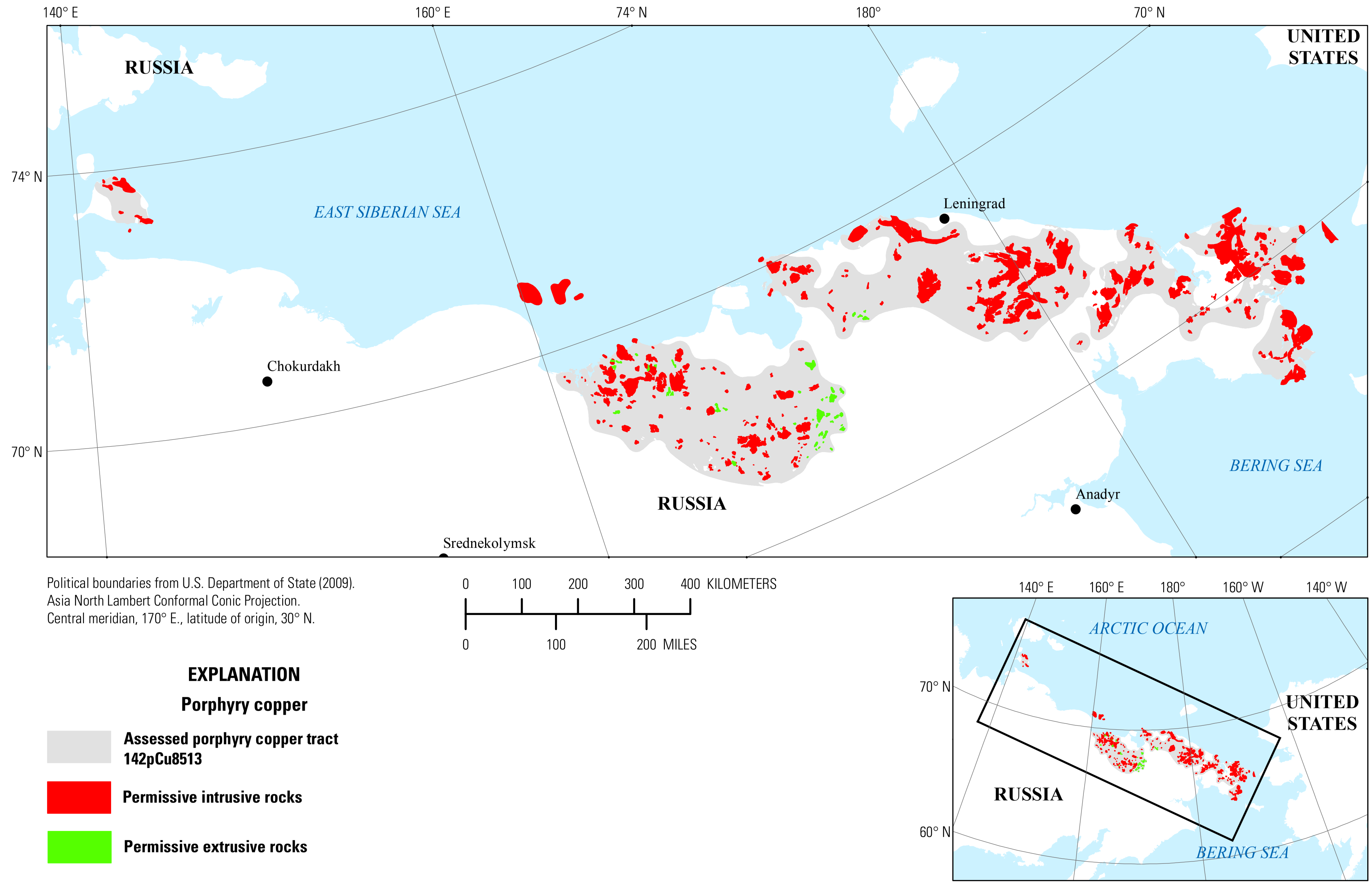

Figure C2. Map showing permissive rocks used to delineate tract 142pCu8513, Chukotka—Russia.

Nokleberg and others, 2005) is also host to Au-Ag epithermal vein, disseminated Au-sulfide, and sediment-hosted Hg, hot-spring Hg, and volcanic-hosted Hg.

Known Deposits

There are no porphyry copper deposits known in the tract.

Prospects, Mineral Occurrences, and Related Deposit Types

There is one significant porphyry copper prospect known in the tract (table C2, figs. 8 and C1, appendix F and G). Shurykan is the only identified porphyry copper prospect, but Volkov and others (2006) mention another prospect called Pykarnayan without locating it. Molybdenum appears to be the most important metal in these prospects, as molybdenum grades range from 0.01 to 0.2 percent, whereas copper grades range only from 0.01 to 0.05 percent.

Sources of Information

The assessment team relied primarily on (1) smaller-scale compilations (see table 1 for map scales) that do not include sufficient information to adequately resolve geologic and metallogenic features in more detail, (2) the experience and knowledge of our assessment team's international collaborators, and (3) academic publications in the scientific literature. Most useful to this assessment were the expertise and insights about existing research and data provided by our international collaborators, as well as regional- and local-scale metallogenic studies and maps from scientific papers and exploration company materials. In addition, Google Earth imagery and user-uploaded personal photographs often provided a means by which to verify the locations of deposits and prospects.

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. Given the varied magmatic environments present, the general model was deemed the most appropriate to represent the types of porphyry copper deposits that could possibly form in this tract.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The Chukotka tract is one of the smallest of the five northeast Asia tracts, making up a little less than 10 percent of the total area of all the tracts combined. Only one significant prospect is known, Shurykan, located in the central part of the tract (see table C3, appendix F and G). It is described as a Mo-Cu porphyry system for which no tonnage data are available, but exploration sample grade information is available. There are no other known prospects. Shurykan appears to be a porphyry-type occurrence, but it is the only porphyry copper prospect in a regional metallogenic environment dominated by Mo-, W-, Sn-, and polymetallic-vein and hot-spring Hg prospects and deposits.

Table C2. Significant prospects in tract 142pCu8513, Chukotka—Russia.

[Ma, million years; %, percent; g/t, grams per metric ton. See deposits and prospects database in appendix F for sources of information]

Name	Latitude	Longitude	Age (Ma)	Comments
Shurykan	68.700	174.339	85	Grade of 0.01–0.05% Cu, 0.01–0.2% Mo, 0.2–0.5 g/t Au, 1–10 g/t Ag

Table C3. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu8513, Chukotka—Russia.

[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, square kilometers; area, area of permissive tract in square kilometers; density, 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	2	6	12	12	3.1	3.4	110	0	3.1	210,360	1.5

The assessment team noted that an appropriate mix of permissive igneous lithologies is present in the Chukotka tract, and that the proportion of volcanic to intrusive rock types indicates that the regional level of erosion is appropriate for the exposure and preservation of porphyry systems. The team was also impressed by the numerous and extensive zones of iron-staining and oxidation, visible as color anomalies in Landsat imagery, suggesting possible widespread hydrothermal activity, although of unknown origin and age. But, despite these factors and a northeast-dipping oceanic-continental crust subduction regime beneath the southwestern margin of Chukotka, the overall metallogenic environment does not appear particularly favorable for porphyry copper mineralization.

Based upon available information, the assessment team felt that the level of mineral exploration in the region was low to moderate. Many of the areas within the tract are remote, particularly in the far eastern part of the tract. Index maps showing geologic mapping conducted in the 1910s and 1930s (fig. 13; S.R. Tikhomirova, written commun., 2011) suggest that mineral exploration, before the late 1930s, was minimal. By 1938, it appears that most of the tract region had some research efforts (although specifically what that entailed is not defined). Most of this area has not been mapped at large-scales (such as 1:50,000 scale), and nearly all of the 1:200,000 geologic mapping in the tract region, carried out by VSEGEI (A.P. Karpinsky Russian Geological Research Institute), was done before 1979, with the exception of a few places in the western part of the tract, which were done between 1996 and 2004.

The assessment team estimated a 50-percent chance of 2 or more deposits, a 10-percent chance of 6 or more deposits, and a 5-percent chance of 12 or more deposits for a mean of 3.1 expected undiscovered deposits (table C3). Ambiguity related to the setting of permissive units, a metallogenic environment that does not appear to be particularly conducive to the formation of porphyry copper deposits, and the presence of only one known significant prospect, is reflected by a large uncertainty in the number of undiscovered deposits estimated ($C_v\%$ = 110) relative to the other tracts in this assessment.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table C4 (also see fig. 13). Results of the Monte Carlo simulation are also presented as a cumulative frequency plot (fig. C3), which shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table C4. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu8513, Chukotka—Russia.

[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	3,500,000	30,000,000	50,000,000	12,000,000	0.27	0.20
Mo	0	0	41,000	780,000	1,500,000	320,000	0.21	0.34
Au	0	0	68	810	1,300	290	0.26	0.31
Ag	0	0	330	9,400	17,000	3,700	0.22	0.42
Rock	0	0	830	6,400	10,000	2,400	0.27	0.20

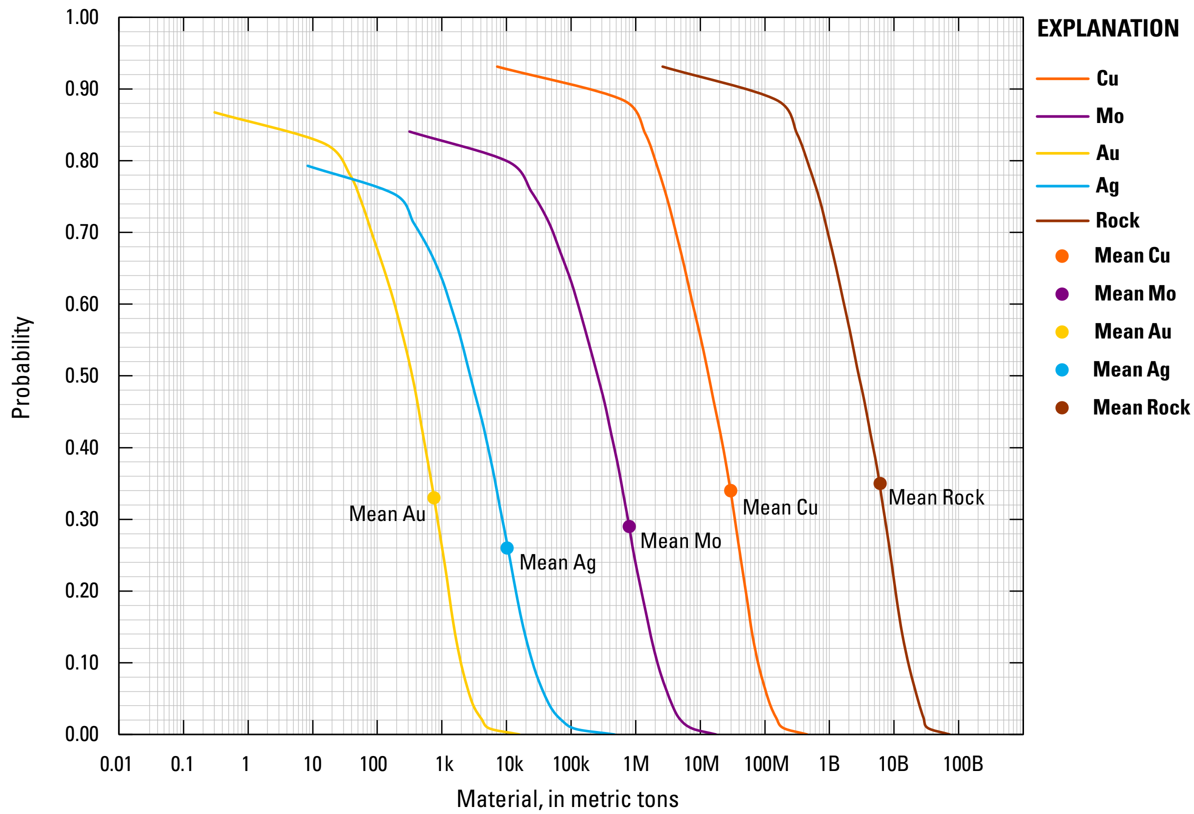

Figure C3. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract142pCu8513, Chukotka—Russia. (k=thousands, M=millions, B=billions).

