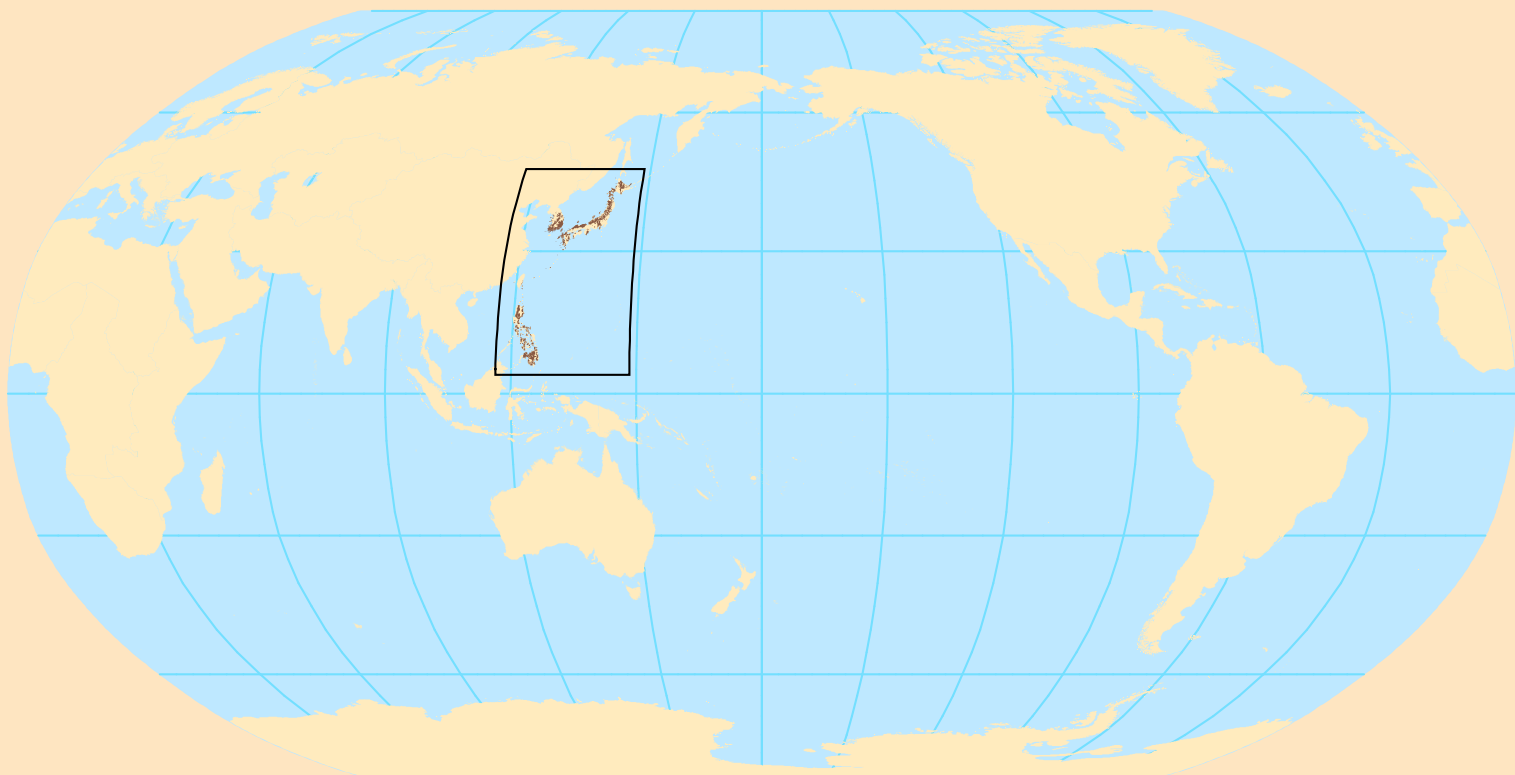


**Global Mineral Resource Assessment**

**Porphyry Copper Assessment of East and Southeast Asia—  
Philippines, Taiwan (Republic of China), Republic of Korea  
(South Korea), and Japan**



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

Scientific Investigations Report 2010–5090–P



# **Global Mineral Resource Assessment**

## **Porphyry Copper Assessment of East and Southeast Asia—Philippines, Taiwan (Republic of China), Republic of Korea (South Korea), and Japan**

By Jane M. Hammarstrom, Arthur A. Bookstrom, Michael W. DeMarr, Connie L. Dicken, Steve Ludington, Gilpin R. Robinson, Jr., and Michael L. Zientek  
with contributions from Dennis P. Cox, Claro Jose C. Manipon, Lilian A. Rollan, Takehiro Sakimoto, Tetsuichi Takagi, and Yasushi Watanabe

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# Conversion Factors, Abbreviations and Acronymns, and Chemical Symbols

## Conversion Factors

Inch/Pound to SI

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
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 <sup>2</sup> )
square foot (ft <sup>2</sup> )	0.09290	square meter (m <sup>2</sup> )
square mile (mi <sup>2</sup> )	259.0	hectare (ha)
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
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 <sup>2</sup> )	0.0002471	acre
square meter (m <sup>2</sup> )	10.76	square foot (ft <sup>2</sup> )
hectare (ha)	0.003861	square mile (mi <sup>2</sup> )
square kilometer (km <sup>2</sup> )	0.3861	square mile (mi <sup>2</sup> )
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)

## Acronyms and Abbreviations Used

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<b>ANOVA</b>	analysis of variance
<b>GIS</b>	geographic information system
<b>g/t</b>	grams per metric ton
<b>kt</b>	thousand metric tons
<b>IP</b>	induced polarization geophysical technique
<b>LILE</b>	large ion lithophile elements
<b>Ma</b>	million of years before the present
<b>Mt</b>	million metric tons
<b>PGE</b>	platinum-group elements
<b>REE</b>	rare-earth elements
<b>SHRIMP</b>	sensitive high resolution ion microprobe
<b>SSIB</b>	small-scale digital international boundaries
<b>t</b>	metric ton (tonne) or megagram (Mg)
<b>USGS</b>	U.S. Geological Survey

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## Chemical Symbols Used

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<b>Ag</b>	silver
<b>Au</b>	gold
<b>Bi</b>	bismuth
<b>Co</b>	cobalt
<b>Cu</b>	copper
<b>Mo</b>	molybdenum
<b>Pb</b>	lead
<b>Zn</b>	zinc

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# Porphyry Copper Assessment of East and Southeast Asia—Philippines, Taiwan (Republic of China), Republic of Korea (South Korea), and Japan

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## Abstract

The U.S. Geological Survey collaborated with member countries of the Coordinating Committee for Geoscience Programmes in East and Southeast Asia (CCOP) on an assessment of the porphyry copper resources of East and Southeast Asia as part of a global mineral resource assessment. The assessment covers the Philippines in Southeast Asia, and the Republic of Korea (South Korea), Taiwan (Province of China), and Japan in East Asia. The Philippines host world class porphyry copper deposits, such as the Tampakan and Atlas deposits. No porphyry copper deposits have been discovered in the Republic of Korea (South Korea), Taiwan (Province of China), or Japan.

Thirteen geographic areas were delineated as tracts that are permissive for porphyry copper deposits in the assessed area. Individual tracts range from about 3,000 to 100,000 square kilometers in area. Permissive tracts are delineated on the basis of mapped distributions of igneous rocks of specific age ranges that define subduction-related magmatic arcs or magmatic belts that might contain porphyry copper deposits. Most of these magmatic arcs are subduction related, although some porphyry deposits and prospects are present in back-arc or poorly understood tectonic settings. Maps at various scales were used in the compilation; however, the final tract boundaries are intended for use at a scale of 1:1,000,000.

Numbers of undiscovered deposits were estimated at different levels of confidence for 10 permissive tracts in the Philippines including one area that extends to eastern Taiwan

(Republic of China); permissive tracts in South Korea and Japan are discussed qualitatively. Estimates of numbers of undiscovered deposits were combined with grade and tonnage models using Monte Carlo simulation to estimate amounts of undiscovered resources. Grades and tonnages of known porphyry copper deposits in the study area were compared with global grade and tonnage models to determine the appropriate model for simulation of undiscovered resources. Most of the known deposits are best described as copper-gold subtypes of porphyry copper deposits. For some permissive tracts, a general porphyry copper-gold-molybdenum model was used.

Thirty-eight porphyry copper deposits are known in the Philippines; the mean number of undiscovered deposits was estimated to be 28. Mean (arithmetic) resources that could be associated with the undiscovered deposits are 90 million metric tons of copper and 5,800 metric tons of gold, as well as byproduct molybdenum and silver. Additional resources that could be discovered in extensions to known deposits were not evaluated. Assessment results, presented in tables and graphs, indicate expected amounts of total contained metal and mineralized rock in undiscovered deposits at different quantile levels, as well as the arithmetic mean for each tract.

The Philippines have a long history of porphyry exploration cycles and mine development, interrupted at times by political and social unrest, environmental concerns, and natural disasters. Changes in mining laws within the region and the recent high price of gold on the world market have prompted renewed interest in porphyry copper deposits in the region. South Korea and Japan have been thoroughly explored for many types of mineral deposits. Available data suggest that the permissive rocks in South Korea typically are too deeply eroded to preserve porphyry copper deposits. Porphyry copper systems may be present in Japan, but are likely to lie at depths greater than the 1 kilometer from the surface protocol adopted for this study.

Descriptions of the geologic basis for delineating each tract, the data used, the geologic criteria and rationale for the assessment, and results of the assessment are included in

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appendixes along with the description of a geographic information system (GIS) that includes tract boundaries, known porphyry copper deposits and significant prospects, and assessment results.

## Introduction

The Southeast Asia region hosts world-class examples of porphyry copper deposits, including Tampakan, Atlas, and six other deposits in the Philippines (fig. 1, table 1). Porphyry copper deposits provide approximately 60 percent of the world copper supply and produce gold, molybdenum, and silver (Singer, 1995). In recent years, new target areas have been recognized in Southeast Asia, historical mining districts continue to be explored, and new deposits continue to be discovered through greenfields exploration (that is, exploration targets away from known deposits). Permissive geologic settings for porphyry copper deposits also exist in the East Asia countries of the Republic of Korea (South Korea), Taiwan (Republic of China), and Japan although no such deposits have been discovered.

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

CCOP<sup>6</sup> is an intergovernmental organization founded to facilitate and coordinate applied geoscience projects. The CCOP mission is to contribute to economic development and improve the quality of life in the region. CCOP has 11 member countries—Cambodia, China, Indonesia, Japan, Malaysia, Papua New Guinea, Philippines, Singapore, South Korea, Thailand, and Vietnam. Fourteen other countries, including the United States, participate in CCOP activities as cooperating countries.

The large area that covers CCOP member countries was divided into broadly defined geographic/geologic areas for assessment. This assessment report covers parts of the CCOP-member countries of the Philippines, Taiwan (Province of China), Republic of Korea (South Korea), and Japan (fig. 1). A separate report on the porphyry copper assessment of Southeast Asia covered Cambodia, Indonesia, Lao People's

Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Singapore, Thailand, parts of India, and the Melanesian island nations of the Solomon Islands, Vanuatu, and Fiji (Hammarstrom and others, 2013).

Several workshops were held between CCOP and USGS authors, in which CCOP representatives gave country reports, provided data, and participated in tract delineation and estimation of undiscovered resources. Project workshops were held in Bangkok, Thailand (2003, 2004), Kunming, China (2005), and Busan, South Korea (2010). Preliminary results from the early workshops were updated for the 2010 meeting, and refined after formal reviews.

The assessment data and results for each permissive tract are presented in a standardized format in appendixes A through M of this report. Permissive tract boundaries and point locations of significant deposits and prospects are included in a geographic information system (GIS) that accompanies this report (appendix N). Appendix O lists the assessment participants, along with their particular expertise, affiliation, and role in the assessment. Political boundaries are based on data maintained by the U.S. Department of State (2009).

The assessment was based primarily on data compiled through 2010, although deposit and prospect data were updated where possible to reflect new information available through the first quarter of 2012. Many active exploration projects are large concession areas that attracted attention due to reported gold associated with historical workings. Epithermal gold deposits are the initial targets of many projects owing to the current high price of gold. Company reports mention porphyry systems associated with some of these targets, and the association of these deposit types with porphyry copper deposits is well-known in Southeast Asia (see, for example, Cooke and others, 1998). Such comments may be speculative, however, and delineation of a porphyry copper deposit, if present, awaits further exploration in most cases.

## Three-Part Assessment

The three-part approach to mineral resource assessment is based on mineral deposit models (Singer 1993, 2007a, b; Singer and Berger, 2007; Singer and Menzie, 2005). In applying this approach, geographic areas (permissive tracts) are delineated on the basis of geologic, geochemical, and geophysical features typically associated with the type of deposit under consideration. The amount of metal contained in undiscovered deposits is estimated using grade and tonnage models<sup>7</sup>. Estimates of numbers of undiscovered porphyry copper deposits are made at different confidence levels using a variety of estimation strategies to express the degree of

<sup>7</sup>Grade and tonnage models are frequency distributions of tonnages and grades of well-explored deposits, based on total production, reserves, and resources at the lowest available cutoff grade. For porphyry copper deposit models, a spatial rule is used to group grade and tonnage information to represent deposits as geologic entities—all mineralized rock or alteration within 2 kilometers is combined as one deposit for model construction (Singer and others, 2008).

<sup>6</sup><http://www.ccop.or.th/>

belief that some fixed but unknown number of deposits exists within the tract. A crucial step in the estimation process is selecting an appropriate grade and tonnage model; 80 percent of the undiscovered deposits should lie between the 90th and 10th percentile model values and half of the deposits should be above the model median in grade or tonnage (Singer and Menzie, 2010). The probabilistic estimates are a measure of the favorability of the tract and the estimator's uncertainty about what may exist (Singer, 2007a).

## Porphyry Copper Models

Porphyry copper deposits are large-tonnage (hundreds of millions of metric tons), low-to moderate-grade (0.3–2 percent copper) deposits of disseminated copper minerals (John and others, 2010). The most common ore minerals in porphyry copper deposits are chalcopyrite ( $\text{CuFeS}_2$ ) and bornite ( $\text{Cu}_5\text{FeS}_4$ ), distributed in stockwork veinlets and disseminations in hydrothermally altered intrusions and adjacent wall-rock. Secondary copper minerals, such as chalcocite ( $\text{Cu}_2\text{S}$ ), in oxidized, supergene enrichment zones comprise a major part or all of the ore in some deposits. Molybdenum, silver, and gold are important coproducts or byproducts in many deposits.

Mineral deposit models describe the characteristics and environments of formation of a specific type of mineral deposit. Porphyry copper mineral deposit models used for the assessment described here include those of Singer and others (2008), Cox (1986a, b), Berger and others (2008), and John and others (2010). In addition, models for the porphyry copper in the Philippines (Sillitoe and Gappe, 1984) and porphyry copper-gold deposits in Australia and the western Pacific also apply (Cooke and others, 1998). These latter two models are appropriate for use in many of the tectonic settings of Southeast Asia. Conceptual exploration models for southwest Pacific Rim gold-copper systems, including porphyry copper deposits, are included in Corbett and Leach (1998). A comprehensive overview of porphyry copper systems by Sillitoe (2010) discussed features to consider in exploration.

Although porphyry copper deposits typically form in subduction-related magmatic arcs, other tectonic settings also are recognized as permissive environments. These include collisional and extensional back-arc settings for the formation of porphyry copper (typically gold-rich) deposits, where processes such as postsubduction lithosphere thickening or extension, delamination, slab rollback, and asthenospheric upwelling may have facilitated remelting of lithosphere (Richards, 2009). Postsubduction porphyry copper-gold deposits generally are associated with mildly alkaline, rather than calc-alkaline, magmas, and may form isolated complexes in contrast to volcanoplutonic arcs (Richards, 2009).

Porphyry copper deposits in the western Pacific region typically are gold-rich in island arcs but tend to be molybdenum-rich where they formed in continental margin arcs or

within cratons (Cooke and others, 1998). Intrusive rocks associated with many Cenozoic western Pacific porphyry deposits are calc-alkalic to shoshonitic in composition, were emplaced at shallow (1–2 kilometer, km) depths, have distinctive steep-sided, cylindrical form (“pencil porphyries”), and are spatially associated with diatremes, epithermal gold deposits, and, if carbonate rocks are present, skarn deposits. Gold-rich porphyry copper deposits associated with alkaline (high-K) rocks, typically syenites, also are present in Southeast Asia. Characteristic settings for these deposits include subduction-related oceanic arcs within or along calderas at lineament or fault intersections. Associated rocks typically have elevated  $\text{K}_2\text{O}$  contents, are enriched in chlorine, fluorine, and light rare-earth elements, and have oxidized, magnetite-bearing magma sources (Müller and Groves, 1999).

## Magnetite and Ilmenite Series Granitoids

Worldwide, porphyry copper deposits are associated with magnetite-series rocks. The classification of granitoids into magnetite- and ilmenite-series rocks based on redox state and the relation of those series to associated mineral deposit type was established by Ishihara's landmark studies of the Cretaceous-Paleogene metallogenic provinces of Japan (Ishihara, 1979, 1981, 2004). Those studies showed that magnetite-series granitoids are correlated with I-type granitoids and associated with sulfide-rich base-metal, precious-metal, and molybdenum deposits, including porphyry, skarn, and kuroko-type massive sulfide deposits. In Japan, however, no porphyry copper deposits have been discovered. Ilmenite-series granitoids can be correlated with both I- and S-type granitoids and are associated with sulfide-poor tin and tungsten deposits. The boundary between the reduced ilmenite-series rocks and the more oxidized magnetite series rocks is 0.1 percent modal magnetite.

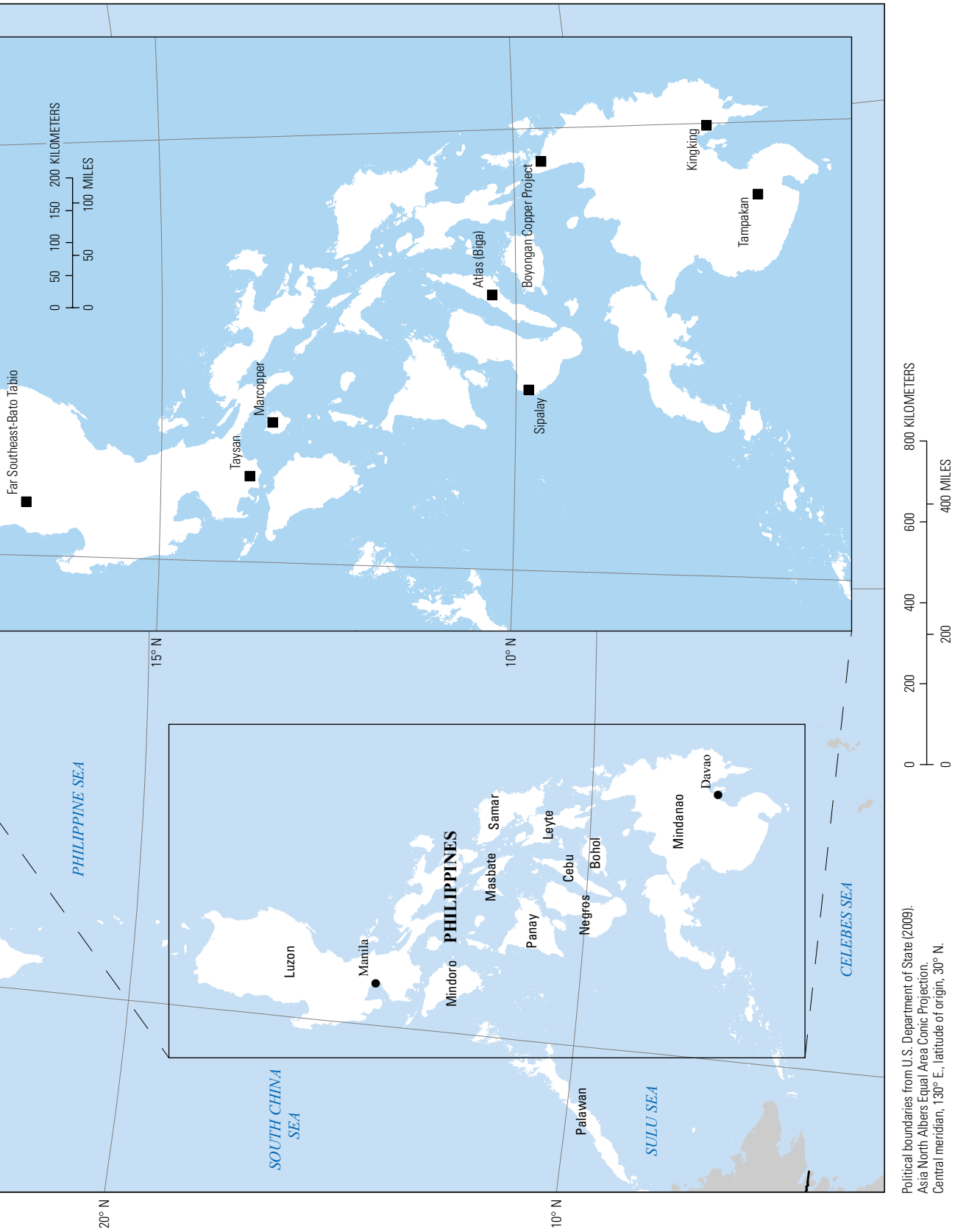
Differences between the granitoid series reflect differences in the redox state of the magma chamber, which is related to the sulfur content (Takagi and Tsukirma, 1997). During late-magmatic stages, sulfur dioxide ( $\text{SO}_2$ ) gas oxidizes silicate melts such that at  $\text{SO}_2$  concentrations greater than 250 parts per million (ppm) magnetite-series granitoids form. The magnetite-series granitoid magmas in Japan likely acquired sulfate by subduction of altered oceanic crust that reacted with seawater whereas the ilmenite-series magmas assimilated sedimentary sulfide, in which most of the  $\text{SO}_2$  was reduced to  $\text{H}_2\text{S}$  (hydrogen sulfide). Increases in subduction erosion and sediment assimilation rates due to increases in plate convergence rates and (or) climate effects that promoted erosion in Cretaceous time may explain the distribution of the magnetite and ilmenite series in Japan (Takagi, 2004) and may have application elsewhere.



4 Porphyry Copper Assessment of East and Southeast Asia—Philippines, Taiwan, Republic of Korea, and Japan







**Figure 1.** Map showing location of the study area in East and Southeast Asia. Countries included in this report are shown in white. Inset shows location for world class porphyry copper deposits (those that contain more than 2 million metric tons of copper) in the Philippines. See table 1 for data.

**Table 1.** Summary of identified resources in porphyry copper deposits in the Philippines.

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; n.d., no data. Subtype: NA, not applicable (classified as general Cu-Au-Mo model); Cu-Au, deposits with Au (g/t)/Mo (%) ratios  $\geq 30$  or Au  $>0.2$  g/t. JORC and NI 43-101 refer to Australian and Canadian resource reporting regulations, respectively. Contained metals are rounded to 2 significant figures]

Tract	Tract Name	Name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Au (t)	Subtype	Source/Comments
World-class porphyry copper deposits (>2 Mt contained copper)												
142pCu7312	Cotobato Arc	Tampakan	4.25	2,940	0.52	0.006	0.17	n.d.	15,000,000	500	NA	Indophil Resources NL (2012); JORC-compliant
142pCu7306	Bohol-Cebu Area	Atlas	108	1,420	0.45	0.018	0.24	1.8	6,400,000	340	NA	Singer and others (2008); includes Carmen, Biga, Lutopan pits.
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Far Southeast-Bato Tabio	1.4	657	0.65	n.d.	0.94	0.93	4,300,000	620	Cu-Au	Lepanto Consolidated Mining Company (2008); 1995 geological resource
142pCu7305	Masbate-Negros Arc System	Sipalay	30.0	807	0.47	0.014	0.05	1.5	3,800,000	40	NA	Singer and others (2008); includes Baclao, Cansibit-Bumulig
142pCu7309	Philippine Arc	Kingking	10.0	1,151	0.25	n.d.	0.32	5	2,900,000	370	Cu-Au	Hester and others (2010); JORC- and NI 43-101 compliant
142pCu7301c	Luzon Arc: Western	Taysan	7.3	968	0.22	0.003	0.09	0.68	2,100,000	87	Cu-Au	Crazy Horse Resources, Inc. (2012); prefeasibility
142pCu7301c	Luzon Arc: Western	Marcopper	20.5	372	0.55	0.004	0.11	0.7	2,000,000	41	Cu-Au	Singer and others (2008); includes San Antonio, Tapan
142pCu7309	Philippine Arc	Boyongan-Bayugo	3.5	244	0.82	n.d.	0.83	n.d.	2,000,000	200	Cu-Au	Ferreira (2008, 2009); Total indicated and inferred resources for the two discrete deposits (located 1.4 km apart)
Smaller porphyry copper deposits (<2 Mt contained copper)												
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Santo Tomas II (Padcal Expansion)	1.5	449	0.38	0.001	0.70	1.5	1,700,000	310	Cu-Au	Singer and others (2008)

**Table 1.** Summary of identified resources in porphyry copper deposits in the Philippines.—Continued

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; n.d., no data. Subtype: NA, not applicable (classified as general Cu-Au-Mo model); Cu-Au, deposits with Au (g/t)/Mo (%) ratios  $\geq 30$  or Au  $> 0.2$  g/t. JORC and NI 43-101 refer to Australian and Canadian resource reporting regulations, respectively. Contained metals are rounded to 2 significant figures]

Tract	Tract Name	Name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Au (t)	Subtype	Source/Comments
142pCu7305	Masbate-Negros Arc System	Hinoba-an	17.5	432	0.37	n.d.	0.14	0.34	1,600,000	60	NA	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Guinaoang (Mankayan)	3.5	400	0.38	n.d.	0.42	n.d.	1,500,000	170	Cu-Au	Bezant Resources plc (2011); JORC-compliant
142pCu7305	Masbate-Negros Arc System	Basay	30.0	262	0.44	0.008	0.29	1.5	1,200,000	76	NA	Singer and others (2008); open; includes Nabuangan-Bunkville
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Santo Niño	9.5	286	0.35	0.008	0.20	1.7	990,000	57	Cu-Au	Singer and others (2008); includes Southwest, Ullman, Suluakan
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Tawi-Tawi	4.6	225	0.40	0.008	0.30	1.7	900,000	68	Cu-Au	Solfotara Mining Corporation (2012)
142pCu7302	Cordon Alkalic Complex	San Fabian	20.6	314	0.27	n.d.	0.21	n.d.	850,000	66	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	St. Anthony (San Antonio-Philex)	n.d.	170	0.44	0.001	0.07	1.2	750,000	12	Cu-Au	Singer and others (2008)
142pCu7301c	Luzon Arc: Western	Dizon	2.7	187	0.36	0.003	0.93	2	670,000	170	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Boneng Lobo	10.5	225	0.28	0.005	0.26	4	640,000	59	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Batong Buhay Gold project	7.0	87	0.60	0.002	0.31	2	520,000	27	Cu-Au	Singer and others (2008)
142pCu7302	Cordon Alkalic Complex	Dipidio (Dinkidi)	23.2	121	0.39	n.d.	0.97	n.d.	470,000	120	Cu-Au	Singer and others (2008)

Smaller porphyry copper deposits (<2 Mt contained copper)—Continued

**Table 1.** Summary of identified resources in porphyry copper deposits in the Philippines.—Continued

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; n.d., no data. Subtype: NA, not applicable (classified as general Cu-Au-Mo model); Cu-Au, deposits with Au (g/t)/Mo (%) ratios  $\geq 30$  or Au >0.2 g/t. JORC and NI 43-101 refer to Australian and Canadian resource reporting regulations, respectively. Contained metals are rounded to 2 significant figures]

Tract	Tract Name	Name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Au (t)	Subtype	Source/Comments
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Botilao	n.d.	82	0.52	n.d.	0.19	n.d.	430,000	16	Cu-Au	Singer and others (2008)
142pCu7309	Philippine Arc	Amacan	10.0	110	0.37	n.d.	0.40	2.5	400,000	44	Cu-Au	Singer and others (2008)
142pCu7309	Philippine Arc	Tagpura-Maangob	n.d.	76	0.44	0.008	0.50	4	330,000	38	Cu-Au	Singer and others (2008); historical data; open; part of Comval exploration project
142pCu7309	Philippine Arc	Mapula	10.0	78	0.40	n.d.	0.37	3.6	310,000	29	Cu-Au	Singer and others (2008)
142pCu7304b	Sierra Madre Arc: Southern	Lumbay	n.d.	78	0.40	0.001	0.03	n.d.	310,000	2	Cu-Au	Singer and others (2008)
142pCu7301c	Luzon Arc: Western	Ino-Capayang	n.d.	50	0.50	0.005	0.03	1.3	250,000	2	NA	Singer and others (2008)
142pCu7302	Cordon Alkalic Complex	Marian	25.0	55	0.43	n.d.	0.24	n.d.	240,000	13	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Kenyon South East/Black Mountain	2.1	62	0.38	0.013	0.33	4	230,000	20	Cu-Au	Singer and others (2008)
142pCu7309	Philippine Arc	Matanlang (Larap)	20.5	65	0.35	0.005	0.40	n.d.	230,000	26	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Hale-Mayabo	n.d.	35	0.50	0.005	0.35	2.5	180,000	12	Cu-Au	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Kilongolao	n.d.	50	0.35	n.d.	n.d.	n.d.	180,000	n.d.	NA	Singer and others (2008); historical estimate

Smaller porphyry copper deposits (<2 Mt contained copper)—Continued

**Table 1.** Summary of identified resources in porphyry copper deposits in the Philippines.—Continued

[Ma, million years; Mt, million metric tons; t, metric tons; %, percent; g/t, grams per metric ton; n.d., no data. Subtype: NA, not applicable (classified as general Cu-Au-Mo model); Cu-Au, deposits with Au (g/t)/Mo (%) ratios  $\geq 30$  or Au  $>0.2$  g/t. JORC and NI 43-101 refer to Australian and Canadian resource reporting regulations, respectively. Contained metals are rounded to 2 significant figures]

Tract	Tract Name	Name	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Contained Au (t)	Subtype	Source/Comments
Smaller porphyry copper deposits (<2 Mt contained copper)—Continued												
142pCu7305	Masbate-Negros Arc System	Aya Aya	19.5	40	0.30	0.022	0.08	1.5	120,000	3	NA	Singer and others (2008)
142pCu7301b	Luzon Arc: Luzon Central Cordillera	Manag	n.d.	20	0.50	n.d.	1.10	n.d.	100,000	22	Cu-Au	Singer and others (2008)
142pCu7309	Philippine Arc	Luna-Asiga	3.5	26	0.36	0.01	0.00	n.d.	94,000	n.d.	NA	Singer and others (2008)
142pCu7305	Masbate-Negros Arc System	Suguibon	n.d.	26	0.35	0.015	n.d.	n.d.	91,000	n.d.	NA	Singer and others (2008)
142pCu7309	Philippine Arc	Kalamatan	n.d.	26	0.34	n.d.	0.37	n.d.	88,000	10	Cu-Au	Singer and others (2008); historical data; open; part of Comval exploration project
142pCu7301c	Luzon Arc: Western	Pisumpan	2.1	20	0.41	n.d.	0.60	3	82,000	12	Cu-Au	Singer and others (2008)
142pCu7306	Bohol-Cebu Area	Balak-5	n.d.	5	0.80	n.d.	n.d.	n.d.	40,000	n.d.	NA	Singer and others (2008)
Total for Philippine Archipelago									39,000,000	3,100		

## Terminology

The terminology used in this report follows the definitions used in the 1998 U.S. Geological Survey 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). This terminology is intended to represent standard definitions that reflect general usage by the minerals industry and the resource assessment community.