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Appendix D. Porphyry Copper Assessment for Tract 142pCu8514, Pacific Margin—Russia and China

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Deposit Type Assessed: Porphyry Copper

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

Location

The Pacific Margin tract is a continuous narrow belt about 4,000 km in length and as much as 350 km at its widest part (fig. D1). The belt extends across the entire Pacific Ocean margin of Russia (inboard of the Kamchatka Peninsula), from the Chukchi Peninsula in the northeast to the southern end of the Sikhote-Alin Mountains near the border with China and North Korea. Most of the tract lies within the Chukot Autonomous Province, Maga Buryatdan (Magadan) Region, and Khabarovsk and Primor'ye territories of Russia, with small areas extending into the northeastern Manchuria region of China (fig. 1[5]).

Table D1. Summary of selected resource assessment results for tract 142pCu8514, Pacific Margin—Russia and China.

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

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2011	1	1,138,430	890,000	150,000,000	95,000,000

Geologic Feature Assessed

The tract outlines an assemblage of Cretaceous through middle Tertiary volcanic and intrusive rocks along the Pacific margin of the Russian northeast and southeast. These rocks represent a series of subduction-related continental- and island-arc complexes that were successively accreted and superimposed from west-to-east onto the paleomargin of northeast Asia in response to subduction of the ancestral Pacific Plate (figs. 4, 5, and 6).

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[3]Geological Institute, Russian Academy of Sciences, Moscow, Russia.

[4]XDM Geological Consultants, Victoria, British Columbia, Canada.

[5]Refers to figures in the main text.

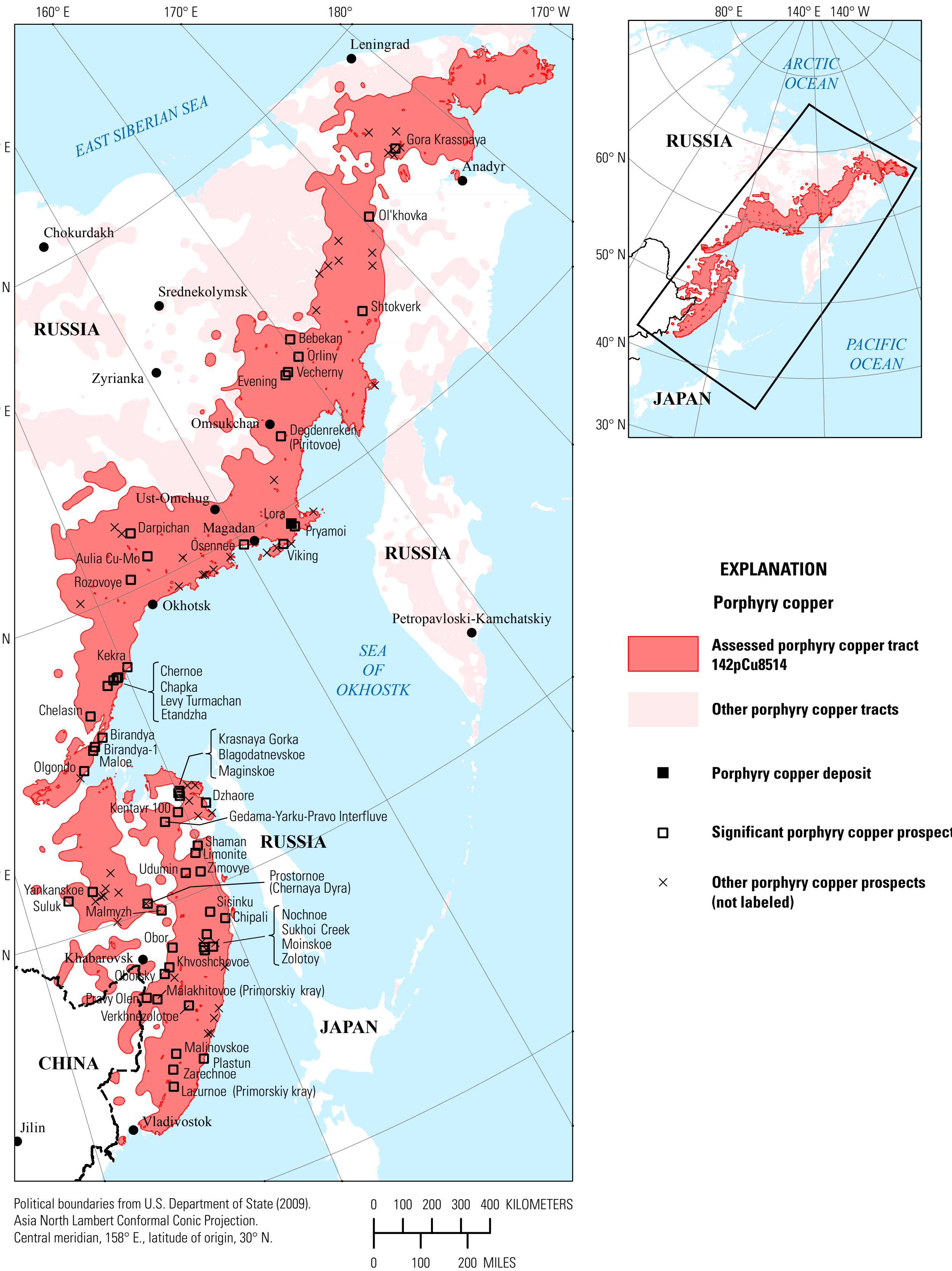

Figure D1. Map showing tract location and known porphyry copper occurrences for tract 142pCu8514, Pacific Margin—Russia and China.

Delineation of the Permissive Tract

Geologic Criteria

The Pacific Margin tract was delineated on the basis of igneous rock lithology, tectonomagmatic and metallogenic features, and known mineral deposits and prospects. It is constrained, where possible, by regional-scale structural boundaries and the distribution of other related and unrelated deposit types.

In late Mesozoic and Cenozoic time, following the amalgamation of the Kolyma-Omolon and Arctic Alaska–Chukotka microcontinents to the Siberian craton during the Jurassic and Early Cretaceous (see appendix C; figs. 4 and 5), orogenic activity shifted southeast (present day geography) to the newly consolidated Pacific margin of northeast Asia. Further south, the Mongol-Okhotsk Ocean was closing as the North China cratonal block and accretionary collages to the north (the Manchurides and Altaids of Inner and Outer Mongolia, or the Amuria block; Zonenshain and others, 1990; Cogné and others, 2005; see fig. 3) converged with the southern and southeastern margin of the Siberian craton, culminating in the formation of the Mongol-Okhotsk Suture in Late Jurassic–Early Cretaceous time (Cogné and others, 2005) (see fig. 6).

Beginning in middle Mesozoic time, a series of continental- and island-arc complexes successively formed on, or were accreted west-to-east onto, the paleomargin of northeast Asia along the northwestern boundary of the ancestral and present-day Pacific Plate (Zonenshain and others, 1990; Parfenov and others 2009, 2011; and Nokleberg, 2010). In general, the age of these arc complexes decreases towards the Pacific plate margin (Akinin and Miller, 2011). They include the (1) Uda-Murgal (2) Okhotsk-Chukotka, (3) Khingan-Okhotsk, (4) East Sikhote-Alin, and (5) younger arcs of the Koryak, Kamchatka, and Kuril island chain regions. The Uda-Murgal, Okhotsk-Chukotka, Khingan-Okhotsk, and East Sikhote-Alin arc complexes are included in this tract (see us, oc, ko, and ea on fig. 4; also figs. 5 and 6). The younger Koryak, Kamchatka, and Kuril islands arc complexes are included in the Kamchatka tract, discussed in appendix E.

The Uda-Murgal and Okhotsk-Chukotka arc complexes are located north of the Mongol-Okhotsk Suture (see figs. 4 and 5). Rocks of the Okhotsk-Chukotka volcanic belt, known also as the Okhotsk-Chukotka Arc or arc complex (figs. 4 and 6), are more extensive and volumetrically dominant relative to Uda-Murgal rocks. The Uda-Murgal complex is Late Jurassic to Early Cretaceous in age and composed of continental- and island-arc rocks. It is fragmented along its length, representing multiple magmatic arc segments accreted to one another (Zonenshain and others, 1990), and (or) thrust and lateral fault-displaced tectonic units that combine to form the greater Uda-Murgal arc complex (Sokolov and others, 2009). The southern and central parts of the complex include continental-arc rocks, whereas the northern segments include mainly island-arc and related continental margin and marine accretionary units and oceanic terrane fragments (Parfenov and others, 2009, 2011; Sokolov and others, 2009).

The Uda-Murgal arc complex is broadly overlapped, intruded, and deformed by younger magmatic rocks of the Okhotsk-Chukotka volcanic belt (see figs 3, 4, and 5). The Okhotsk-Chukotka volcanic belt is a middle to Late Cretaceous age Andean-style continental-arc and is the largest part of an arc complex that spans the entire eastern margin of the Asian continent (Zonenshain and others, 1990; Hourigan and Akinin, 2004; Akinin and Miller, 2011). The Okhotsk-Chukotka volcanic belt formed in response to subduction of the ancestral Pacific Plate (Parfenov and others, 2009). Termination of Okhotsk-Chukotka magmatism occurred in Late Cretaceous time (about 81 Ma), perhaps because of the collision of a microcontinental block or oceanic plateau with the margin (see Hourigan and others, 2009, and references therein; Konstantinovskaya, 2011, and references therein). This resulted in an eastward shift of subduction, from a continental setting along the paleo-Pacific Ocean margin, to an outboard oceanic setting (Akinin and Miller, 2011) characterized by an early phase of island-arc accretion and a later phase of continental-arc development in the Kamchatka-Koryak Mountains region (see fig. 1).