- *Mineral deposit*—A mineral concentration of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have potential for economic development.
- *Undiscovered mineral deposit*—A mineral deposit believed to exist 1 km or less below the surface of the ground, or an incompletely explored mineral occurrence or prospect that could have sufficient size and grade to be classified as a deposit.
- *Mineral prospect*—A mineral concentration that is being actively examined to determine whether a mineral deposit exists.
- *Mineral occurrence*—A locality where a useful mineral or material is found.
- *Permissive tract*—The surface projection of a volume of rock where the geology permits the existence of a mineral deposit of a specified type. The probability of deposits of the type being studied occurring outside the boundary is negligible.
- *Resource*—A mineral concentration of sufficient size and grade, and in such form and amount, that economic extraction of a commodity from the concentration is currently or potentially feasible.
- *Identified resources*—Resources whose location, grade, quality, and quantity are known or can be estimated from specific geologic evidence. For this report, known resources are those in the porphyry copper deposits that are included in the grade and tonnage models used in the assessment. 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 by deposit type, grade, and tonnage to meet commonly used reporting guidelines, such as those established by the U.S. Securities and Exchange Commission, JORC<sup>8</sup>, or CRIRSCO<sup>9</sup>.
- *Calc-alkaline, calc-alkalic; alkaline, alkalic*—These terms are used in a general, nonrigorous manner to refer

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

- *Adakite*—The term “adakite” appears in much of the recent literature on igneous rocks associated with porphyry copper deposits, including studies of deposits in East and Southeast Asia (John and others, 2010; Sajona and Maury, 1998; Sajona and others, 2000). The term “adakite” was introduced by Defant and Drummond (1990) to describe the magnesian andesite near Adak Island in the Aleutian Arc in the North Pacific Ocean described by Kay (1978) as a possible product of reacting partially melted subducted oceanic crust with asthenospheric mantle. The term has become problematic because in addition to the geochemical criteria used to define adakites, an unequivocal origin by melting of a subducted slab of oceanic crust may be implied. Richards and Kerrich (2007) showed that processes other than slab melting also could produce “adakite” and proposed the use of the term “adakite-like rocks” to describe the suite of rocks that have the following general characteristics: SiO<sub>2</sub> ≥56 percent, Al<sub>2</sub>O<sub>3</sub> ≥15 percent, MgO <3 percent, Sr ≥400 ppm, Y ≤18 ppm, Yb ≤1.9 ppm, Ni ≥20 ppm, Cr ≥30 ppm, Sr/Y ≥20, La/Yb ≥20, and <sup>87</sup>Sr/<sup>86</sup>Sr ≤0.7045. They showed that these compositions can result from crustal processes involving normal tholeiitic to calc-alkalic arc magmas, such as melting-assimilation-storage-homogenization (MASH) and assimilation-fractional crystallization (AFC), and cannot be unambiguously ascribed to slab melts. The term adakite-like is used in this report for rocks that meet the geochemical criteria for adakite; no particular origin is implied.

## Assessment Data

### Geologic Maps

Geologic maps at several scales were used as information sources during this assessment. Maps included proprietary data provided by CCOP country representatives, commercially available digital geologic compilations, and paper geologic maps. These included a 1:2,000,000-scale digital geologic map of East and Southeast Asia (Coordinating Committee for Coastal and Offshore Geoscience Programmes in

<sup>8</sup>The Australasian Code for Reporting of Exploration results, Mineral Resources and Ore Reserves ([http://www.jorc.org/jorc\\_code.asp](http://www.jorc.org/jorc_code.asp)).

<sup>9</sup>Committee for Mineral Reserves International Reporting Standards (2006) (<http://www.criusco.com/welcome.asp>).



East and Southeast Asia (CCOP) and Geological Survey of Japan, 1997), a 1:1,000,000-scale digital geologic map of Japan (Geological Survey of Japan, 2003), geologic maps of the Philippines at scales of 1:1,000,000, 1:1,500,000, and 1:2,500,000 and selected 1:200,000-scale maps (Philippine Bureau of Mines and Geosciences, 1963, 2004a; Balace and others, 1974), a 1:800,000-scale neotectonic map of the Philippines (Pubellier and others, 1993), a 1:500,000-scale map of Taiwan (Wei and others, 2006), and a series of 1:1,000,000-scale maps of South Korea (Korea Institute of Geology, Mining and Materials [in 2001, the name was changed to the Korea Institute of Geoscience and Mineral Resources, KIGAM], 1995a–d).

Paper maps were scanned and georectified to incorporate as images in GIS projects, including some 1:50,000-scale geologic maps for the Philippines (see <http://www.mgb.gov.ph/lgmp.aspx> for available maps; Philippine Mines and Geosciences Bureau, undated index map). Page-size figures from a variety of publications were used as references to identify tectonic features and the extent of magmatic arcs. Specific data used for each tract are listed in the appendixes.

## Mineral Occurrence Data

A global database of porphyry copper deposits and prospects by Singer and others (2008) was supplemented with other global and regional mineral occurrence databases, including those maintained by the Geological Survey of Canada (Dunne and Kirkham, 2003), a mineral resource map of Asia (Kamitani and Naito, 1998), and proprietary data from CCOP. The Philippine Bureau of Mines and Geosciences provided a digital database of mineral occurrences for their country (Philippine Bureau of Mines and Geosciences, 2004b). In addition, commercially available databases (InfoMine<sup>10</sup>, Intierra<sup>11</sup>, Metals Economic Group<sup>12</sup>), metallogenic maps, technical reports, company Web sites, publications and Web sites of geological surveys, and geological literature were consulted. The USGS (2012) On-Line Mineral Resources Data (MRDS)<sup>13</sup> includes information on mines, prospects, and mineral occurrences worldwide. The 1984 CCOP report on Philippine porphyry copper deposits summarizes the results of a project on porphyry copper deposits initiated by the Philippine Bureau of Mines and Geology (Sillitoe and Gappe, 1984). The CCOP report includes a comparative study of 48 porphyry copper deposits and prospects in the Philippines, 20 of which were mined. Divis (1983) summarized the geology and geochemistry of Philippine porphyry copper deposits. Dr. Claro Manipon (a contributor to this report) provided additional data on porphyry copper deposits and prospects in the Philippines (written commun., 2006).

<sup>10</sup> <http://www.infomine.com/>

<sup>11</sup> <http://www.intierra.com/Homepage.aspx>

<sup>12</sup> <http://www.metalseconomics.com/default.htm>

<sup>13</sup> <http://mrdata.usgs.gov/>

The assessment team classified sites as either deposits or prospects. The term “deposit” is limited to sites where the location, deposit characteristics and type, and resource grades and tonnages are thoroughly characterized. Some prospects reported in data sources could not be unambiguously classified as porphyry copper deposit types. Deposits and prospects that the assessment team could classify as porphyry copper or porphyry-copper-related are discussed in the appendixes and included in the database for this report (appendix N).

Many islands of the Philippines were being actively explored during the course of this study, owing primarily to recent high gold prices. Many prospects change hands, new exploration data become available, and identified resources for deposits may change over time. We attempted to update information on deposits and prospects during final report preparation, but because of the dynamic exploration environment, still newer data may be available.

Spatial rules are used in mineral resource assessment to define consistent sampling units for constructing tonnage and grade models. For porphyry copper deposits, all mineralized rock or alteration within 2 km of each other are combined as one deposit. In this study, prospects that lie within a 2-km distance of known deposits are grouped with those deposits because they are likely to represent extensions of identified resources. For example, the tonnage and grade reported for the Atlas deposit (table 1) include data for the Carmen, Biga, and Lutopan pit areas. Similarly, clusters of prospects within 2 km of each other are grouped to avoid over-representing numbers of prospects that could, if fully explored, meet reporting criteria for identified resources.

Distributions of gold placers, skarns, and epithermal deposits, as well as unclassified copper and gold occurrences, were considered during the assessment but generally are not included in the database. Skarns and epithermal deposits may be included if the assessment team considered it likely that a porphyry system is associated.

## Other Data

Other types of data were available for some areas. Mining tenement maps, geologic information, and updates on mining in the Philippines are available on the Web site of the Mines and Geosciences Bureau of the Department of Natural Resources, Republic of the Philippines (<http://www.mgb.gov.ph/>). A two-volume summary of the geology and mineral resources of the Philippines (Philippine Bureau of Mines and Geosciences, 1981, 1986) and maps therein were also used. The second edition of the geology of the Philippines was released in 2010 (Philippine Mines and Geosciences Bureau, 2010).

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

A regional magnetic anomaly map at a scale of 1:4,000,000 covers much of the study area (Geological Survey of Japan, 1996). Global-scale magnetic data are available but are of limited use at the scale of the assessment (National Geophysical Data Center, 2009). Site-specific magnetic data are available on some exploration company Web sites or in published reports. A database of radiometric ages for Southeast Asia provided locations of dated samples of igneous rocks and information about rock type (Malaihollo and others, 2002).

## **Delineation of Permissive Tracts**

### **Fundamental Basis for Porphyry Copper Assessment**

The fundamental geologic feature that is used to delineate a permissive tract for porphyry copper deposits is a subduction-related magmatic arc or a postsubduction or postcollisional magmatic belt of a given age. Porphyry copper deposits form in hydrothermal systems that are spatially and temporally associated with apical, generally porphyro-aphanitic parts of felsic to intermediate stocks that were emplaced at shallow depths, typically less than 4 km.

Permissive tracts for porphyry copper deposits are delineated as geographic areas that include volcanic and intrusive rocks of a specified age range that typically can be related to a particular tectonic setting (such as a subduction-boundary zone). Tracts are based primarily on geologic map units that define the magmatic arc or belt.

A complex collage of island arcs and continental-arc fragments developed in response to subduction and plate reorganization related to the geodynamic evolution of the borders of the Eurasian and Indian-Australian continents, the lifecycle of seas in the region, and the movement of the Pacific Plate over time. This complex tectonic evolution has led to the development of arc fragments, microcontinents, accreted terranes, and sea basins, many of which are of uncertain origin. Building on the work of Hamilton (1979) and Mitchell

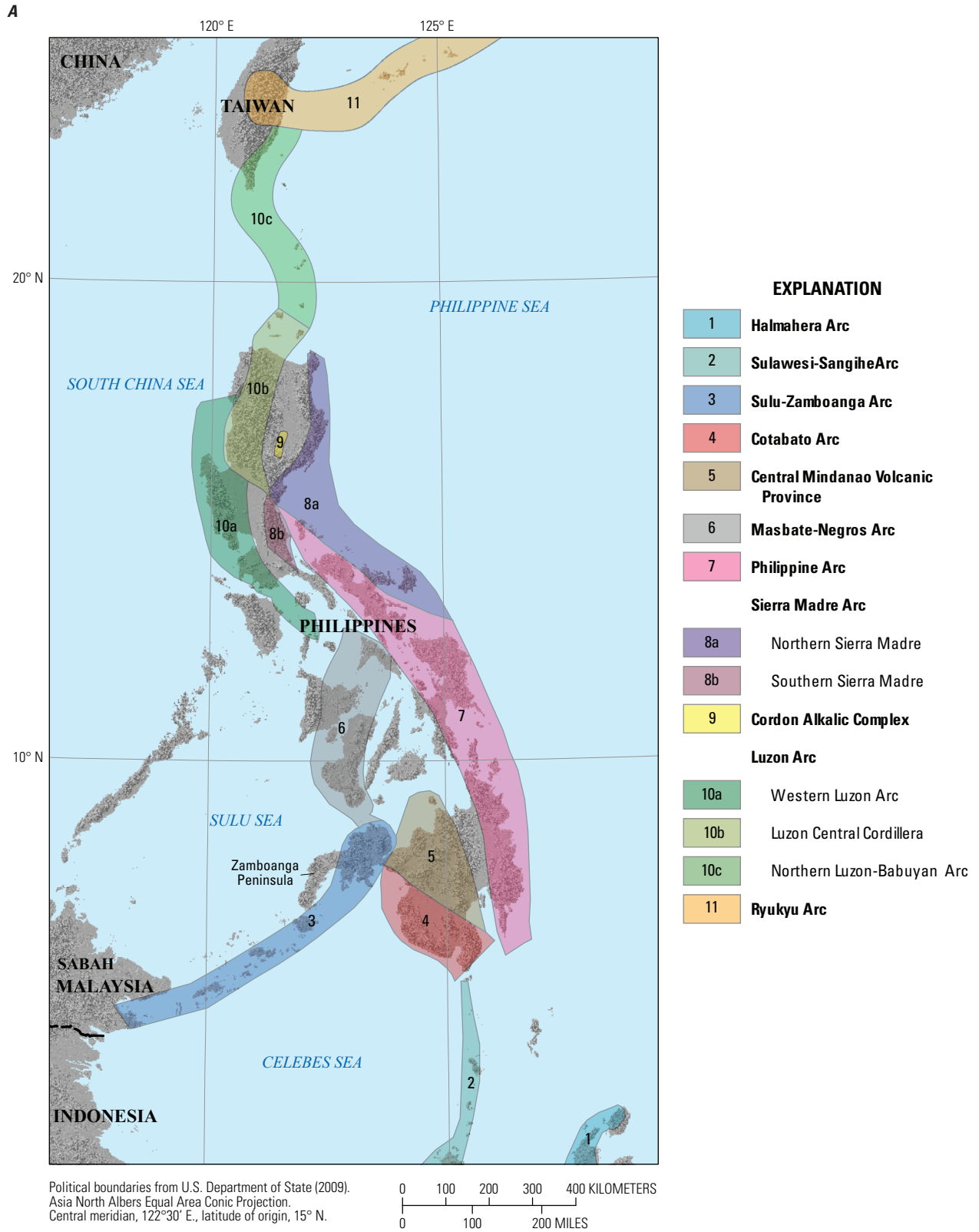
and Leach (1991), Garwin and others (2005) described the tectonic setting, the geology, and the characteristics of gold and copper deposits of the principal Cenozoic magmatic arcs in the southeast Asia-western Pacific region. Their delineation of arcs provided the basic framework for delineation of most of the permissive tracts in this assessment. A new regional-scale compilation of geodynamic maps prepared for the global assessment also was used to document the extent and nature of arcs (D. Alexeiev, Russian Academy of Science, written commun., 2011). The magmatic arcs and belts that were used as the basis for delineating permissive tracts for porphyry copper deposits are outlined on figure 2.

### **Tract Delineation Strategy**

The first step in delineating a permissive tract for porphyry copper deposits is identifying appropriate tectonic settings based on characteristics described in mineral deposit models. In East and Southeast Asia, the initial framework for delineating permissive tracts was established by identifying subduction-related magmatic arcs in the region (fig. 2, table 2). Many of the arcs are composite systems that include oceanic- as well as continental-arc segments, or arcs that formed on accretionary basement or deformed ophiolites; these latter arc systems developed on thin, immature crust lacking granitoids in the basement in contrast to continental arcs that typically are underlain by older granitoids complexes (D. Alexeiev, 2010, written commun.). Some of the arcs include submarine arc segments that are not included in permissive tracts; most of the Izu-Bonin Arc is submerged.

Once the main tectonic elements and age ranges were identified, the tracts were delineated by selecting the igneous rocks that define the terrestrial extent of the arcs based primarily on geologic maps. The geology-based strategy for permissive tract delineation used in this assessment is described here. Tracts may consist of multiple segments. The appendixes contain detailed descriptions for individual tracts, along with figures that show the intrusive and extrusive rocks that define the tract and tables listing the maps used, and the map units included, for each tract.





**Figure 2.** Maps showing the principal magmatic arcs and belts of East and Southeast Asia. *A*, Southeast Asia—Philippines and Taiwan (Republic of China); *B*, East Asia—Republic of Korea (South Korea) and Japan.

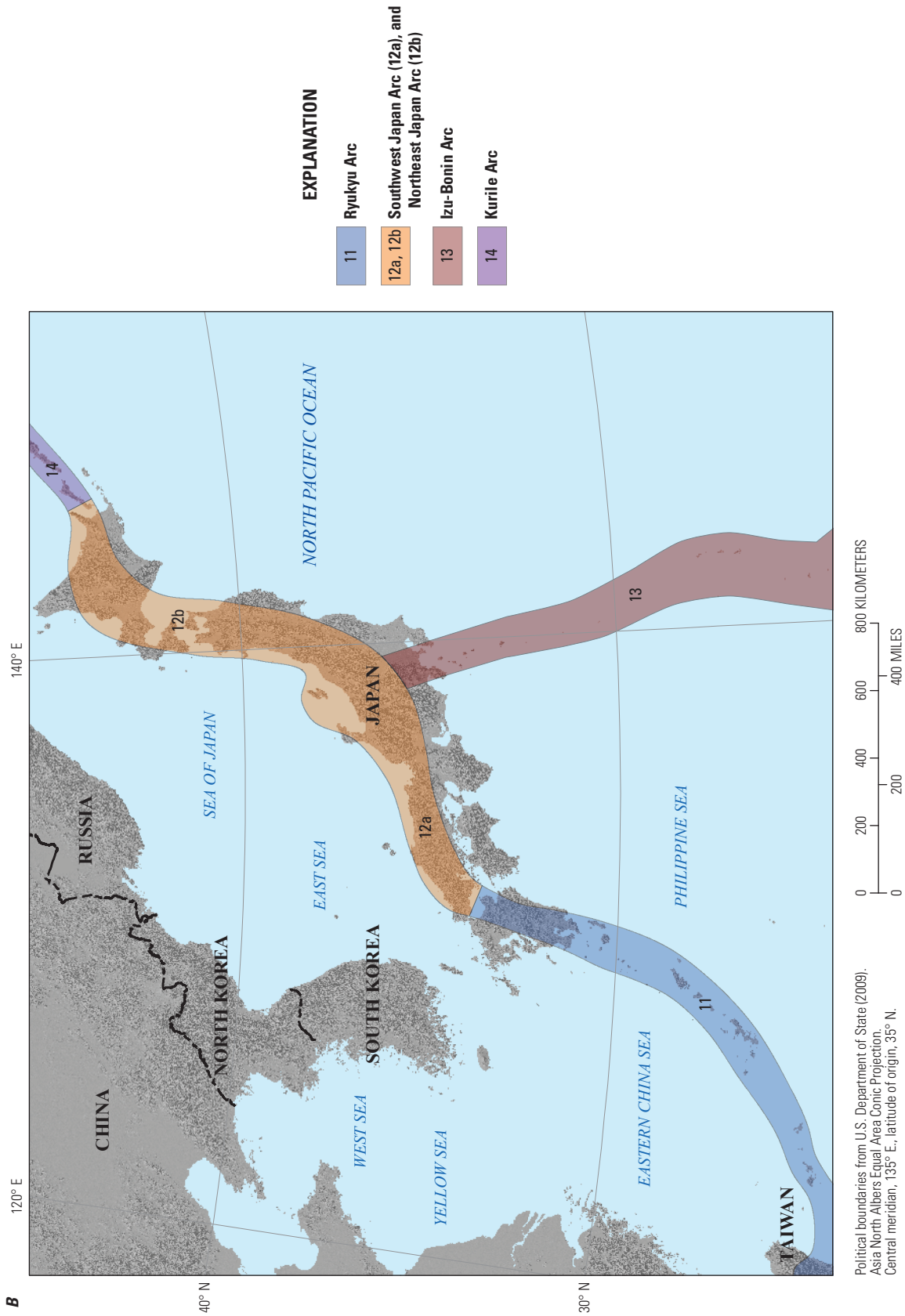


Figure 2.—Continued

**Table 2.** Principal magmatic arcs of East and Southeast Asia.

[Map key for figure 2; arcs and magmatic provinces based on Garwin and others (2005), Mitchell and Leach (1991), and D. Alexeiev (written commun., 2010)]

Map key	Magmatic arcs and belts	Age range	Arc Length (km)	Arc /crust type	Key reference
1	Halmahera Arc	Neogene to Holocene	400	oceanic (N); continental (S)	Garwin and others (2005)
2	Sulawesi-Sangihe Arc	Miocene to Pliocene	1,200	oceanic (NE); continental (SW)	Garwin and others (2005)
3	Sulu-Zamboanga Arc	Miocene to Holocene	400	oceanic (NE); continental (SW)	Garwin and others (2005)
4	Cotabato Arc	Miocene to Holocene	300	oceanic/ accretionary basement	Garwin and others (2005)
5	Central Mindanao Volcanic Province	Miocene to Holocene	350	residual arc?	Garwin and others (2005)
6	Masbate-Negros Arc	Eocene to Holocene	400	oceanic/ accretionary basement	Garwin and others (2005)
7	Philippine Arc	Oligocene to Holocene	1,000	oceanic/ accretionary basement	Garwin and others (2005)
8a	Northern Sierra Madre Arc	Eocene-Oligocene	200	oceanic/ accretionary basement	Mitchell and Leach (1991)
8b	Southern Sierra Madre Arc				
9	Cordon Alkalic Complex	Late Oligocene to Early Miocene	<100	back-arc rift	Garwin and others (2005)
10a	Western Luzon Arc	Oligocene to Holocene	1,200	oceanic/ accretionary basement	Garwin and others (2005)
10b	Luzon Central Cordillera				
10c	Northern Luzon-Babuyan Arc				
11	Ryukyu Arc	Eocene, Miocene to Holocene	1,200	continental (no porphyry copper)	Garwin and others (2005)
12a	Southwest Japan Arc	Late Cretaceous-Paleogene; Miocene to Holocene	1,800	continental (no porphyry copper)	Garwin and others (2005)
12b	Northeast Japan Arc				
13	Izu-Bonin Arc	Eocene to Holocene	1,200	oceanic (no porphyry copper)	Garwin and others (2005)
14	Kurile Arc	Miocene to Holocene	2,200	continental (no porphyry copper)	Garwin and others (2005)

Digital geologic data were processed in a GIS using Esri ArcGIS software, as follows:

- Regional-scale geologic maps, geodynamic maps, and geologic literature were used to identify fundamental units for tract delineation, which were defined as magmatic arcs, belts, or large complexes of igneous rocks of a given age range.
- Digital geologic maps were then used to select map units to define preliminary permissive tracts for porphyry copper deposits. Igneous map units were separated by age groups and classified as permissive or nonpermissive based on lithology. Permissive rocks include calc-alkalic and alkalic plutonic and volcanic rocks. Types of igneous rocks that are unlikely to be associated with porphyry copper deposits were classified as nonpermissive. Examples of nonpermissive lithologies include ultramafic rocks, ophiolite complexes, highly evolved granites, peraluminous granites, rhyolites, and pillow basalts.
- Buffers were applied to polygons that represent permissive rocks. A 10-km buffer was applied to plutonic rock polygons and a 2-km buffer to volcanic rock polygons; this generally expanded the area of the tract to include all known porphyry copper deposits and significant associated prospects.
- Available data on mineral deposits and occurrences, locations of dated igneous rock samples, structural, geophysical, and geochemical information were examined to ensure that the tract included any other evidence of unmapped permissive rocks or hydrothermal systems.
- An aggregation and smoothing routine was applied to the resulting buffered polygons, followed by editing by hand to honor postmineral fault boundaries. In some cases, more detailed geologic maps were acquired to resolve tract boundary issues or page-size map illustrations from the literature were incorporated to fill in gaps.
- Volcanic centers and other areas of volcanic cover where the thickness of cover was known to exceed 1 km were excluded from tracts, either by using a buffer zone of 10 km around the volcano or based on topography. Intrusions younger than the designated tract age and ophiolitic and ultramafic rocks were also excluded. Volcanic rocks younger than the designated tract age, but inferred to be less than 1-km thick, may be present as cover and included in permissive areas.

- Resulting tract boundaries were clipped to shorelines to eliminate undersea areas by using small-scale digital international land boundary polygon files from the U.S. Department of State (2009), which incorporate high tide coastline data from the U.S. National Geospatial-Intelligence Agency's World Vector Shoreline<sup>14</sup> dataset.

## Permissive Tracts for Porphyry Copper Deposits in East and Southeast Asia

Thirteen permissive tracts for porphyry copper deposits were delineated within the study area (fig. 3, table 3). Probabilistic estimates of numbers of undiscovered porphyry copper deposits were made for the 10 tracts in the Philippines. Three other tracts, one in South Korea and two in Japan, are discussed qualitatively. These three tracts delineate permissive lithologies; however, no porphyry copper deposits are known in Japan, and only a few porphyry-type prospects are known in South Korea, although future discoveries cannot be ruled out. The geologic rationales that have been proposed for the lack of significant porphyry-style deposits in these areas are discussed.

Permissive tracts are listed by geographic area, along with the countries included within each tract and the fundamental geologic feature used as a basis for each tract (table 3). Porphyry copper deposits with reliable identified resources are listed in table 1, in order of decreasing contained copper content. The following discussion provides an overview of the geodynamic settings for porphyry copper deposits in the study area and brief descriptions of the permissive tracts, starting with the Southeast Asia area.

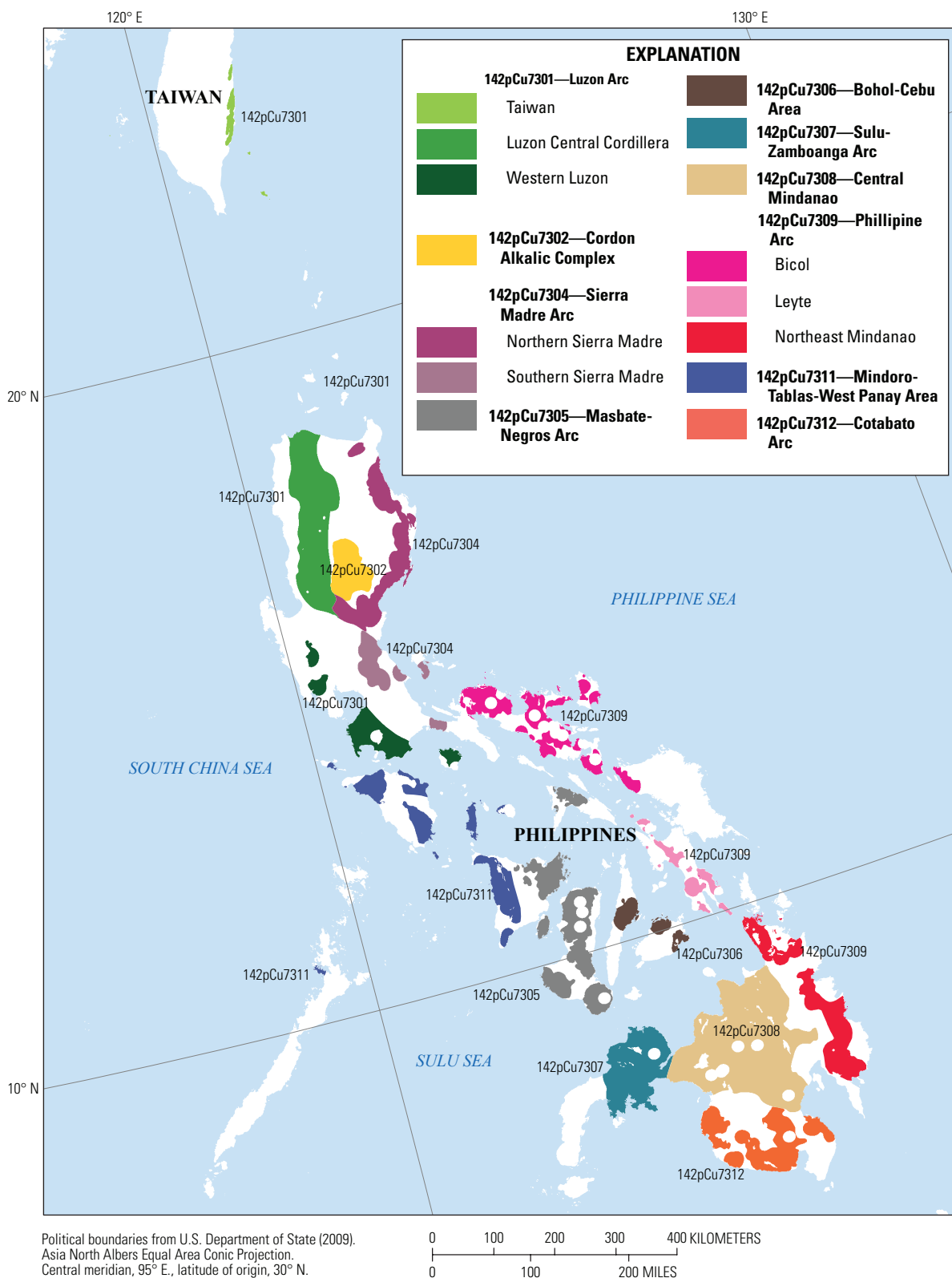
### Southeast Asia (The Philippines and Taiwan)

#### The Philippine Archipelago

The Philippine archipelago consists of more than 7,000 islands that cover a land area of about 300,000 square kilometers (km<sup>2</sup>) (fig. 1). Locations of porphyry copper deposits and prospects in the Philippines and Taiwan (Republic of China) are plotted in figure 4A–E along with physiographic features mentioned in this report.