South of the Mongol-Okhotsk Suture (see figs. 4 and 6), subduction-related volcanic and intrusive rocks coeval with Okhotsk-Chukotka volcanic belt are recognized in the western Sikhote-Alin region in the Khingan-Okhotsk Arc (ko, fig. 4; also see fig. 6; Zonenshain and others, 1990; Şengör and Natal'in, 1996; Hourigan and Akinin, 2004; Seltmann and others, 2010). The Khingan-Okhotsk Arc is a middle to Late Cretaceous age continental arc that is considered by some (for example, Khanchuk and others, 2006) to be the southern extension of the Okhotsk-Chukotka volcanic belt (Faure and Natal'in, 1992; Kirillova, 2003; Natal'in, 2007; Parfenov and others, 2009). Khingan-Okhotsk arc magmatism was terminated by the collision and accretion of central and southern Sikhote-Alin tectonic units at the end of the Late Cretaceous (Zonenshain and others, 1990; Faure and others, 1995), forming the Amur Suture that separates the Khingan-Okhotsk magmatic arc on the west from the accreted terranes and younger magmatic rocks of the East Sikhote-Alin arc complex on the east (see figs. 4 and 6; Kirillova, 2003; Sato and others, 2004; Gonevchuk and others, 2010). The East Sikhote-Alin (ea, fig. 4; also see fig. 6) is a Late Cretaceous to early Paleogene age continental- and island-arc complex, consisting of the East Sikhote-Alin continental-arc on the west, and the Kema island-arc (ke on fig. 4) with accretionary basement on the east (Malinovsky and others, 2006; Volkov and others, 2006; Parfenov and others, 2009; Nokleberg, 2010). During Eocene time, the Sikhote-Alin active margin evolved to a transform margin characterized by northeast-trending, large-offset, left-lateral strike-slip faults (Natal'in, 2007; Nokleberg, 2010; Parfenov and others, 2011).

The Pacific Margin tract was defined using primarily calc-alkaline, intermediate-composition igneous map units with ages K_1, $K_{1\text{-}2}$, and mainly K_2, with less frequent units with K_2-E_1, E_1, E_2, and E_3 ages (fig. D2; see appendix H for descriptions of ages). Intrusive units include granite and granodiorite (including porphyries), quartz diorite, diorite, plagiogranite, granosyenite, quartz monzonite, with lesser amounts of leucogranite and

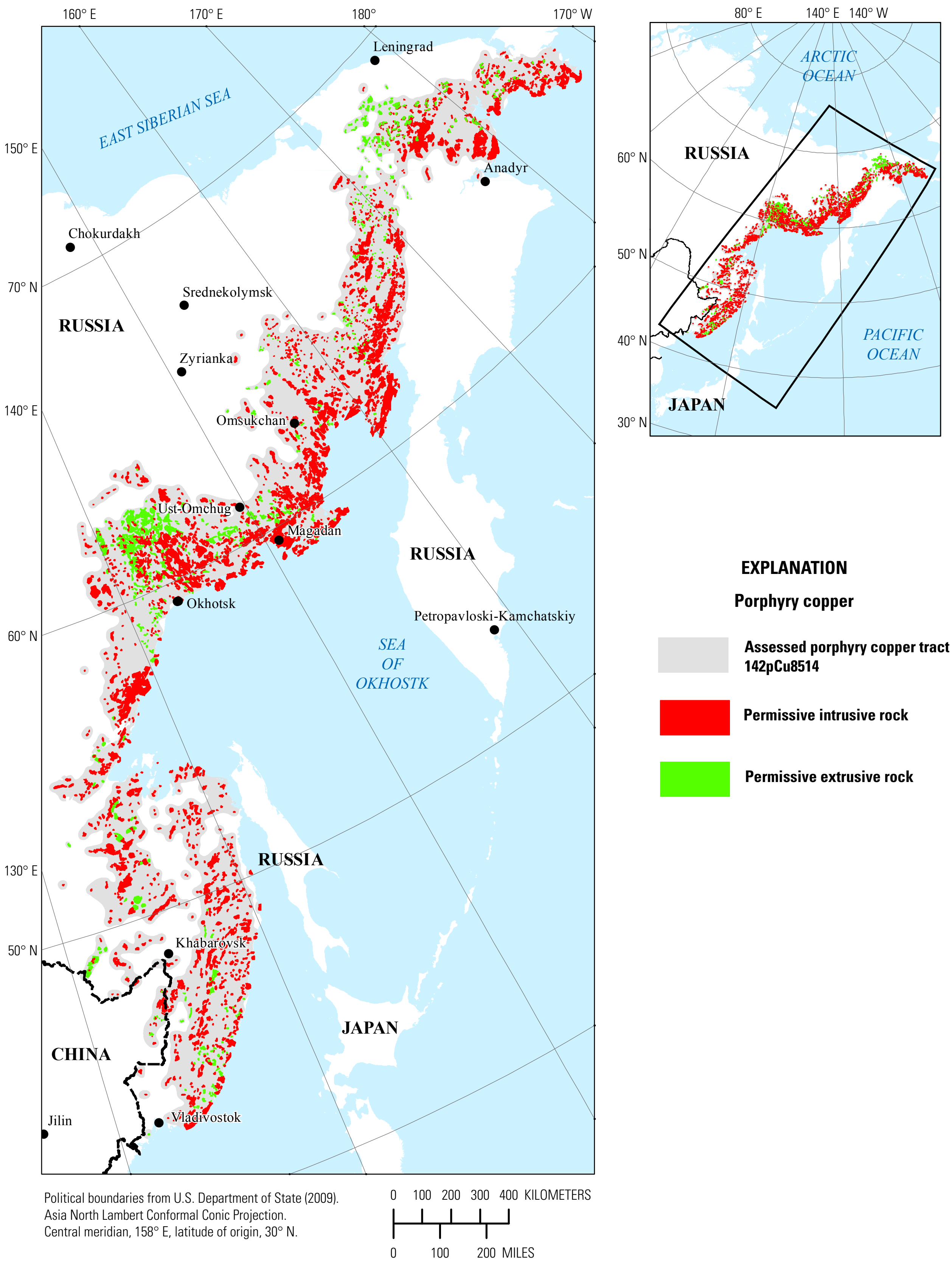

Figure D2. Map showing permissive rocks used to delineate tract 142pCu8514, Pacific Margin—Russia and China.

leucogranite porphyry, tonalite, quartz-gabbro, gabbro, diorite, monzonite, and syenite. Volcanic units include primarily rhyolite, rhyodacite, and dacite, closely associated with permissive intrusive units, with lesser amounts of andesite and various trachytes.

The Pacific Margin tract is not bound by any major crustal structures on its northwestern side, as the Cretaceous and younger magmatic arc rocks that form the tract intrude and overlap Early Cretaceous and older structures related to pre-existing tectonomagmatic events (see figs. 4, 5, and 6). The Late Jurassic–Early Cretaceous Mongol-Okhotsk Suture broadly divides the tract into northern and southern parts. The northeastern half of the northern part of the tract is bound to the east by latest Cretaceous and Paleogene sutures between younger volcanic rocks, fold belts, and terranes. The southwestern half of the northern part of the tract is bound to the east by subduction margin structures along forearc accretionary wedge complexes, and by a presumed Late Cretaceous suture along the western margin of the Okhotsk sea block. The southern part of the tract (south of the Mongol-Okhotsk Suture) is bound to the east by Late Cretaceous and Paleogene structures along the western margins of forearc and backarc basins. It is bound to the west by structures along the eastern margins of Mesozoic and Cenozoic accreted terranes and microcontinental blocks. No consensus exists on the nature, location, orientation, extent, and component parts of these structural features, and the regions they enclose. When aligned with aeromagnetic anomalies, many of these features as mapped coincide only in a general way. The extent of the tract is primarily constrained by selected permissive map units and the distribution of mineral deposits.

The Cretaceous to Tertiary temporal (time-slice) rationale and criteria used for selecting the igneous rock map units that compose the framework of this tract are consistent with metallogenic epochs and provinces (or belts) identified by Zvezdov and others (1993), Yakubchuk (2002), Sato and others (2004), Volkov and others (2006), Goryachev and others (2006), Nokleberg and others (1993, 1998, and 2005), and Parfenov and others (2011) (also see figs. 10 and 12).

Zvezdov and others (1993, fig. 1) delineated the Mesozoic and Cenozoic Okhotsk-Chukotka and Sikhote-Alin porphyry copper provinces, which are coincident with much of the southern and northern parts of the Pacific Margin tract. In an analysis of lithotectonic schemes and metallogeny of the North Pacific orogenic collage, Yakubchuk (2002, fig. 3) identified a Cretaceous episode of porphyry Cu-(Au-Mo) formation in the Sikhote-Alin segment of the Okhotsk-Alaska arc-backarc, which corresponds to the southern Sikhote-Alin part of the Pacific Margin tract. Sato and others (2004, figs. 2, 3, 4, and 8) note a similar episode of metallogenesis, but also distinguish between earlier, reduced-type (with Sn) granitoid magmatism in the western region of Sikhote-Alin (Khingan-Okhotsk continental arc) and later, oxidized-type (with Au) in the eastern region (East Sikhote-Alin continental arc). The Uda-Murgal, Okhotsk-Chukotka, and East Sikhote Alin metallogenic belts of Volkov and others (2006, fig.1 and table 2) correlate well with the Pacific Margin tract, and are defined on the basis of K_1, K_2, and K_2-E_1 magmatic rocks emplaced, respectively, in island-arc and marginal continental-arc settings. Goryachev and others (2006; figs. 8.8, 8.9, and 8.10) delineate a number of Early Cretaceous (136–99 Ma), Late Cretaceous (99–70 Ma), and Late Cretaceous and Paleocene (70–55 Ma) metallogenic belts that fully correspond with the Pacific Margin tract, and host Cu (±Au) porphyry, Cu-Mo (±Au, Ag) porphyry, and related deposit types such as epithermal Au-Ag. The Pacific Margin tract also corresponds with the accretionary–postaccretionary, Late Cretaceous through early Tertiary continental-arc-related metallogenic belts identified by Nokleberg and others (1993, 1998, 2005) and Parfenov and others (2011, plate "Time Stage 10 – Late Cretaceous (85 Ma)"). These include several metallogenic belts (Samarka, Sergeevka, Kema, and Lower Amur) in the southern part of the Pacific Margin tract that host porphyry Cu-Mo, porphyry Cu, and related epithermal Au-Ag and granite-related Au. In the northern part of the Pacific Margin tract, the metallogenic belts in Nokleberg and others (1993, 1998, 2005) and Parfenov and others (2011) include the eastern Asia Okhotsk Zone and Koni-Yablon Zone (among many others), which host porphyry Cu-Mo, porphyry Mo, and other deposit types such as epithermal Au-Ag, hot-spring and volcanic-hosted Hg, and granite-related Au.

Known Deposits

There is one known porphyry copper deposit in the tract (table D2, figs. 8 and D1, appendix F and G). Lora, a medium size deposit (see fig. 9) also known as Nakhatandjin, was described by Nokleberg and others (2005). It has a resource of 178 Mt, with grades of 0.5 percent copper, 0.025 percent molybdenum, and 2.1g/t silver (table D2). There is no information about gold. The mineralized zone, which has been tested by about 100 shallow drill holes, is in Early Cretaceous tonalite, granodiorite, and breccia that intrude older volcanic rocks. Much of the deposit is affected by sericitic and propylitic alteration.

Prospects, Mineral Occurrences, and Related Deposit Types

There are 53 significant porphyry copper prospects and at least 50 other smaller prospects (only the significant prospects are listed in table D3; figs. 8 and D1 show significant prospects as well as other prospects; also see appendix G and F). Malmyzh, Limonite, and Krasnaya Gorka are three significant prospects in the Sikhote Alin area in the southern part of the tract that are being actively drilled (Fortress Minerals Corporation, 2010). Obor, a prospect in the same general area, was reported to have an estimated resource of more than 400,000 t of copper in a press release from 1997, but more recent exploration results are unknown (Mosquito Consolidated Gold Mines, 1997).