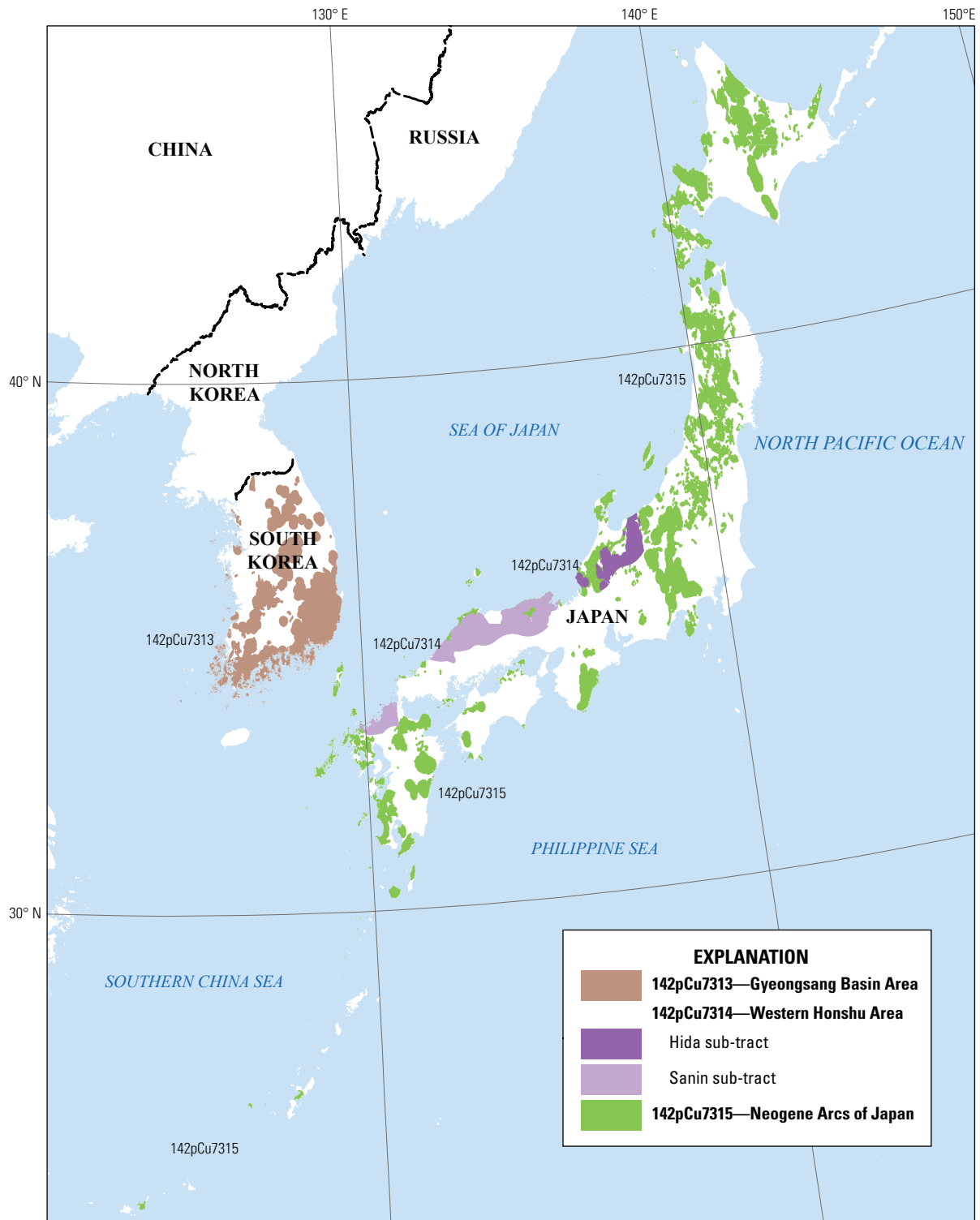
<sup>14</sup><http://shoreline.noaa.gov/data/datasheets/wvs.html>

A



**Figure 3.** Maps of permissive tracts for porphyry copper deposits in countries covered in this report. A, Southeast Asia—Philippines and Taiwan (Republic of China); B, East Asia—Republic of Korea (South Korea) and Japan.

B



Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 125° E., latitude of origin, 30° N.

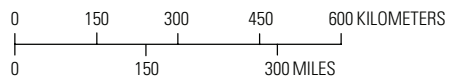


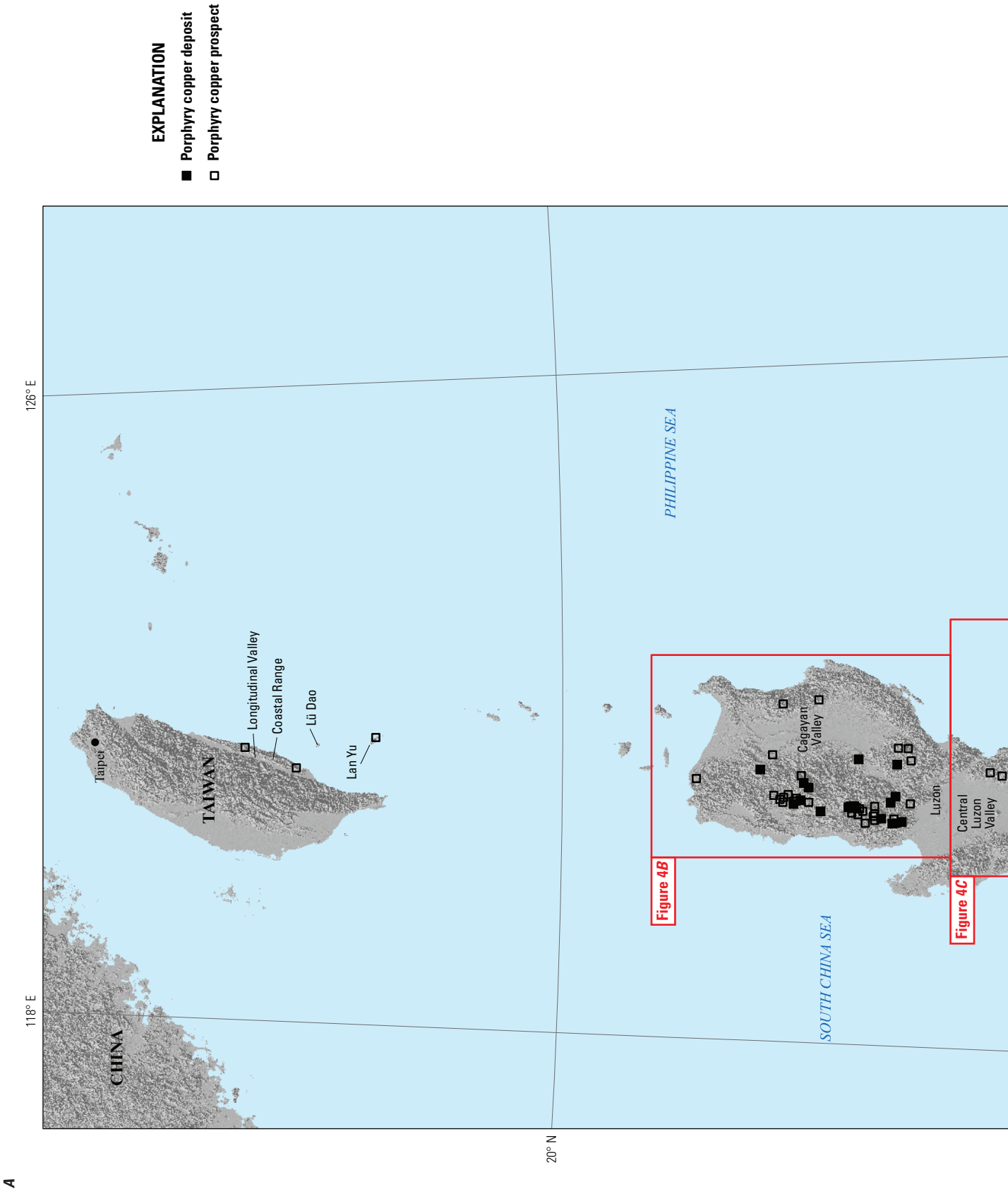
Figure 3.—Continued

**Table 3.** Permissive tracts for porphyry copper deposits in East and Southeast Asia.

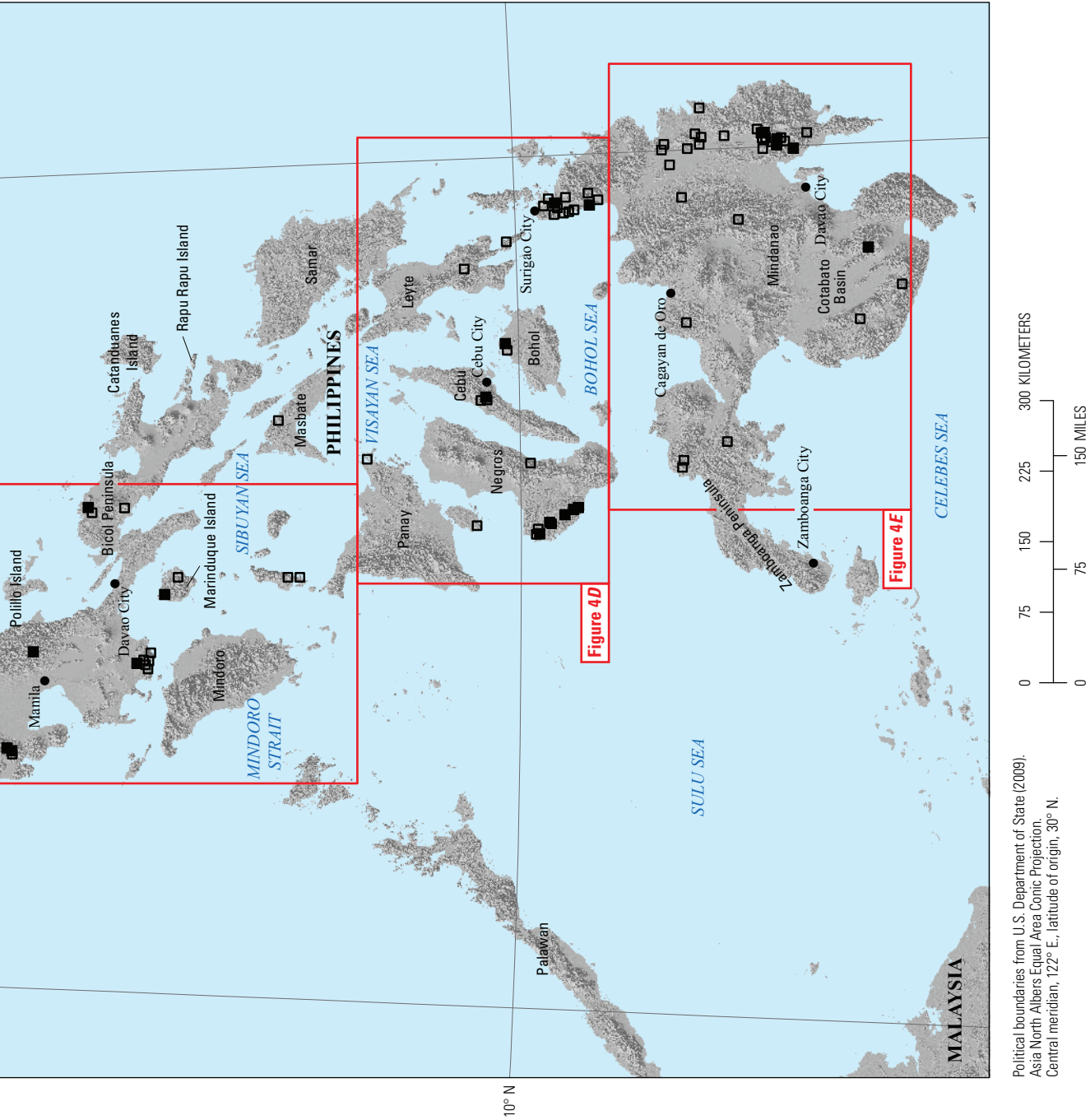
 [km<sup>2</sup>, square kilometers]

Coded_Id	Tract Name	Countries	Geologic feature assessed	Tract area (km <sup>2</sup> )	Appendix
Philippine Archipelago					
142pCu7312	Cotabato Arc	Philippines	Miocene to Pleistocene Colobato Arc	9,700	A
142pCu7308	Central Mindanao Volcanic Province	Philippines	Pliocene Central Mindanao Volcanic Province	29,320	B
142pCu7307	Sulu-Zamboanga Arc	Philippines	Northern late Miocene to Holocene Sulu-Zamboanga Arc	10,180	C
142pCu7305	Masbate-Negros Arc System	Philippines	Masbate- Negros island arc system ( Eocene to Miocene W, Miocene to Holocene E)	12,230	D
142pCu7309	Philippine Arc	Philippines	Oligocene to Pleistocene Philippine Arc	23,700	E
142pCu7302	Cordon Alkalic Complex	Philippines	Late Oligocene to early Miocene K-alkaline magmatic province at south end of Cagayan rift basin.	4,860	F
142pCu7304(a,b)	Sierra Madre Arc	Philippines	Eocene-Oligocene Sierra Madre Arc	14,000	G
142pCu7311	Mindoro-Tablas-West Panay Area	Philippines	Neogene Mindoro-Tablas-Western Panay magmatic arc	9,170	H
142pCu7306	Bohol-Cebu Area	Philippines	Miocene Bohol Arc; Cretaceous rocks on Cebu	2,600	I
142pCu7301(a,b,c,d)	Luzon Arc	Philippines, Taiwan	Oligocene to Holocene Luzon Arc	23,700	J
South Korea					
142pCu7313	Gyeongsang Basin	South Korea	Late Cretaceous calc-alkalic igneous rocks of the southeastern Korean Peninsula	46,300	K
Japan Archipelago					
142pCu7314	Western Honshu Area	Japan	Late Cretaceous to Paleogene magnetite-series igneous rocks of the Japan Arc	27,600	L
142pCu7315	Subaerial Neogene Arcs of Western Japan	Japan	Subaerial parts of the Miocene and younger Kurile, Northeast Japan, Izu, Southwest Japan, and Ryukyu volcanic arcs	120,590	M

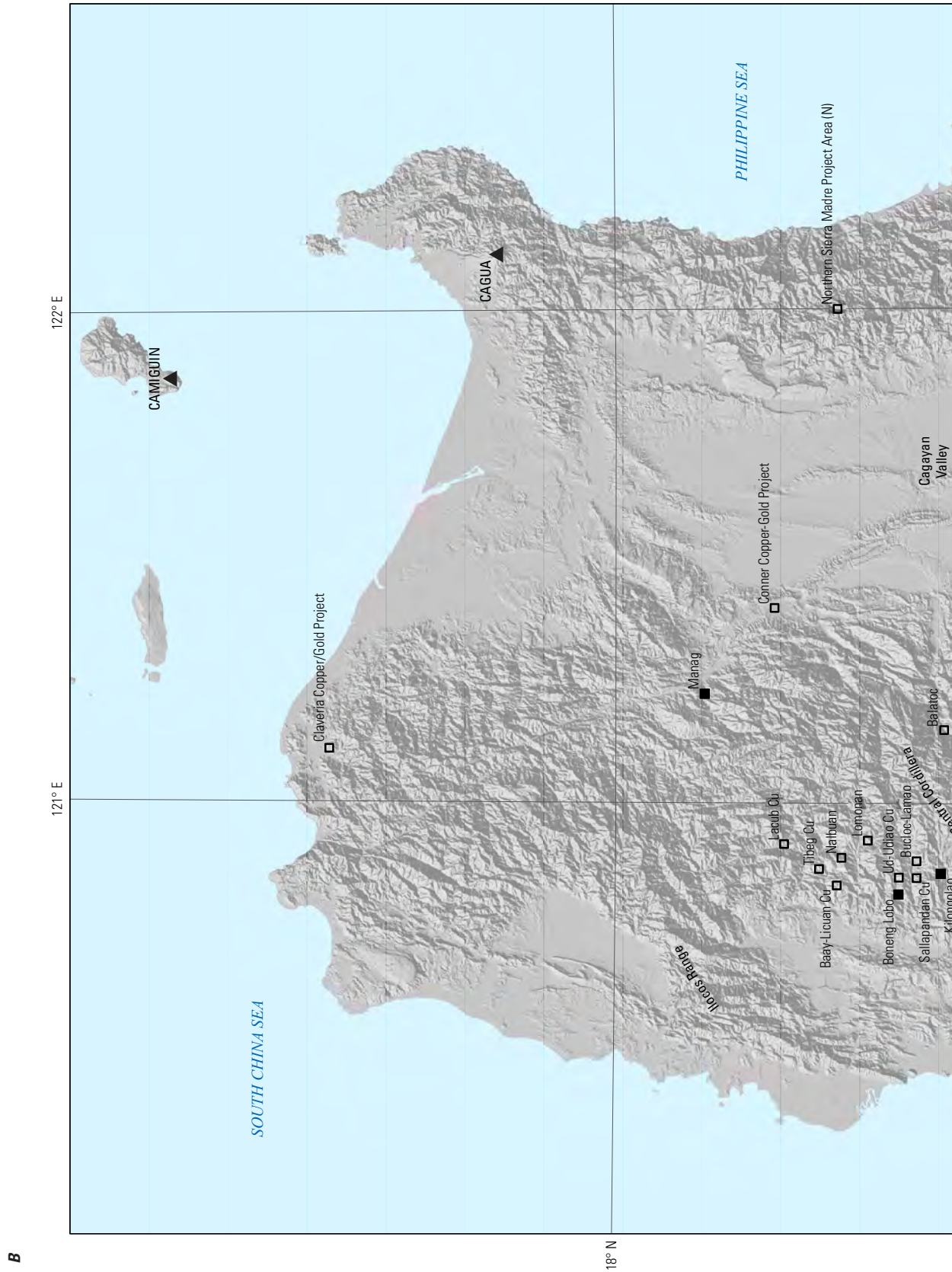






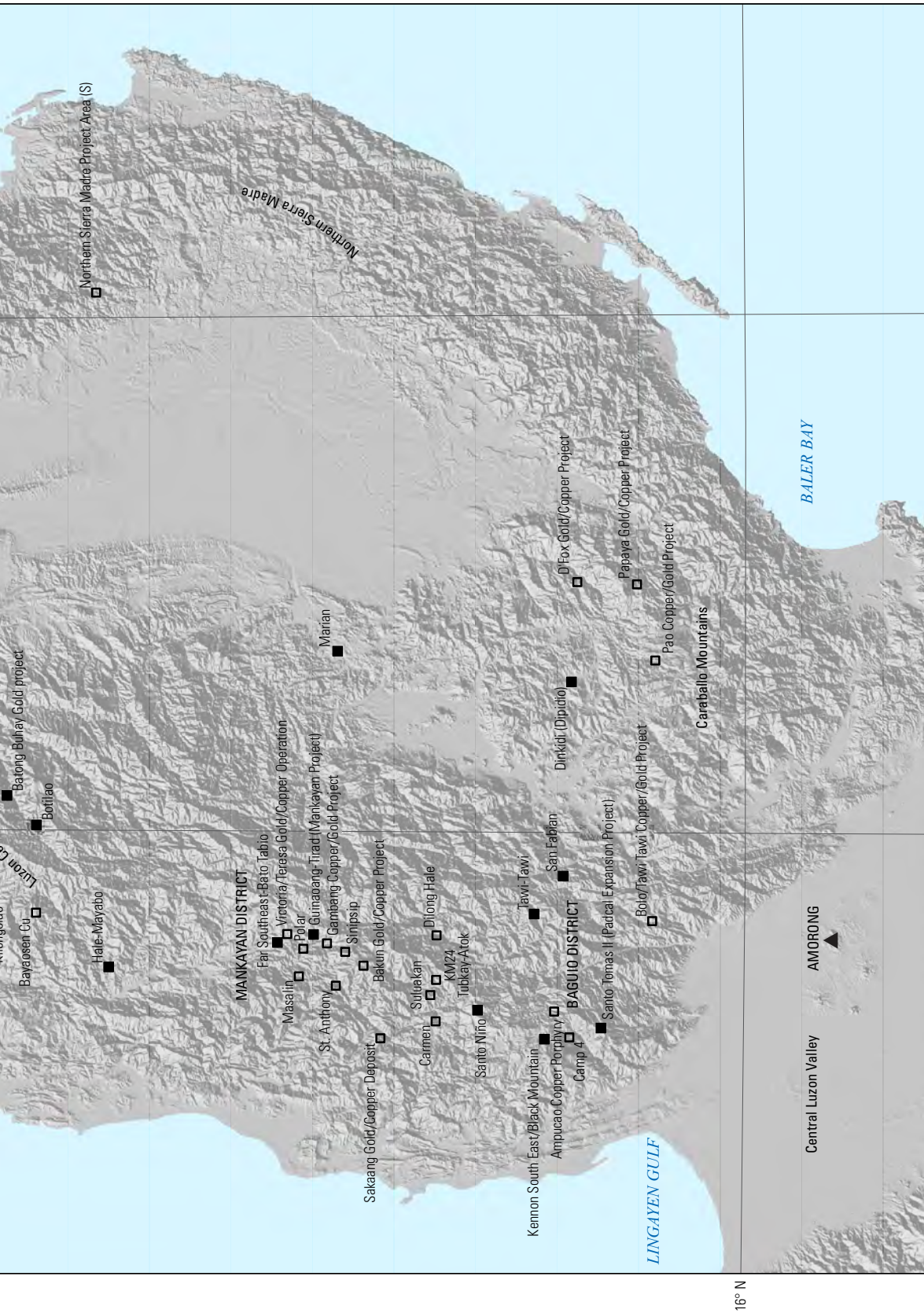


**Figure 4.** Maps showing physiographic features and locations of porphyry copper deposits (named) and prospects in the Philippines and Taiwan (Republic of China). A, Study area showing prospect names in Taiwan and outlines of detailed maps for the Philippines (B–E, arranged from north to south). B, Northern Luzon, Mindoro, and the Bicol Peninsula. C, Southern Luzon, Negros, Cebu, Bohol, Leyte, and northeastern Mindanao. E, Mindanao.



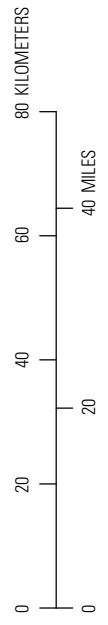
B





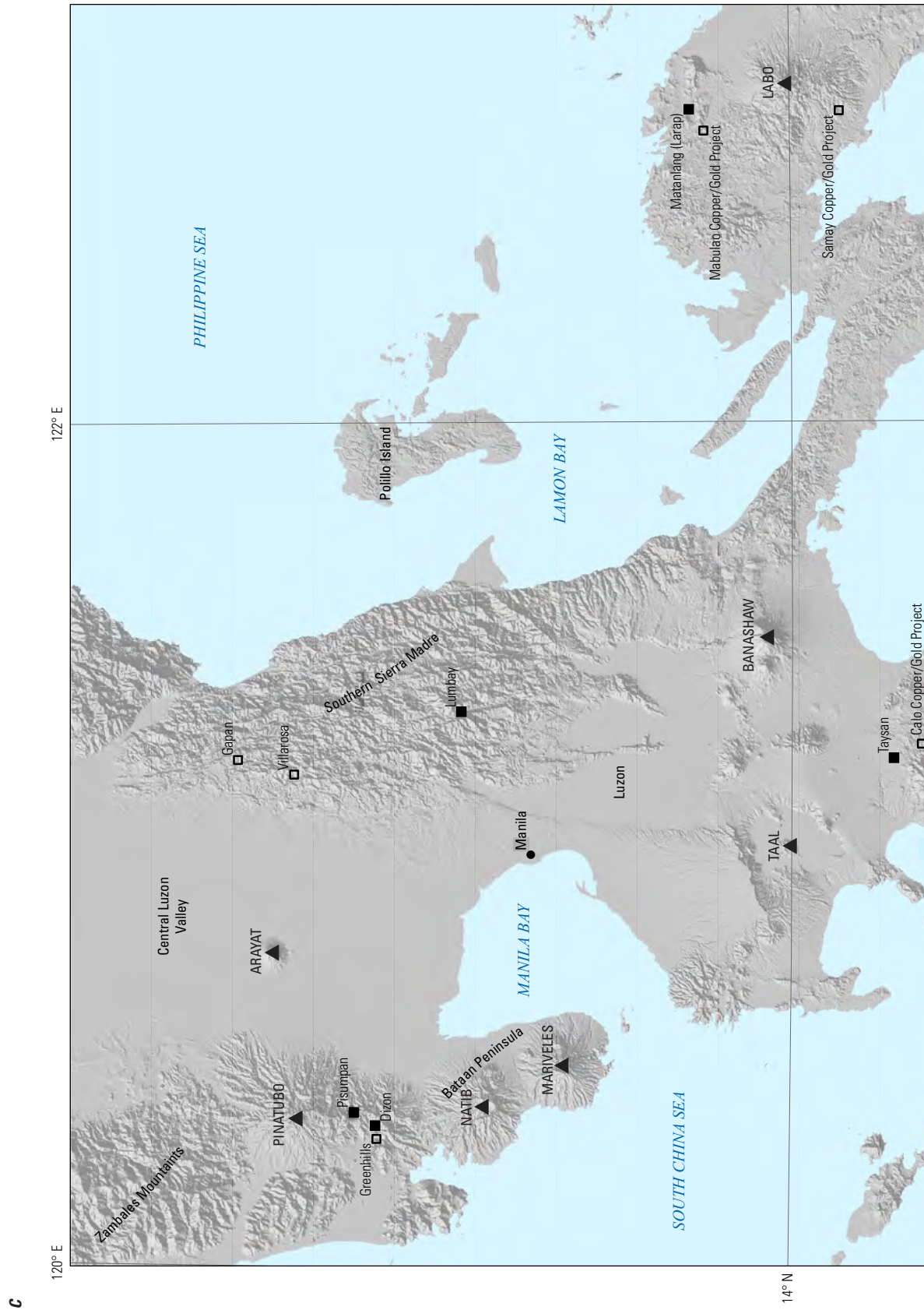
16° N

- EXPLANATION**
- Porphyry copper deposit
  - Porphyry copper prospect
  - ▲ Volcano

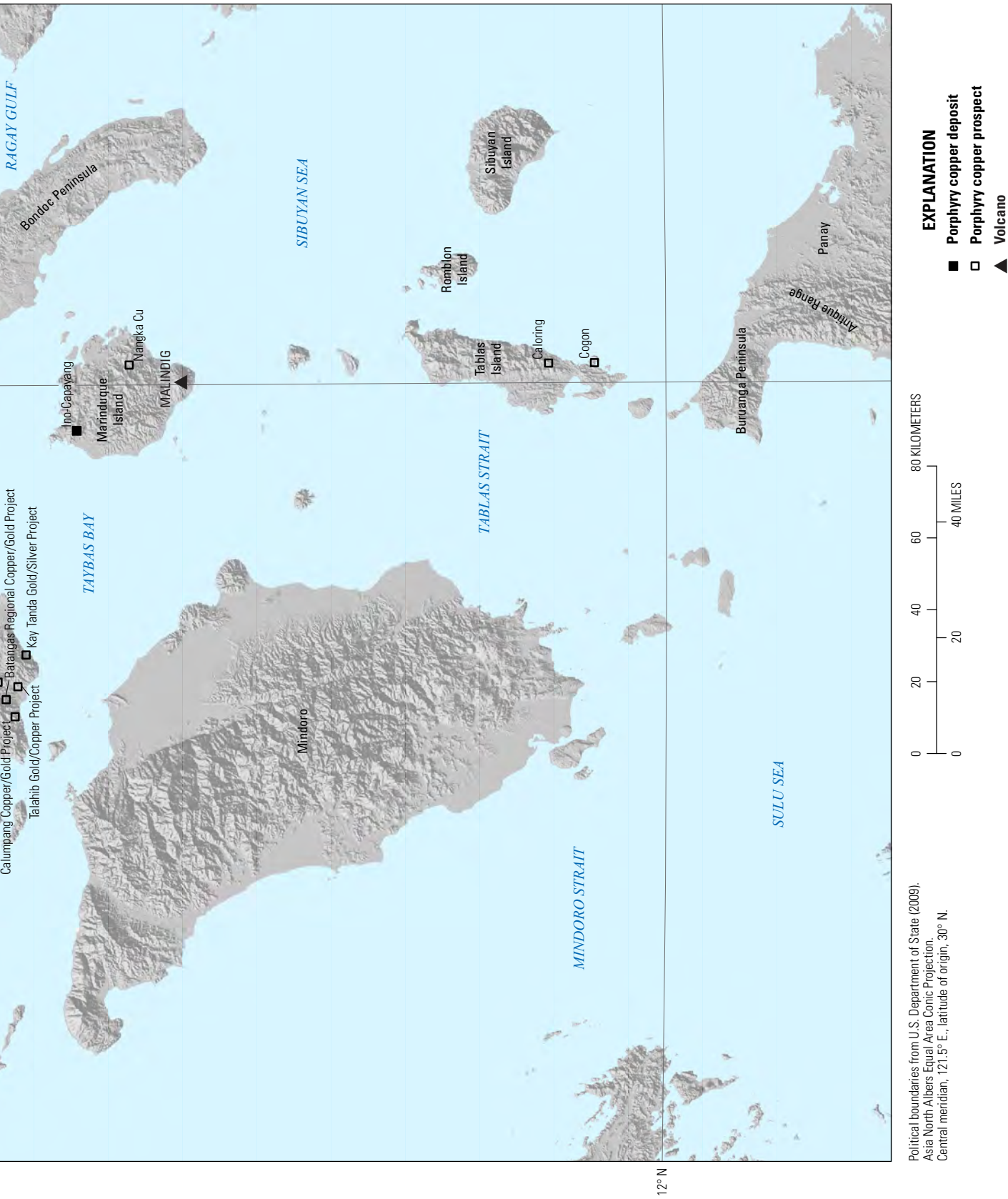


Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 121.5° E.; latitude of origin, 30° N.

Figure 4.—Continued







Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 121.5° E., latitude of origin, 30° N.

Figure 4.—Continued



Figure 4.—Continued





**EXPLANATION**

- Porphyry copper deposit
- Porphyry copper prospect
- ▲ Volcano



E



Political boundaries from U.S. Department of State (2009).  
Asia North Albers Equal Area Conic Projection.  
Central meridian, 124.5° E., latitude of origin, 30° N.