Sources of Information

The assessment team relied primarily on (1) smaller-scale compilations (see table 1 for map scales) that do not include sufficient information to adequately resolve geologic and

Table D2. Porphyry copper deposits in tract 142pCu8514, Pacific Margin—Russia and China.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt*1,000,000) * Cu grade (percent)/100]

Name	Latitude	Longitude	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)
Lora	59.400	153.450	95.4	178	0.5	0.025	n.d.	2.1	890,000

Table D3. Significant prospects in tract 142pCu8514, Pacific Margin—Russia and China.

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; ppm, parts per million; min, minimum; max, maximum; avg, average. See deposits and prospects database in appendix F for sources of information]

Name	Latitude	Longitude	Age (Ma) or age range	Comments
Aulia	60.800	144.267	Late Jurassic through Paleogene	Cu (%): 0.01 min, 0.54 max, 0.1 avg; Mo values of 0.38 g/t max, and 0.02 g/t avg
Bebekan	64.337	160.337	Late Jurassic through Paleogene	avg 0.5% Mo, 0.7% Cu with minor Pb, Zn, W, Au, and Ag
Birandya	55.971	137.231	Late Jurassic through Paleogene	Grab samples: 1–3% Cu; 0.2 g/t Au; 30 g/t Ag
Birandya-1	55.774	136.619	Late Jurassic through Paleogene	Grab samples: >1% Pb; Cu in water 0.217 mg/l, pH 7.6
Blagodatnevskoe	53.318	140.067	Late Jurassic through Paleogene	Pyrite > chalcopyrite in quartz-carbonate-biotite veinlets; 1 to 6 g/t Au. Resources 5 t Au.
Chapka	57.614	139.347	Late Jurassic through Paleogene	Cu up to 0.5–1% in grab samples.
Chelasin	56.767	137.020	Late Jurassic through Tertiary	Grade of 1.0–9.4% Cu, up to 10.0 g/t Au, up to 1,119 g/t Ag, up to 3.0% Pb, up to 3.0% Zn
Chernoe	57.618	139.456	Late Jurassic through Paleogene	Channel samples: Cu 0.005–0.86% (avg 0.17%); Ag 10–70 ppm; Au 0.1–0.3 ppm. Cu 0.1–0.15% outside of metasomatites area. Chip samples: 0.02–0.04% Cu; 0.0004% Mo; 0.02 ppm Au; 0.02–0.06% Pb and Zn
Chipali	48.832	139.768	Late Jurassic through Paleogene	Stream sediment Cu-Mo anomaly (10 by 6 km), pyrite halo (10 by 10 km)
Darpichan	61.692	143.920	Late Jurassic through Tertiary	Grade of 0.01–2.0% Cu, 0.02–0.40% Mo, up to 0.3 g/t Au, and up to 96 g/t Ag
Degdenreken (Piritovoe)	62.015	155.928	Late Jurassic through Paleogene	A speculative resource of about 800 Mt at 0.5% Cu and 0.02% Mo (includes 0.05 g/t Au and 1 g/t Ag)
Dzhaore	52.659	141.249	Late Jurassic through Paleogene	Au up to 3 g/t
Etandzha	57.487	138.654	Late Jurassic through Tertiary	Grade of 0.02-2.0% Cu, 0.02-0.74% Mo; up to 4 g/t Au, up to 15 g/t Ag
Evening	63.517	158.567	Late Jurassic through Paleogene	Cu 0.05% avg; Mo 0.1% avg
Gedama-Yarku-Pravo Interfluve	52.738	139.622	Late Jurassic through Paleogene	Cu, Zn, Pb up to 0.3% each, Au 0.01 g/t, Hg 0.7%
Gora Krassnaya	66.580	175.518	85	avg grades 0.5–1.0% Cu, 0.2–1.0 g/t Au, 1–10 g/t Ag
Kekra	57.808	140.213	Late Jurassic through Paleogene	Cu grades in altered volcanic rocks (grab samples) as high as 1% Cu and 1 g/t Au; veins up to 3% Cu and 30 g/t Au
Kentavr 100	52.607	138.757	Late Jurassic through Paleogene	Cu grades in grab samples range from 0.06 to 0.5% Cu and avg about 0.7 g/t Au
Khvoshchovoe	47.974	136.186	Late Jurassic through Tertiary	Grade of 0.02–0.4% Cu, 0.01–0.20% Mo, 0.01–0.09% W
Krasnaya Gorka	53.376	140.159	Late Jurassic through Tertiary	Cu grade: up to 0.3% at the Central quartz limonite stockwork and up to 0.8% in an area of unaltered bedrock lower on the flanks of the Krasnaya Gorka hill; Au 3 g/t

Table D3. Significant prospects in tract 142pCu8514, Pacific Margin—Russia and China.—Continued

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; ppm, parts per million; min, minimum; max, maximum; avg, average. See deposits and prospects database in appendix F for sources of information]

Name	Latitude	Longitude	Age (Ma) or age range	Comments
Lazurnoe (Primorskiy kray)	44.100	134.400	105.5	Contains up to 3 g/t Au, 0.3–0.6% avg Cu, 0.008–0.2% Mo. The porphyry stockwork zone has an avg concentration of approximately 0.15% Cu
Levy Turmachan	57.583	139.117	Late Jurassic through Paleogene	Channel samples with up to 0.52% Cu; grab samples anomalous in Cu, Zn, Pb, B, Ag
Limonite	51.250	139.650	Late Jurassic through Tertiary	Cu grade: 0.11%; Mo grade: 0.28%. Classic porphyry copper geochemical and geophysical signature
Maginskoe	53.278	140.122	Late Jurassic through Paleogene	Phelps Dodge Exploration Corp. 2004, 1 chip sample of quartz-sericite metasomatite: Cu 60 ppm, Au 0.02 ppm, Mo 80 ppm
Malakhitovoe (Primorskiy kray)	47.098	135.072	112.5	Small deposit, grade of 0.1–1.6% Cu in stockwork; up to 0.5% Cu in breccia zone
Malinovskoe	45.136	135.037	105.5	Grade of 0.6–12.9 g/t Au, 0.42–4.5% Cu
Malmyzh	49.870	136.846	Late Jurassic through Tertiary	Cu grade: 23 drill holes ranging from 0.12%–0.58% with the highest amounts in the 'Central' target; Au g/t: ranging from 0.01–1.49, most are within 0.05–0.20
Maloe	55.722	136.581	Late Jurassic through Paleogene	Cu up to 1%, Ag 30 ppm
Moinskoe	48.097	138.637	Late Jurassic through Paleogene	Range up to 0.3% Cu, 0.3% Mo
Nochnoe	48.564	138.571	69	Grade ≥0.6% Cu
Obor	48.564	136.694	Late Jurassic through Tertiary	Estimated resource in 1997: 65.7 Mt at 0.67% Cu, 0.1% Mo, and 0.42 g/t Au
Oborsky	47.824	135.860	Late Jurassic through Paleogene	Soil anomalies (ppm): Cu (50–300), Mo (3–30). Linear bodies of hypogene mineralization (600–1500 m by 50–200 m) at Cu 0.11%, Au 0.04 ppm, Mo 0. 011%; tapers out at a depth of 150–200 m.
Olgondo	55.153	135.551	Late Jurassic through Paleogene	Grab samples up to 0.3% Cu, 0.01% Mo; chip samples are 0.01 - 0.02% Cu.
Ol'khovka	65.685	170.483	Late Jurassic through Paleogene	Avg grades 0.5–1.0% Cu (listed for prospects Ol'khovka, Probny).
Orliny	63.751	160.067	Late Jurassic through Paleogene	Possible greisen. 0.01–0.03% Mo.; 0.05–0.1% Cu, 0.07% Mo.
Osennee	59.717	150.317	94.5	≤0.1% Cu, 0.1 to 0.33% Mo, 0.1g/t Au, 1–5g/t Ag; no production, but 0.6 Mt of ore have been estimated.
Plastun	44.653	136.203	Late Jurassic through Tertiary	Associated skarn contains 30–350 g/t Ag, 0.3–0.8% Cu.
Pravy Olen	47.267	134.600	Late Jurassic through Paleogene	Grab samples: Mo 0.001–0.6%, Cu 0.001–0.4%, W 0.001–0.06%, Sb 0.005–0.5%; Other reported grades: Cu (%), 0.01 min, 0.06 max, 0.02 avg; Mo (%), 0.6 max, 0.01 avg
Prostornoe (Chernaya Dyra)	50.252	136.293	Late Jurassic through Paleogene	The induced polarization anomaly called "Chernaya Dyra" corresponds with an interval of 32–40 m with reported grades of 2.5% Cu, 5.7 ppm Au, and up to 0.4% Pb, Zn, and Sb. Core samples: 0.02–0.1% Cu, up to 3 ppm Au; The best hole is DDH 329 (17.6 m at 0.54% Cu)

metallogenic features in more detail, (2) the experience and knowledge of our assessment team's international collaborators, (3) academic publications in the scientific literature, and (4) promotional materials from the Web sites of mineral exploration companies. Most useful to this assessment were the expertise and insights about existing research and data provided by our international collaborators, as well as regional- and local-scale metallogenic studies and maps from scientific papers and exploration company materials. In addition, Google Earth imagery and user-uploaded personal photographs often provided a means by which to verify the locations of deposits and prospects.

Grade and Tonnage Model Selection

The general porphyry copper grade and tonnage model of Singer and others (2008) was used. There is only one known porphyry copper deposit in the tract (Lora, table D2) with available grade and tonnage data. The results of an analysis of variance (ANOVA) test, applied at the 1-percent confidence level using log-transformed values for ore tonnage and grades of copper, molybdenum, silver, and gold, indicate that overall, Lora is indistinguishable from the general model.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The Pacific Margin tract is the largest of the five northeast Asia tracts, making up a little less than 53.5 percent of the total area of all the tracts combined. There is one known deposit, Lora, and at least 53 significant prospects (see table D2 and D3, appendixes F and G). With respect to contained copper, Lora is a medium- to small-size deposit compared to deposits world-wide (see fig. 9), and there are only a few significant and smaller porphyry copper prospects within 10 to100 km. Significant prospects are otherwise distributed along the entire length of the tract, but are more numerous in the southern Sikhote-Alin region of the tract. Most have been explored and sampled in some detail, and grades are reported for a number of them. Obor has a 1997 estimated resource of 65.7 Mt of ore with a copper grade of 0.67 percent. In addition, there are at least 50 other prospects that have been identified on various maps and in related datasets (Nokleberg and others, 1993, 1998, 2005; Rodnov and others, 2001; see appendix F and G).

The assessment team noted that although there is only one porphyry copper deposit, Lora, there are many high-quality significant and other prospects, including many occurrences such as epithermal Au-Ag that are possibly porphyry-related. The western part of the southern part of the tract, in the Sikhote-Alin region, however, was considered to be less prospective than regions to the east because of a higher concentration of Mo-, W-, Sn-, and polymetallic-vein and hot-spring Hg prospects and deposits. Nevertheless, the team still considered this area prospective because it hosts at least one significant porphyry Cu(Au)-Mo prospect (Malmyzh) and six other prospects described as "porphyry Mo-Cu(Au) associated with granite-granodiorite and diorite-monzonite intrusions" (Andrei F. Chitalin, consultant, written comm., 2009; Rodnov and others, 2001).