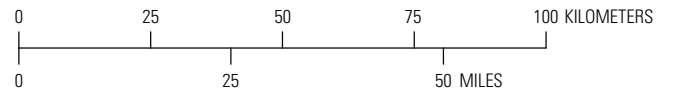


Figure 4.—Continued

125° E



**EXPLANATION**

- Porphyry copper deposit
- Porphyry copper prospect
- ▲ Volcano



The Philippine island arc system is at the intersection of the oceanic Pacific Plate to the east, the continental Eurasian Plate to the west, and the oceanic and continental Indo-Australian Plate to the south (fig. 5A). The archipelago is a complex collage of subduction and collision zones, island arcs, marginal basins, and rifted and accreted microcontinental blocks (Philippine Mines and Geosciences Bureau, 2010). Arcs range in age from Cretaceous to Quaternary (table 2).

The Cretaceous was a period of oceanic crust formation, documented by Cretaceous ophiolite complexes containing fragmentary preserved evidence of arc magmatism. Cretaceous igneous rocks reported on Cebu, southeastern Luzon, and northeastern Luzon have subduction-related geochemical signatures (Dimalanta and Yumul, 2006). These rocks host the oldest porphyry copper deposit known in the Philippines, the 108-Ma (million-year-before-present/mega-annum) Atlas (Biga) deposit on Cebu (fig. 4D).

The Oligocene-Miocene magmatic arcs of the Philippines are preserved as more coherent belts that extend from Luzon to Mindanao. The majority of the porphyry copper and epithermal gold deposits of the Philippines are associated with Oligocene-Miocene arcs (Philippine Mines and Geosciences Bureau, 2010).

The Miocene collision of a microcontinent with an oceanic island arc formed the two major geologic blocks that constitute the Philippines. The Philippines Mobile Belt (fig. 5B) is a seismically active block characterized by faulting, earthquakes, and active volcanoes. The aseismic Palawan microcontinental block (fig. 5B) is a rifted fragment of an Asian Andean-type continental margin that drifted southward as the South China Sea opened in late Eocene to early Miocene time (37–16 Ma). The Palawan block (referred to as the Palawan indenter) collided with the northwestward-moving Philippine Mobile Belt near Mindoro Island in the central part of the archipelago about 20–16 Ma (Yumul and others, 2009). Studies of ophiolites, accretionary prisms and mélanges, and paleomagnetism indicate that different islands in the central Philippines rotated in different directions, and that multiple collisions may have occurred (Yumul and others, 2009). Some data contradict the generally accepted interpretation of a northwest-southeast initial orientation of the central Philippines islands (Yumul and others, 2003, 2009).

The modern archipelago is situated between two opposing subduction zones. To the west, the South China Sea, Sulu Sea, and Celebes Sea are subducting eastward along the Manila-Negros-Sulu and Cotabato Trenches (fig. 5B). On the east side of the archipelago, the Philippine Sea Plate is subducting westward along the East Luzon Trough-Philippine trench system (fig. 5B). A 1,200-km-long sinistral strike-slip fault system, the northwest-trending Philippine Fault accommodates strain from convergence of surrounding subduction zones (Dimalanta and Yumul, 2006; Yumul and others, 2008a).

Most of the Cenozoic arcs can be directly related to specific subduction zones; some arcs are composite or long-lived (table 2). The Luzon, Negros-Masbate, and Cotabato arc systems (fig. 2A) were formed by subduction along the east-dipping Manila-Negros-Cotabato trench system (fig. 5B); the Bicol and Philippine arc systems are related to west-dipping

subduction of the Philippine Sea Plate along the Philippine Trench. Interpretations of the tectonic settings of some arcs continue to evolve as more data become available.

With the exception of the Atlas Mine on Cebu Island (fig. 4D), all of the known porphyry copper deposits of the Philippines are Oligocene or younger. Deposits include both porphyry copper-molybdenum-gold and porphyry copper-gold subtypes. Miocene and younger deposits are present in the western and eastern parts of the archipelago, whereas Miocene and Oligocene deposits mainly are confined to a central belt (fig. 6). As noted by Yumul and others (2003), the distribution of porphyry copper deposits in the Philippines is approximately coextensive with the distribution of epithermal gold systems, and the main magmatic episodes for porphyry copper emplacement are Cretaceous (95–110 Ma on Cebu), Oligocene (30 Ma on Negros), Miocene (15–20 Ma on Marinduque), and Pliocene (Baguio district on Luzon) (figs. 4A, B).

The major arc systems of the region (fig. 2, table 2) and the permissive tracts delineated by the assessment team (fig. 3, table 3) are described below, from south to north. Most of the arcs in the Philippines developed on older accretionary basement or on deformed ophiolites on thin, immature crust devoid of granitoid basement (D. Alexeiev, written commun., 2010).

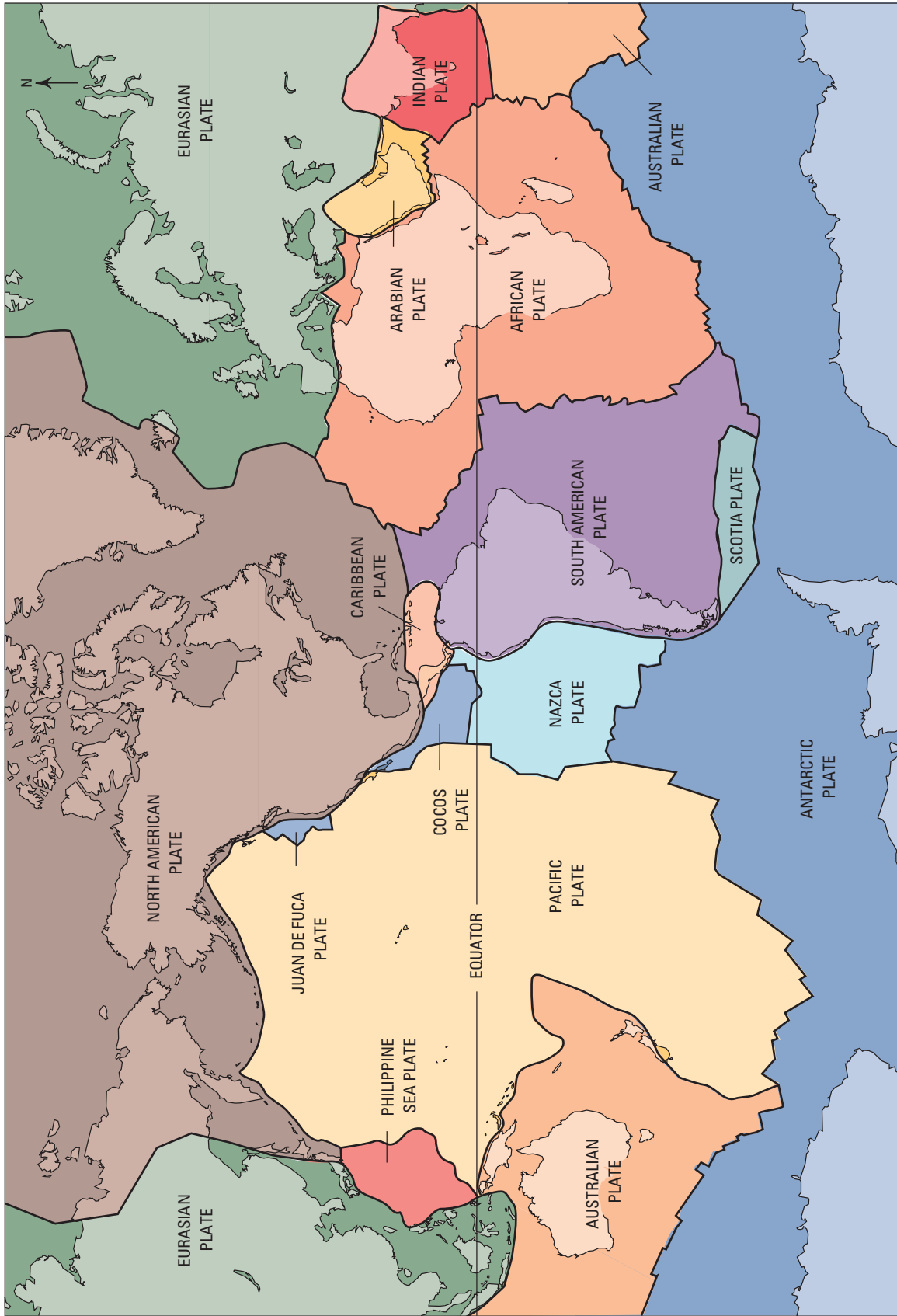
## Cotabato Arc

### Tectonic Setting

The 300-km-long Miocene to Holocene Cotabato composite arc system in western Mindanao is the northern extension of the Sangihe Arc, and may be coextensive with the Masbate-Negros Arc to the north (fig. 2). The modern Cotabato Arc is associated with subduction of oceanic crust of the Celebes Sea at the Cotabato Trench (fig. 5). The Pliocene to Quaternary calc-alkalic and adakitic arc overlies Oligocene tholeiitic diorites and Miocene calc-alkalic andesites developed on older accretionary basement (Pubellier and others, 1991). The Cotabato Fault (fig. 5) forms the boundary between the northern part of the arc and the Central Mindanao Volcanic Belt to the east.

### Permissive Tract 142pCu7312 (Cotabato)

The Cotabato tract, 142pCu7312, delineates arc-related calc-alkalic igneous rocks in southwestern Mindanao (fig. 3A). The tract hosts the Pliocene (3.5 Ma) Tampakan deposit (fig. 4E). The Tampakan porphyry copper-gold deposit, with 2,940 million metric tons (Mt) of 0.52 percent copper, is considered to be one of the largest undeveloped deposits in Southeast Asia (Middleton and others, 2004). Tampakan represents an epithermal system telescoped on a porphyry copper deposit. A feasibility study and mining plan were completed; however, plans for development of a mine were impeded by legislation passed in 2010. Porphyry copper-gold prospects, epithermal gold deposits, and skarns are associated with Neogene diorite stocks, hypabyssal porphyries, and eroded stratovolcanoes in the tract area.



A

**Figure 5.** Map showing the tectonic setting of the Philippines. A, Relation of the Philippine Plate to surrounding plates. B, Principal tectonic features of the Philippine Archipelago.

B

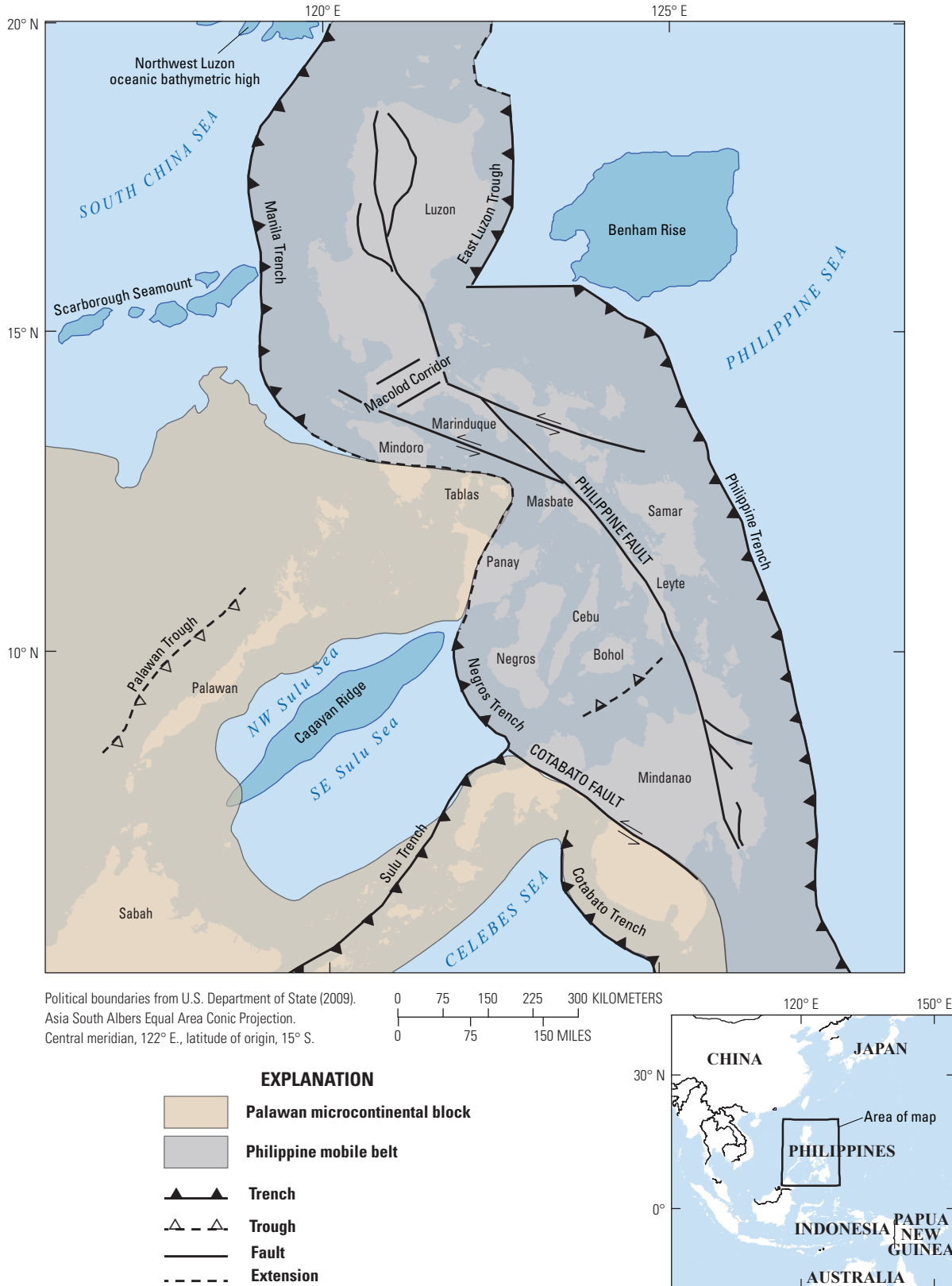
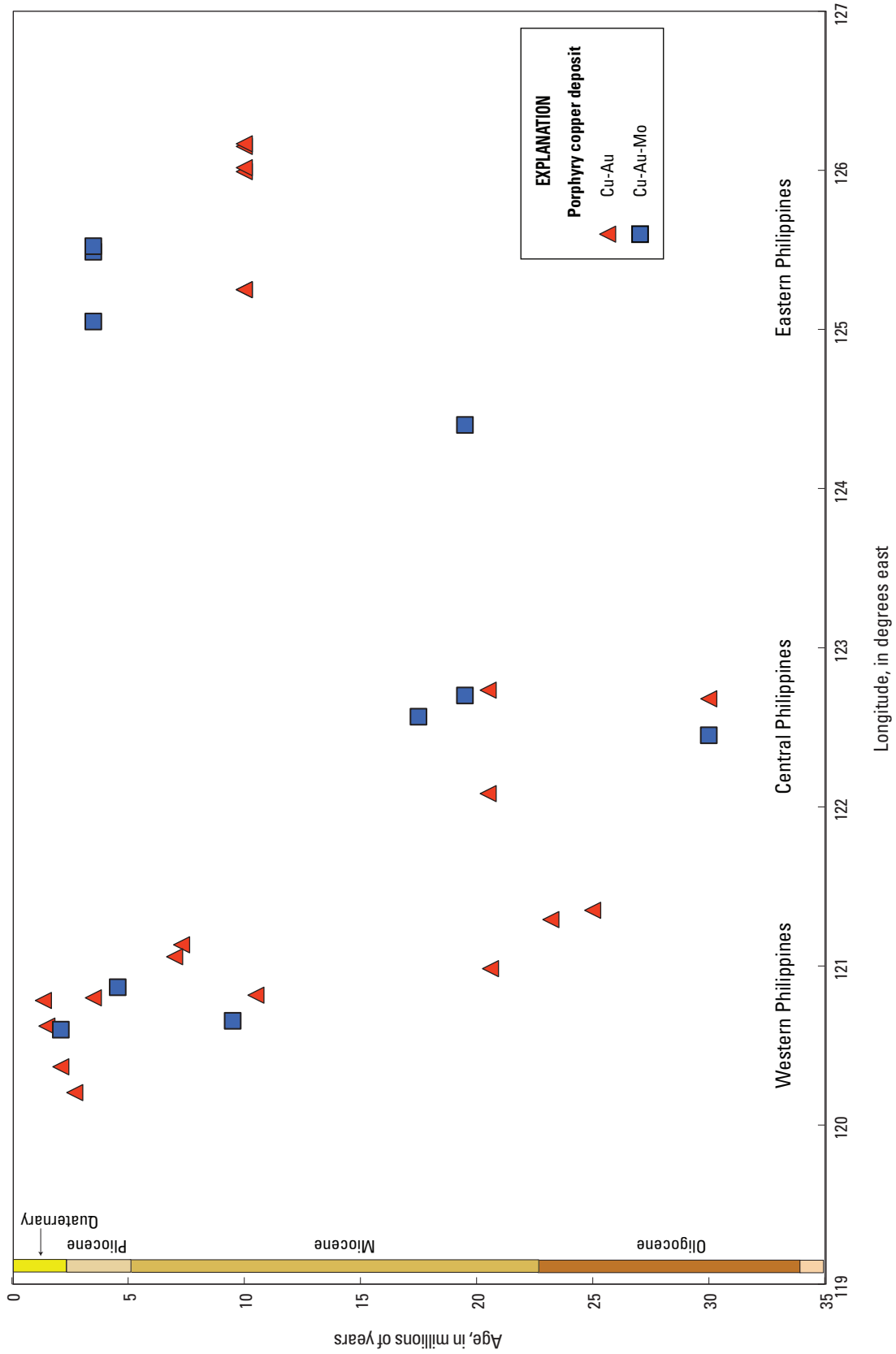