The team recognized that the tract as a whole is comparable in tectonic setting, dimensions, and geologic age-range to the North American Cordillera of the United States and Canada. It includes a wide variety of intrusion-related deposit types and permissive rock types, but also many rocks that, because of lack of information, could not be unequivocally excluded as nonpermissive (for example, S-type granitoids). In general, the proportion of volcanic to intrusive rocks suggests that the level of erosion across this vast region is appropriate for near-surface exposure of porphyry systems, although not uniformly because large areas are covered by ignimbrite units.

When making estimates for undiscovered deposits for the Pacific Margin tract as a whole, the assessment team took into consideration that the tract appears to have three regions, each with different levels of prospectivity: (1) north of the Mongol-Okhotsk Suture, including the Cretaceous Okhotsk-Chukotka volcanic belt and underlying Late Jurassic-Early Cretaceous Uda-Murgal continental- and island-arc complex (figs. 4, 5, and 6), (2) southeast of the Mongol-Okhotsk Suture, including the East Sikhote-Alin continental- and island-arc complex (figs. 4 and 6), and (3) immediately south of the Mongol-Okhotsk Suture inland and west of the East Sikhote-Alin complex (figs. 4 and 6; see Faure and others, 1995; Khanchuk and others, 2006; Parfenov and others, 2009; and Nokleberg, 2010).

Akinin and Miller (2011) characterized the Okhotsk-Chukotka volcanic belt as a tectonotype of continental margin volcanic belts containing much greater volumes of felsic ignimbritic volcanics compared to the Andean continental margin, but, like the Andean margin, having rocks enriched in K, Ti, and P, with a compositional trend toward high-potassium calc-alkaline series. In addition to elevated K in the volcanic rocks, Seltmann and others (2010) also noted the widespread occurrence of ignimbrites, which generally pre-date mineralization. The assessment team regarded this characterization as prospective for the presence of undiscovered Cu- and Cu-Au porphyry copper deposits.

The Sikhote-Alin region of the tract, south of the Mongol-Okhotsk Suture, can be subdivided metallogenically into two provinces: (1) the middle to Late Cretaceous Khingan-Okhotsk magmatic arc (fig. 6), characterized by Sn-bearing reduced-type granitoids, and (2) the Late Cretaceous-Paleogene East Sikhote-Alin magmatic arc (fig. 6), characterized by Au-bearing oxidized-type granitoids (Sato and others, 2004). The East Sikhote-Alin Arc is considered to have much potential for undiscovered deposits. According to Andrei Chitalin (oral commun., 2009), of Regional Mining Company LLC, Russia, the East Sikhote-Alin magmatic arc has many prospective Cu-Au, Cu-Mo, and Mo-Cu porphyry systems, commonly associated with high sulfidation epithermal gold mineralization. The East Sikhote–Alin area is best known as a gold belt that hosts low-sulfidation epithermal gold-silver deposits such as the MNV (Mnogovershinnoe) deposit (Sato and others, 2002). In contrast, the Khingan-Okhotsk magmatic arc, located west, inland of the East Sikhote-Alin arc, is a well-known source of tin, accounting for approximately 70 percent of Russia's production (Gonevchuk and others, 2010). In the Khingan-Okhotsk arc region, Nokleberg and others (2004, 2006) delineated and described Late Cretaceous metallogenic belts that include deposit types such as Sn-W greisen, Sn-W stockwork and quartz vein, and porphyry-and rhyolite-hosted Sn. Many of the tin deposits are associated with S- and A-type granites. These metallic deposit suites and granitic rock types are not typically associated with porphyry copper mineralization. Although there are a few porphyry copper prospects in this region, the assessment team considered the metallogenic environment and tectonomagmatic setting not particularly favorable for the formation of porphyry copper deposits, and decidedly less prospective than the other parts of the Pacific Margin tract that include rocks of the Okhotsk-Chukotka/Uda-Murgal and East Sikhote-Alin arc complexes.

The assessment team concluded that the level of mineral exploration was variable along the length of the tract. In general, the northernmost parts of the tract have lower levels of exploration, whereas those regions of the tract along the Sea of Okhotsk are moderately explored and emerging. Many of the regions within the tract have limited accessibility, particularly in the far northern part of the tract. Index maps showing geologic mapping conducted in the 1910s and 1930s (fig. 13; S.R.Tikhomirova, written commun., 2011) suggest that exploration during this time was sparse, concentrating mainly in the northernmost Magadan region, and less so throughout the Sikhote-Alin region. Most of this area has not been mapped at large scales (such as 1:50,000 scale), and most of the 1:200,000 geologic mapping, carried out by VSEGEI (A.P. Karpinsky Russian Geological Research Institute), was done before 1979 and between 1980 and 1995 for the northern part of the tract, and before 1979 for much of the central and southern parts of the tract. Mapping conducted between 1996 and 2004 is scattered across the full extent of the tract. The assessment team concluded that, despite a 50-year or longer history of research, the Okhotsk-Chukotka volcanic belt remains poorly understood. Most of the established Au-Ag deposits and prospects have been explored at only a reconnaissance level, and geochemical anomalies have not been further investigated (Sidorov and others, 2009). No high-quality geophysical surveys aimed at the discovery of hidden ore bodies have been conducted, and epithermal mineralization and their possible links to porphyry copper systems at depth remain ambiguous. In contrast, the Sikhote-Alin region is probably the best explored area of the tract because of its tin mining history (Gonevchuk and others, 2010), particularly since the bulk of Russia's output comes from lode deposits, rather than placers (Levine and Bond, 1994).

The assessment team estimated a 90-percent chance for 10 or more undiscovered deposits in the tract, a 50-percent chance of 20 or more deposits, and a 10-percent chance of 100 or more deposits, for a mean of 40.0 expected undiscovered deposits (table D4; also see fig. 13). Relative to the other tract estimates in this assessment, a smaller uncertainty in the number of undiscovered deposits estimated (C_v% = 84) reflects the presence of a porphyry copper deposit and numerous significant prospects, a reasonably well understood tectonomagmatic framework, and a comparable geologic setting of the Pacific Margin tract with the North American Cordillera of the United States and Canada.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table D5 (also see fig. 13). Results of the Monte Carlo simulation are also presented as a cumulative frequency plot (fig. D3), which shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table D4. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu8514, Pacific Margin—Russia and China.

[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, square kilometers; area, area of permissive tract in square kilometers; density, 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}		
10	20	100	100	100	40.0	34.0	84	1	41.0	1,138,430	3.6

Table D5. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu8514, Pacific Margin—Russia and China.

[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	8,300,000	17,000,000	95,000,000	370,000,000	430,000,000	150,000,000	0.39	0.01
Mo	99,000	260,000	2,300,000	10,000,000	14,000,000	4,100,000	0.36	0.02
Au	160	370	2,400	9,300	11,000	3,800	0.39	0.02
Ag	910	2,600	27,000	120,000	160,000	49,000	0.36	0.03
Rock	1,900	3,700	20,000	74,000	87,000	31,000	0.39	0.01

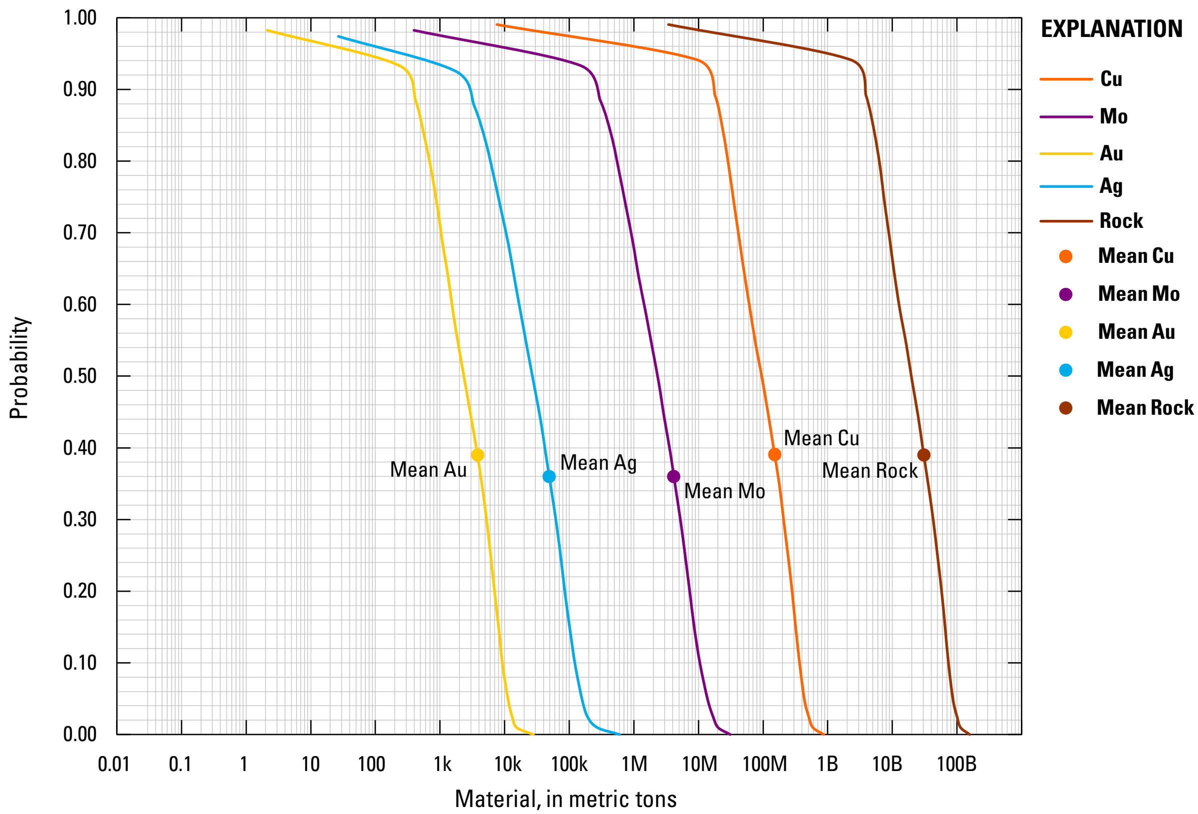

Figure D3. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract142pCu8514, Pacific Margin—Russia and China. (k=thousands, M=millions, B=billions).

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Appendix E. Porphyry Copper Assessment for Tract 142pCu8515, Kamchatka-Kuril—Russia

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Deposit Type Assessed: Porphyry Copper

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

Location

The Kamchatka-Kuril tract is a semifragmented belt about 2,500 km in length and 300 km at its widest (fig. E1). It extends south from the latitude of Anadyr (see fig. 1[5]), across the Koryak Mountains and Central Range of the Kamchatka Peninsula, to Kunashir Island at the southern end of the Kuril Islands (fig. 1). Most of the tract lies within the Chukot and Koryak Autonomous Provinces and the Kamchatka Region of Russia, with a narrow trend of permissive areas that extend southwest into the Sakhalin Region along the Kuril Islands.

Table E1. Summary of selected resource assessment results for tract 142pCu8515, Kamchatka-Kuril—Russia.

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

Date of assessment	Assessment depth (km)	Tract area (km^2)	Known copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2011	1	195,150	-	34,000,000	20,000,000

Geologic Feature Assessed

An assemblage of latest Cretaceous through Quaternary volcanic and intrusive rocks that extend along the Kamchatka Peninsula and Kuril Islands of the Russian northeast and southeast was assessed as the Kamchatka-Kuril tract. The rocks represent a series of continental- and island-arc complexes that were successively accreted and superimposed west-to-east onto the outboard margin of northeast Asia in response to subduction of the ancestral and present-day Pacific Ocean plate (figs. 7).

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[3]Geological Institute, Russian Academy of Sciences, Moscow, Russia.

[4]XDM Geological Consultants, Victoria, British Columbia, Canada.

[5]Refers to figures in the main text.

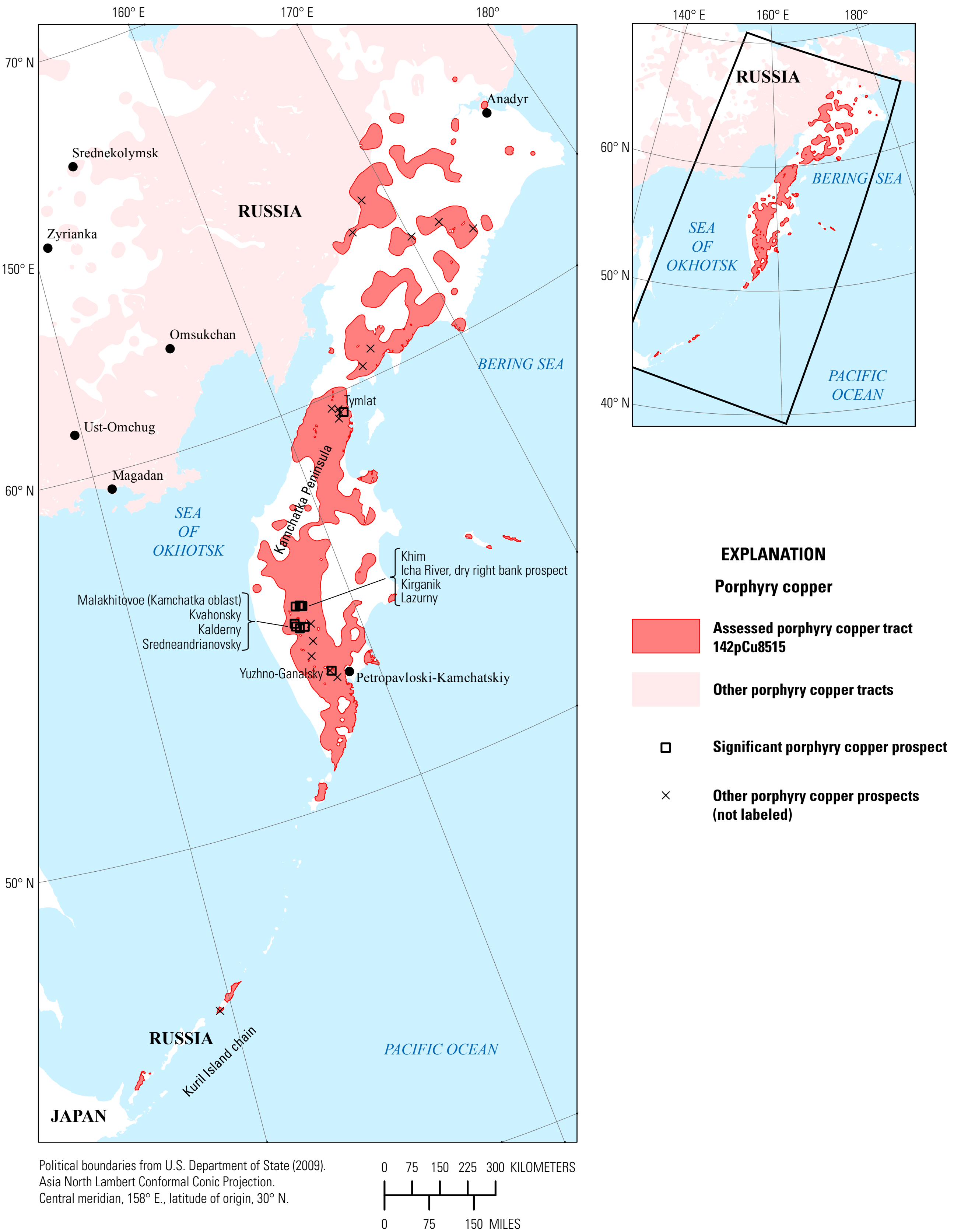

Figure E1. Map showing tract location and known porphyry copper occurrences for tract 142pCu8515, Kamchatka-Kuril—Russia.

Delineation of the Permissive Tract

Geologic Criteria

The Kamchatka-Kuril tract was delineated on the basis of igneous rock lithology, tectonomagmatic and metallogenic features, and known mineral deposits and prospects. Regional-scale structural boundaries and the distribution of other deposit types were considered in constraining tract boundaries. Holocene volcanoes and cones were excluded from the tract.

In late Mesozoic and Cenozoic time, following the amalgamation of the Kolyma-Omolon and Arctic Alaska–Chukotka microcontinents to the Siberian craton during the Jurassic and Early Cretaceous (appendix C), orogenic activity shifted southeast (present day geography) to the newly consolidated Pacific Margin of northeast Asia. During middle to Late Cretaceous time, the Andean-style Okhotsk-Chukotka continental-arc developed in response to subduction of the ancestral Pacific Plate under Eurasia (figs. 4, 5, and 6; Zonenshain and others, 1990; Hourigan and Akinin, 2004; Parfenov and others, 2009; Akinin and Miller, 2011; see appendix D). Termination of Okhotsk-Chukotka magmatism in Late Cretaceous time (about 81 Ma) may reflect the collision of a microcontinental block or oceanic plateau with the margin (see discussions in Hourigan and others, 2009, and Konstantinovskaya, 2011). As a result, orogenic activity shifted eastward to an oceanic tectonic setting (Akinin and Miller, 2011) with the accretion of island-arc complexes and subsequent continental- and island-arc development in the greater Koryak-Kamchatka-Kuril region (see KOR, EP, ku on fig. 4).

Magmatic rocks of the Koryak-Kamchatka-Kuril region are associated with five arc complexes composed of one or more adjacent or superimposed arcs: (1) Olyutorka-Kamchatka, (2) Koryak-Kamchatka, (3) Central Kamchatka, (4) East Kamchatka, and (5) Kamchatka-Kuril (see OK, kk, kc, ek, and ku on fig. 4; fig. 7). The Late Cretaceous to Paleocene age Olyutorka-Kamchatka island arc (parts of which are variously referred to in the literature as the Achaivayam-Valaginskiy and Irunei Arcs), along with associated accretionary complexes, oceanic terranes, and collision-related continental fragments, forms the basement for much of the Kamchatka Peninsula and Koryak region to the north. The island-arc complex was accreted to a submerged, offshore part of the northeast Asian margin (a microplate or oceanic plateau underlying the Sea of Okhotsk) in early to middle Eocene time after being transported a long distance from the southeast (Harbert and others, 2003; Avdeiko and others, 2007; Hourigan and others, 2009; Shapiro and Solov'ev, 2009; Konstantinovskaya, 2011, and references therein). Subduction was directed southeast, under the island-arc before docking, but polarity apparently switched along the southern extent of the arc complex after collision (see Shapiro and Solov'ev, 2009; also see discussion in Park and others, 2002, and references therein). Shortly after the Olyutorka-Kamchatka island arc accreted, the middle to late Eocene Koryak-Kamchatka continental arc developed in the northwestern Kamchatka-Koryak region in response to the initiation of a short-lived(?), southeast-dipping subduction zone (Zonenshain and others, 1990; Nokleberg and others, 2000, 2005; Hourigan and others, 2009, and references therein).

During the Oligocene to Miocene, magmatic activity shifted southeastward generating the Central Kamchatka continental-arc located along the central-axis of the Kamchatka Peninsula and isthmus (kc on fig. 4; also see fig. 7; Avdeiko and others, 2007; Parfenov and others, 2011). Magmatism was a product of northwest-dipping subduction beneath Kamchatka, presumably related to the switch in subduction polarity after the accretion of Olyutorka-Kamchatka island arc and associated terranes and complexes (Shapiro and Solov'ev, 2009). To the south, contemporaneous arc magmatism was taking place along the Kuril Islands, which can be considered a southern island-arc extension of the continental-arc of Central Kamchatka (Parfenov and others, 2011). Residual magmatism continued in the Central Kamchatka Arc into Pliocene and Quaternary time as the focus of active arc magmatism shifted further to the southeast, developing the Pliocene to recent-time East Kamchatka continental-arc along the southeastern margin of the Kamchatka Peninsula (ek on fig. 4; also see fig. 7). East Kamchatka arc magmatism is associated with northwest-dipping subduction of the present-day Pacific Plate, and can be considered the northern continental-arc extension to ongoing Kamchatka-Kuril island-arc magmatism (ku on fig. 4; also see fig. 7.

The tract was defined using calc-alkaline, intermediate-composition igneous map units with ages N_1, N_2, and Q, and some units designated as K_2-E_1, E_1, E_2, and E_3 (fig. E2; see appendix H for ages descriptions). Intrusive units include diorite, granodiorite, quartz diorite, and granite, including porphyries, with lesser amounts of gabbro-diorite, syenodiorite, plagiogranite, granosyenite, syenite, monzodiorite, and alkaline granites. Volcanic units include primarily andesite, dacite, and rhyolite closely associated with permissive intrusive units, with lesser amounts of rhyodacite, basaltic andesite, and various trachytes.

The Kamchatka-Kuril tract is bound on its northern part along the southeast by an inactive middle Cenozoic subduction trench, and on its southern part by an active present-day subduction trench that extends along the lower portion of the Kamchatka Peninsula and down the Kuril island chain (see figs. 4, 5, and 7). The northeastern and northwestern extents of the tract are bound by sutures and related structures separating Late Jurassic to Late Cretaceous island-arc terranes and volcanic belts to the west, and early Tertiary and younger accreted terranes and fold belts to the east. The western and southwestern extents of the tract are bound by various structures along the margins of Cenozoic sedimentary basins and the Okhotsk Sea backarc basin block. Internally, the tract extents are controlled by subduction-related magmatic belts and sutures related to the accretion of island-arc terranes that were progressively added west-to-east during Paleocene time through the Quaternary.

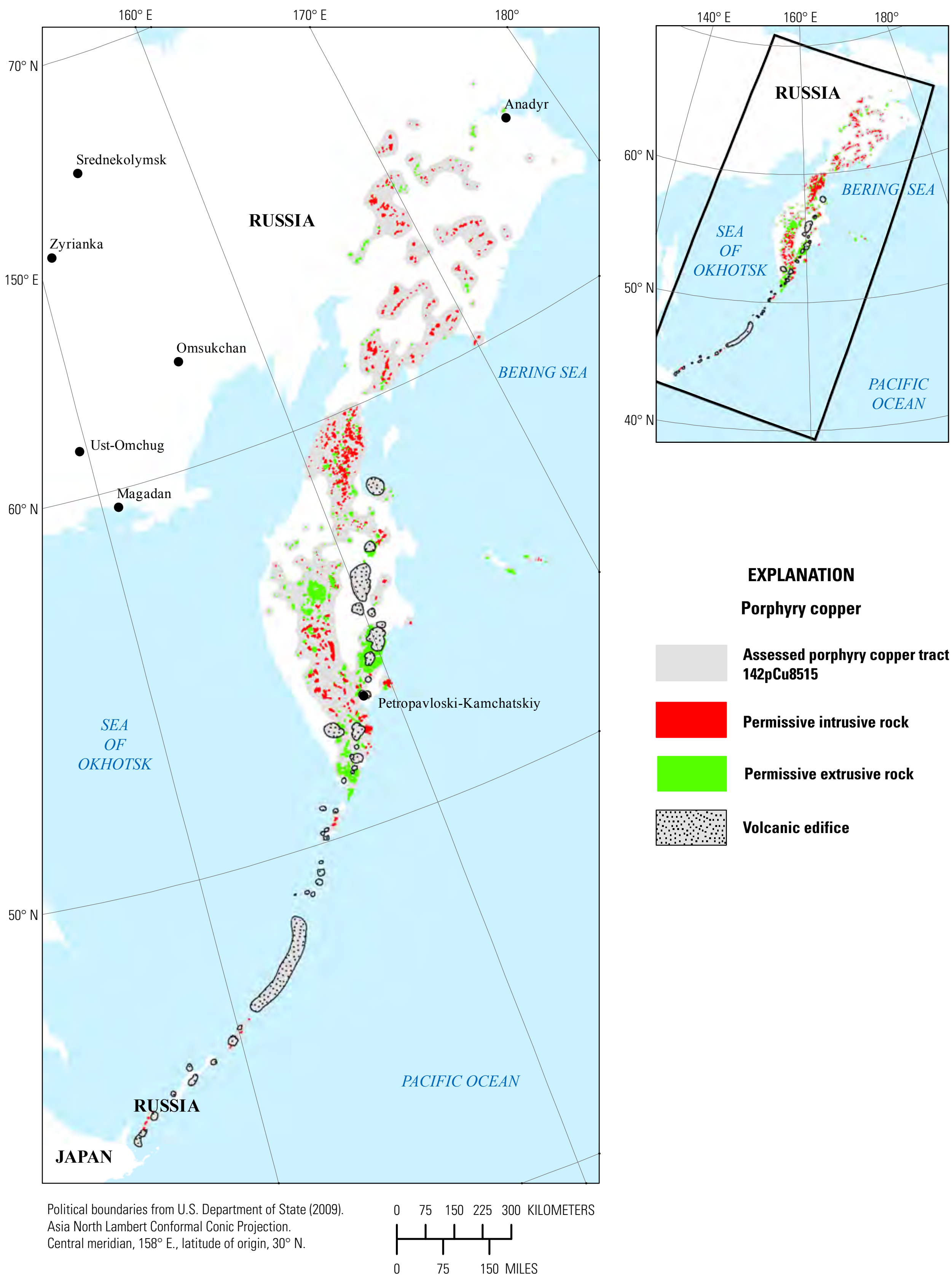

Figure E2. Map showing tract location and known porphyry copper occurrences for tract 142pCu8515, Kamchatka-Kuril—Russia.

The rationale for selecting the latest Cretaceous to Paleogene-Neogene-Quaternary time-slice as a basis for tract delineation and criteria used for selecting the igneous rock map units for this tract are consistent with metallogenic epochs and provinces (or belts) identified by Zvezdov and others (1993), Yakubchuk (2002), Litvinov and others (1999), Volkov and others (2006), Goryachev and others (2006), Nokleberg and others (1993, 1998, and 2005), and Parfenov and others (2011) (also see figs. 10 and 12).

Zvezdov and others (1993) delineated the Mesozoic and Cenozoic Kamchatka porphyry copper province, which is coincident with much of the Kamchatka-Kuril tract on the Kamchatka Peninsula presented here. In an analysis of lithotectonic schemes and metallogeny of the North Pacific orogenic collage, Yakubchuk (2002) identified Neogene episodes of porphyry Cu-(Au-Mo) formation in the East Kamchatka and Kuril-Komandor zones of the Kuril-Kamandor arc-backarc complex, which corresponds to the Kamchatka Peninsula and Kuril Island chain part of the tract (fig. E1). Litvinov and others (1999; inset map “Schema of Metallogenic Zoning”) identify precious and base metal metallogenic provinces of Eocene-Oligocene-Miocene-Pliocene age that correspond to the main part of the tract on the Kamchatka Peninsula and the region to the north. In particular, the Central Kamchatka, Kuril-Kamchatka South, Oliutorskii, and Central Koryak provinces of Litvinov and others (1999) are coincident with most of the tract on the peninsula. The Koryak, Central Kamchatka, and Kuril metallogenic belts of Volkov and others (2006) correlate well with the Kamchatka-Kuril tract as a whole, and are defined on the basis of the extent of Eocene through Quaternary magmatic rocks, in volcanic island-arc and marginal continental volcanic belt settings. Goryachev and others (2006) delineate a number of Late Cretaceous and Paleocene (70–55 Ma), Miocene (23–5 Ma), and Late Miocene to Quaternary (5–0 Ma) metallogenic belts, which correspond with nearly the complete extent of the Kamchatka-Kuril tract, and host Mo-, Cu-, Mo-Cu porphyry, and related deposit types such as epithermal Au-Ag and polymetallic vein. The Kamchatka-Kuril tract also corresponds closely with the post-accretionary, middle Eocene through Miocene, continental-arc-related metallogenic belts identified by Nokleberg and others (1993, 1998, 2005) and Parfenov and others (2011, plates “Time Stage 12 – Miocene (10 Ma)” and “Time Stage 13 – Present (0 Ma)”). These include the Central Koryak, Olyutor, Central Kamchatka, East Kamchatka, and Kuril belts, which host porphyry Cu-Mo, porphyry Cu, and coeval deposit types such as epithermal Au-Ag, hot-spring and polymetallic veins.

Known Deposits

There are no porphyry copper deposits known in this tract.

Prospects, Mineral Occurrences, and Related Deposit Types

There are 10 significant porphyry copper prospects and at least 17 other smaller prospects (only the significant prospects are listed in table E2; figs. 8 and E1 shows significant prospects as well as other prospects; also see appendix F and G). Kirganik and Khim are about 12 km apart and are both late Cretaceous in age. Kirganik is described by Nokleberg and others (2005) as an economic porphyry copper deposit hosted in silicic volcanic rocks. It is described as a medium sized deposit, but no resource information is given. In 2013, Rio Tinto won a tender to explore Kirganik in partnership with ICT, a Russian company (Rio Tinto, 2014). Icha River, Lazurny, Malakhitovoe, Kvahonsky, Kalderny, Sredneandrianovsk, and Yuzhno-Ganalsky are all located in southern Kamchatka, in a 250-km-long belt stretching southeastward from Kirganik. They are all reported to be Miocene in age. In addition, Tymlat, for which limited information is available, is part of a group of four Miocene prospects that are about 600 km north of Kirganik, in northern Kamchatka.

Sources of Information

The assessment team relied primarily on (1) smaller-scale compilations (see table 1 for map scales) that do not include sufficient information to adequately resolve geologic and metallogenic features in more detail, (2) the experience and knowledge of our assessment team’s international collaborators, (3) academic publications in the scientific literature, and (4) promotional materials from the Web sites of mineral exploration companies. Most useful to this assessment were the expertise and insights about existing research and data provided by our international collaborators, as well as regional- and local-scale metallogenic studies and maps from scientific papers and exploration company materials. In addition, Google Earth imagery and user-uploaded personal photographs often provided a means by which to verify the locations of deposits and prospects.

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. Given the varied magmatic environments present, the general model was deemed the most appropriate to represent the types of porphyry copper deposits that could possibly form in this tract.

Table E2. Significant prospects in tract 142pCu8515, Kamchatka-Kuril—Russia.

[Ma, million years; %, percent; g/t, grams per metric ton; min, minimum; max, maximum; avg, average. See deposits and prospects database in appendix F for sources of information]

Name	Latitude	Longitude	Age (Ma) or age range	Comments
Icha River, dry right bank prospect	55.267	157.633	Late Cretaceous through Quaternary	0.1–1.0% Cu; 0.2–7.7 g/t Au; 1.5–15.5 g/t Ag
Kalderny	54.700	157.300	Late Cretaceous through Quaternary	Cu (%): 0.5 avg; Mo(%): 0.01 min, 0.02 max, 0.02 avg
Khim	55.280	157.456	Late Cretaceous through Quaternary	0.1–3.34% Cu; 0.1–7.7 g/t Au; 2.5–15.5 g/t Ag
Kirganik	55.241	157.678	70	Avg grades are 0.1–1% Cu and 0.2–0.4 g/t Au in disseminated and veinlet ore, and as much as 0.8 g/t Au in oxidized ore
Kvahonsky	54.783	157.167	Late Cretaceous through Quaternary	Cu (%): 0.05 avg; Mo (%): 0.01 min, 0.03 max, 0.02 avg
Lazurny	55.233	157.750	Late Cretaceous through Quaternary	Cu (%): 0.1 min, 0.46 max; Au (g/t): 0.4 min, 38.2 max; Ag (g/t): 10.3 min, 376.2 max
Malakhitovoe (Kamchatka oblast)	54.761	157.342	Late Cretaceous through Quaternary	Medium deposit, avg grades of 0.55% Cu and 0.021% Mo; also described as small to medium deposit with 0.32% Cu and 0.005% Mo
Sredneandrianovsky	54.700	157.533	Late Cretaceous through Quaternary	Cu (%): 0.5 avg, 0.05 min, 1 max; Mo (%): 0.02 min, 0.03 max
Tymlat	59.480	162.980	Late Cretaceous through Quaternary	2008 Cu-Au exploration by Norilsk Nickel and Rio Tinto
Yuzhno-Ganalsky	53.383	158.000	Late Cretaceous through Quaternary	Max grades: 0.8% Cu, 0.2% Mo, 0.5 g/t Au

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The Kamchatka-Kuril tract is one of the smallest of the five northeast Asia tracts, making up a little more than 9 percent of the total area of all the tracts combined. Ten significant prospects are known, and with the exception of Tymlat, all are located in the central part of the tract (see table E3, appendixes F and G). In addition, there are at least 17 other prospects distributed along the entire length of the tract (including one, the Urup Gold project, in the southern part of the Kuril Islands) that have been identified on various maps and related datasets (Nokleberg and others, 1993, 1998, 2005; Rodnov and others, 2001; see appendixes F and G).

The assessment team considered the Kirganik and Malakhitovoe significant prospects to be promising occurrences with characteristic porphyry copper attributes and reasonable exploration copper grades. It was also noted that there are abundant Cu-Au and Cu-Mo porphyry prospects, as well as many epithermal Au-Ag and hot spring mineral occurrences associated with calc-alkaline rocks.

The team observed that a wide variety of permissive rock compositions are present in the tract, but that volcanic units greatly exceeded the proportion of plutonic rocks, particularly on the eastern side of the Kamchatka Peninsula. Although the presence of volcanic rocks is considered permissive, it indicates that the level of erosion is shallow. Overall, the abundance of volcanic rocks and recent volcanic edifices (volcanic cones, thick lava and debris flow sequences) raises concerns about whether the erosion levels are too shallow to allow exposure of porphyry systems. The team also noted widespread basin development, particularly on the western side of the peninsula, which also may imply the presence of thick overburden. The Late Cretaceous to Paleogene-Neogene volcanic belts of the northern and western parts of the tract are considered more prospective than the eastern and southern late Miocene and younger volcanic belt that extends along the eastern side of Kamchatka and south off the peninsula along the Kuril Island chain. This is because arc rocks associated with the older belts, extending from the mainland south down the center of the peninsula, exhibit less volcanic cover and a deeper level of erosion. The younger volcanic belt represents a continental-arc along an ocean-continent convergent margin to the north on the Kamchatka Peninsula, and an island-arc to the south, along the Kuril Island chain. If porphyry copper systems are present here, they are actively forming and likely buried under thick volcanic cover.

Exploration in the region has focused on epithermal gold systems, rather than porphyry deposits. Index maps showing geologic mapping conducted in the 1910s and 1930s (fig. 13; S.R.Tikhomirova, written commun., 2011) suggest that exploration in general on the Kamchatka Peninsula during this time was sparse, concentrating mainly around the western coast and the inland south-central region. Because of its strategic military importance, much of the peninsula was not open to systematic mineral exploration work by Soviet geologists until the 1970s, and it was not until 1992 that foreigners were given permission to enter Kamchatka (Nally, 2003; see also Lattanzi and others, 1995, and references therein). Most of the 1:200,000 geologic mapping, carried out by VSEGEI (A.P. Karpinsky Russian Geological Research Institute), was done from 1980 through 2004.

The assessment team estimated a 90-percent chance for 2 or more undiscovered deposits in the tract, a 50-percent chance of 6 or more deposits, and a 10-percent chance of 20 or more deposits, for a mean of 8.9 expected undiscovered deposits (table E3; also see fig. 13). The presence of 10 significant porphyry copper prospects as well as other small prospects, a reasonably well understood tectonomagmatic framework, and a favorable metallogenic environment for porphyry copper deposit formation are all factors that contributed to the relatively low uncertainty (C_v% = 75) compared with measures of uncertainty for other tracts in this assessment.

Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table E4 (also see fig. 13). Results of the Monte Carlo simulation are also presented as a cumulative frequency plot (fig. E3), which shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

Table E3. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu8515, Kamchatka-Kuril—Russia.

[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, square kilometers; area, area of permissive tract in square kilometers; density, 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	0	8.9	195,150	4.6

Table E4. Results of Monte Carlo simulations of undiscovered resources for tract 142pCu8515, Kamchatka-Kuril—Russia.

[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	210,000	1,600,000	20,000,000	81,000,000	110,000,000	34,000,000	0.35	0.04
Mo	0	2,700	400,000	2,300,000	3,500,000	920,000	0.30	0.09
Au	0	12	500	2,100	2,900	860	0.35	0.08
Ag	0	0	4,400	29,000	43,000	11,000	0.28	0.14
Rock	51	380	4,300	17,000	23,000	6,900	0.36	0.04

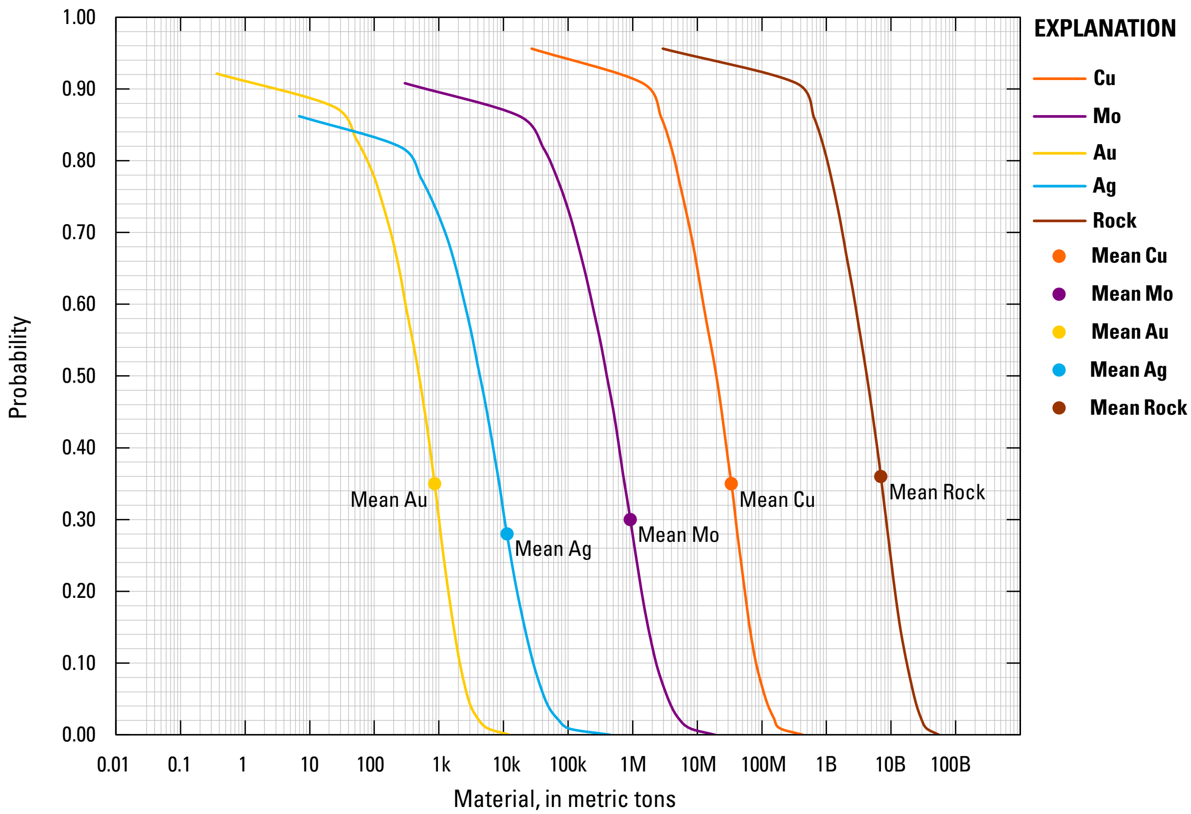

Figure E3. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 142pCu8515, Kamchatka-Kuril—Russia. (k=thousands, M=millions, B=billions).

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Appendix F. Deposits and Prospects

See appendix F Excel file

Appendix G. Spatial Data

By Mark J. Mihalasky[1], Steve Ludington[2], Dmitriy V. Alexeiev[3], Thomas P. Frost[1], Thomas D. Light[1], Deborah A. Briggs[1], and John C. Wallis[1], with contributions by Arthur A. Bookstrom[1], and Andre Panteleyev[4]

Description of GIS Files

An Esri ArcGIS file-geodatabase (142pCu.gdb), containing three feature classes, and an Esri map document (.mxd) are included with this assessment report. These files may be down-loaded from the USGS publications Web site as a compressed file SIR2010–5090–W_GIS.zip.

The file-geodatabase feature classes are as follows:

boundary_142pCu is a vector (polygon) feature class that represents an outline of Russia, including country political boundary and coastline. The dataset was extracted from U.S. Department of State (2009) small-scale digital international boundaries (SSIB) spatial database.

mineral_sites_142pCu is a vector (point) feature class that represents porphyry copper mineral sites (deposits, significant prospects, and prospects) for northeast Asia. This dataset includes an inventory of mineral resources in 2 known porphyry copper deposits, as well as key characteristics for 70 significant porphyry copper prospects and 86 smaller prospects, which are derived from currently available exploration results. Resource and exploration and development activity are updated with information current through February of 2013. See metadata and report for additional details. See appendix F for cited references.

tracts_142pCu is a vector (polygon) feature class that represents porphyry copper mineral resource assessment permissive tracts for northeast Asia. A mineral resource assessment tract is defined as a geographic area (a tract of land) which is determined to possess certain characteristics and attributes that permit the occurrence of a particular type of mineral deposit. This dataset contains five permissive tracts for the occurrence of porphyry copper deposits: three in northeastern Russia, one that extends across northeastern and southeastern Russia, and one on the Kamchatka Peninsula. These polygon features spatially overlap and may require setting a definition query (for example Coded_ID = “142Cu8510”) to separately display the entire tract. When displaying multiple tracts at the same time, portions of some tracts will be concealed. The attribute table associated with each tract contains summary information about geologic setting, mineral deposits, and mineral resource assessment estimates. See report and metadata for additional details.

These feature classes are contained in an Esri map document (version 10.0): GIS_SIR2010-5090-W.mxd. All datasets are provided in Asia North Lambert Conformal Conic projection, WGS1984 datum (see metadata for projection parameters). Also included are separate ASCII files of the metadata for the mineral sites and tracts, located in the folder “142pCu.met”, and layer symbolization files, in the folder “142pCu.lyr”.

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Appendix H. Geologic Time Correlation Chart

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. The chart (fig. H1) shows 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, 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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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	
							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		$Y^2{}_6$
			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	
							T_2	Middle	243	T_2	Middle	241	T_2	Middle	240		$Y^1{}_5$
							T_1	Lower/Early	248	T_1	Lower/Early	245	T_1	Lower/Early	250		

Era	Period symbol	Period	Katalog Mineralov (2005) symbol	Katalog Mineralov (2005) epoch	Katalog Mineralov (2005) start (Ma)	Mongolia (1998) symbol	Mongolia (1998) epoch	Mongolia (1998) start (Ma)	Ma and others (2002) symbol	Ma and others (2002) epoch	Ma and others (2002) start (Ma)	Orogeny	
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		
			O_2	Middle	478	O_2	Middle	464	O_2	Middle	468		Y^2_3
			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		
			$Є_2$	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		Y^1_3
References:			Katalog Mineralov (2005)			Mongolia, Geological Survey, and Mongolian Academy of Sciences, Institute of Geology and Mineral Resources (1998)			Ma and others (2002)				

Figure H1. 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±10	V	Vendian	610	Z_2	Sinian	700	Proterozoic	γ^3_2
				Riphean		R_3 (PR_{23})	1000±50	R_3	Riphean		Z_1		800		
						R_2 (PR_{22})	1350±20	R_2			Pt_3	Early Late Proterozoic	1000		
						R_1 (PR_{21})	1650±50	R_1		1650	Pt_2	Middle Proterozoic	1850		γ^2_2
		PR_1		Upper/Late		PR_{12}	1900±50	PR_1	Lower Proterozoic		Pt_1	Early Proterozoic	2600		γ^1_2
				Lower/Early		PR_{11}	2500±50			2500					
Archean		AR_2		Upper/Late			3150±50	AR_2	Upper Archean	3000-3200?	Ar_3	Late Archean	3000	Archean	γ^3_1
		AR_1		Lower/Early			not defined	AR_1	Lower Archean	not defined	Ar_2	Middle Archean	3500		γ^2_1
											Ar_1	Early Archean	not defined		γ^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 H1.—Continued

Appendix I. Assessment Team Biographies

Dmitriy Alexeiev is a 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 U.S. Geological Survey (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 is an Emeritus Research Geologist with the USGS in Spokane, Washington. 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 is a GIS Specialist with the USGS in Spokane, Washington. 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 element mineral resources.

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