Figure 5.—Continued



**Figure 6.** Graph showing the age and deposit-type distribution of post-Cretaceous porphyry copper deposits across the Philippine Archipelago as a function of longitude across the islands, from west to east.



## Central Mindanao Volcanic Province

### Tectonic Setting

The Central Mindanao Volcanic Province (fig. 4E) is an area of Pliocene (4–5 Ma) collision of two island arcs, followed by postcollisional calc-alkalic to shoshonitic magmatism (2–3 Ma) that produced the largest volcanic field in the Philippines (Pubellier and others, 1996; Sajona and others, 2000). Western and eastern Mindanao constitute the northernmost extents of the Sangihe and Halmahera Arcs (figs. 1, 2A), respectively. These parts of present-day Mindanao were discrete oceanic arcs from the Paleogene until the Pliocene collision event (Sajona and others, 2000; Rangin and others, 1990). The collision event is ongoing to the south, where the Halmahera and Sangihe Arcs are colliding and consuming the intervening Molucca Sea (Sajona and others, 2000).

### Permissive Tract 142pCu7308 (Central Mindanao)

The highlands west of the Philippine Fault (fig. 5B) in Central Mindanao within the Central Mindanao Volcanic Province are delineated as tract 142pCu7308 (fig. 3A). The eastern boundary of this tract is the margin of a basin filled with more than 5 km of Cenozoic sediments (the Agusan-Davao Trough). The western boundary of the Central Mindanao tract is the Cotabato Fault (fig. 5B), which forms the eastern boundary of the Cotabato Arc, tract 143pCu7312. There are three porphyry prospect areas within the tract, but no known deposits. Any porphyry copper deposits are likely to be concealed under volcanic cover.

## Sulu-Zamboanga Arc

### Tectonic Setting

The Sulu-Zamboanga Arc extends for 400 km from eastern Sabah, Malaysia, to the Zamboanga Peninsula of the southern Philippines (fig. 2A). Miocene collision between the northeastern island-arc terrane and a continental fragment that makes up the southwestern part of the peninsula is recorded by a mélangé zone (Garwin and others, 2005; Jimenez and others, 2002).

### Permissive Tract 142pCu7307 (Sulu-Zamboanga)

Paleogene and Neogene intrusions, and late Miocene to Pliocene volcanic rocks in the northern part of the Sulu-Zamboanga Arc are assessed as tract 142pCu7307 (fig. 3A). Porphyry copper prospects and precious- and base-metal occurrences are associated with Pliocene to Pleistocene andesites and hypabyssal intrusions in the northeastern Zamboanga Peninsula, south of the Cotabato Fault (fig. 5B). The tract includes three significant porphyry copper prospect areas, including the undrilled, abandoned Labangan porphyry Cu-Au prospect associated with diorite porphyry, andesitic

to basaltic flows, and northwest-striking faults (Sillitoe and Gappe, 1984).

## Masbate-Negros Arc

### Tectonic Setting

The 400-km-long Masbate-Negros arc system includes an older Eocene to Miocene western arc, and a younger Miocene to Holocene eastern arc, all developed on oceanic arc accretionary crust (Garwin and others, 2005). The younger arc, which overprints the older arc, is related to the subduction of the Sulu Sea basin beneath Negros along the Negros Trench (fig. 5B). The polarity of subduction for the older western arc is not well-established (west- or east-dipping). The younger arc is interpreted as a product of east-dipping subduction associated with a slab at 100 km depth (Gudmundson and Sambridge, 1998).

### Permissive Tract 142pCu7305 (Masbate-Negros)

The Masbate-Negros tract (fig. 3A) was delineated on the distribution of the Neogene igneous rocks that lie within the arc system, as bounded by the Philippine Fault (fig. 5B) on the north, and by the Sulu-Zamboanga Arc (fig. 2A) on the south. The Oligocene arc on Negros includes the Pagatban Batholith (38.4–34.4 Ma) that has intruded andesitic and dacitic rocks (Mitchell and Leach, 1991). On eastern Panay, the pre-Miocene arc rocks include diorites that intrude andesites (Mitchell and Leach, 1991). The mid-Miocene arc is defined by dacite porphyry stocks and dikes that intrude Oligocene diorites associated with porphyry copper deposits on southwestern Negros and andesites in eastern Panay (Mitchell and Leach, 1991). The tract includes Quaternary volcanic rocks in Central and Western Visayas that may cover buried porphyry deposits at shallow depths. The 30-Ma Sipalay deposit (807 Mt, 0.473 percent copper) lies within the tract (fig. 4D).

## Philippine Arc

### Tectonic Setting

The 1,000-km-long Philippine oceanic arc extends from Bicol to eastern Mindanao, parallel to the Philippine Fault (fig. 2A). The 1,200-km-long, left lateral Philippine strike-slip fault (fig. 5B), which spans the length of the Philippine Archipelago, has been active since the mid-Miocene. Different segments of the arc have been active since the Oligocene. Post-Pliocene arc magmatism was related to west-directed subduction of the Philippine Sea Plate at the Philippine Trench (fig. 5B). Pre-Pliocene magmatism may have been related to east-dipping subduction from the west (Garwin and others, 2005). From north to south, arc segments identified along the fault (fig. 5B) include the following (Yumul and others, 2008a):

- *Bicol segment*—Medium- to high-K calc-alkalic rocks, high-Al basalts, and andesites.

- *Leyte segment*—A 250-km-long, southeast-trending belt of Plio-Pleistocene volcanoes characterized as medium- to high-K calc-alkalic rocks, Miocene andesitic rocks.
- *Northeastern Mindanao segment*—Early Oligocene-early Miocene rocks and Pliocene-Quaternary andesites.

#### Permissive Tract 142pCu7309 (Philippine)

The Philippine tract (142pCu7309) outlines the mapped extent of Paleogene and Neogene intrusions, including diorite complexes, and Oligocene-Miocene andesitic volcanic rocks along the Philippine Arc (fig. 2A). The tract includes late Pliocene intrusions associated with porphyry deposits in northeastern Mindanao. Parts of the tract are overlain by Pliocene-Quaternary volcanic cover. The Philippine Fault forms the western boundary of the tract, which extends to the coast of eastern Mindanao. The tract includes eight porphyry copper deposits that range in age from 21 Ma at Matanlang to 4 Ma at Boyangan. These include the 1,151-Mt Kingking porphyry copper-gold deposit, several smaller deposits such as the 110-Mt Amacan deposit, and recent discoveries of the approximately 2.5-Ma concealed deposits at Boyungun (fig. 4D). The Boyungun deposit in northeastern Mindanao is remarkable because of the deep (600 meters, m) oxidation zone that developed in a humid tropical climate, whereas supergene zones typically are 100 m thick or less (Braxton and others, 2009). More than 30 prospect areas lie within the tract, which may be underexplored relative to some other areas of the Philippines, such as the Luzon Central Cordillera (fig. 4B).

#### Cordon Alkalic Complex

##### Tectonic Setting

The Cordon Alkalic Complex is a late Oligocene to early Miocene alkalic province at the southern end of the Cagayan Valley in the Caraballo Mountains of Northern Luzon (fig. 4B). Proposed origins for the distinctive alkalic province, the only one recognized in the Philippines, include back- or intra-arc rifting that occurred after westward subduction along the East Luzon Trench ceased in the late Oligocene and before middle Miocene, east-directed subduction began along the Manila Trench. Intraplate magmatism, partial melting of a subducted slab, or intra-arc extension also have been proposed to explain these rocks. Geochemical data support a large ion lithophile elements (LILE) enriched mantle source that became increasingly enriched over time and a back-arc setting relative to eastward subduction along the western Luzon Arc (Wolfe and others, 2010). In a recent geochemical study, Hollings and others (2011) concluded that the potassic igneous rocks in the Cordon area formed in a back arc associated with the main calc-alkalic Miocene arc that produced the igneous activity in the Central Cordillera, where the arc formed by eastward subduction along the Manila Trench (fig. 5).

#### Permissive Tract 142pCu7302 (Cordon)

The Cordon tract (142pCu7302) outlines the Cordon Alkalic Complex at south end of the Cagayan Valley rift basin on Luzon (fig. 3A). The tract includes alkali syenites, monzonites, and trachyandesites of the Dipidio Igneous Complex, Palali batholith, Cordon Syenite Complex, and alkaline volcanic rocks (Knittel and Cundari, 1990; Knittel and Defant, 1988). The 23.2 Ma Dinkidi deposit (fig. 4B) is notable as it is one of the few recognized alkaline porphyry deposits outside of British Columbia, Canada (Wolfe and others, 2010). Dinkidi contains measured, indicated, and inferred resources of 121 Mt of 0.39 percent copper, 0.97 grams per metric ton (g/t) gold with mining reserves of 23.7 Mt at 0.65 percent copper and 1.8 g/t gold (Joyce and Thomson, 2002). The tract also includes the 340-Mt San Fabian deposit.

#### Sierra Madre Arc

##### Tectonic Setting

Oligocene igneous rocks of intermediate composition along the Pacific coastal area of eastern Luzon in the Sierra Madre (fig. 4B,C) define the Sierra Madre Arc. The northern Sierra Madre is separated from the Luzon Central Cordillera by the Cagayan Valley (fig. 4B), an 8-km-deep sedimentary basin developed on pre-Tertiary ophiolite and Cretaceous-Paleogene arc rocks. Mitchell and Leach (1991) referred to the northern Sierra Madre as the Northeastern Luzon-Polillo-Catanduanes Arc, noting that a large 31-Ma granodiorite pluton that intruded Oligocene(?) volcanic rocks in northeastern Luzon may be coextensive with Oligocene plutons on Catanduanes Island (fig. 4A) and Polillo Island (fig. 4C). The rocks in the northern Sierra Madre may be coextensive with the Oligocene rocks in the southern Sierra Madre (fig. 4C).

#### Permissive Tract 142pCu7304 (Sierra Madre)

The Sierra Madre tract, 142pCu7304, consists of two segments (fig. 3A). The northern segment delineates Oligocene igneous rocks exposed in a discontinuous belt parallel to the east coast of Luzon; no porphyry deposits are known. The southern segment delineates Oligocene quartz diorite and diorites in southeastern Luzon and Miocene quartz diorite. The tract contains the 78-Mt Lumbay porphyry copper-gold deposit and four prospect areas (fig. 4C).

#### Mindoro-Tablas-Western Panay Area

##### Tectonic Setting

Rocks in northeastern Mindoro Island have the island-arc characteristics of the Philippine Mobile Belt, whereas rocks in southwestern Mindoro are linked to the Palawan microcontinent. Miocene arc rocks on Tablas and western Panay extend offshore to the Cagayan Ridge (fig. 5). The Tablas-Cagayan arc segment may represent a mid-Miocene continuation of the western Luzon Arc that existed before the Palawan collision (Mitchell and Leach, 1991).

Permissive Tract 142pCu7311 (Mindoro-Tablas-West Panay)

The Neogene Mindoro-Tablas-Western Panay tract (fig. 3A) is delineated on the extent of mapped Neogene igneous rocks in the collisional area between the Palawan microcontinent and the Philippine Mobile Belt on Mindoro Island, the Romblon Islands, Western Visayas (Panay), and a small area of exposed quartz monzonite in Palawan. The tract is composed of several parts due to the geography of the islands, all west of the Philippine Fault system. No porphyry deposits are known within the tract area; two porphyry-related copper prospects are reported in the tract area.

### Bohol-Cebu Area

#### Tectonic Setting

The geodynamic setting(s) for the calc-alkalic igneous rocks on Bohol and Cebu Islands in the Central Philippines is poorly understood. Cretaceous, Paleogene, and Miocene ages are all reported. A northwest-trending Cretaceous arc fragment extends from northwestern Bohol through central Cebu Island (Philippine Mines and Geosciences Bureau, 2010). The relation of the Cretaceous rocks to subduction is unknown. Mitchell and Leach (1991) described Miocene diorite plutons and andesitic and dacitic volcanic rocks on Bohol Island as the Northwestern Bohol Arc, possibly related to an early Miocene trench that lay to the east of Bohol.

Permissive Tract 142pCu7306 (Bohol-Cebu Area)

Pre-Pliocene igneous rocks associated with known porphyry copper deposits and prospects in Bohol Island and nearby Cebu Island (fig. 4D) are assessed as tract 142pCu7306 (fig. 3A). The tract includes the Balak deposit on Bohol Island that has supergene reserves of 5 Mt of 0.80 percent copper, the Cretaceous Atlas (Biga) mine on Cebu Island, and several prospects. Before the discovery of the Tampakan deposit, the Atlas Mine was the largest porphyry copper deposit in the Philippines (greater than 6 Mt contained copper). The Atlas Mine operated from 1955 to 1995 with production from three separate pits (Biga, Carmen, and Lutopan). Production was restarted in 2007 along with exploration activities to assess historical mine waste dumps (1.2 billion metric tons) for copper recovery and to evaluate partially explored prospects for concealed extensions and satellites of the identified resources (Atlas Consolidated Mining and Development Corporation, 2012).

### Luzon Arc

#### Tectonic Setting

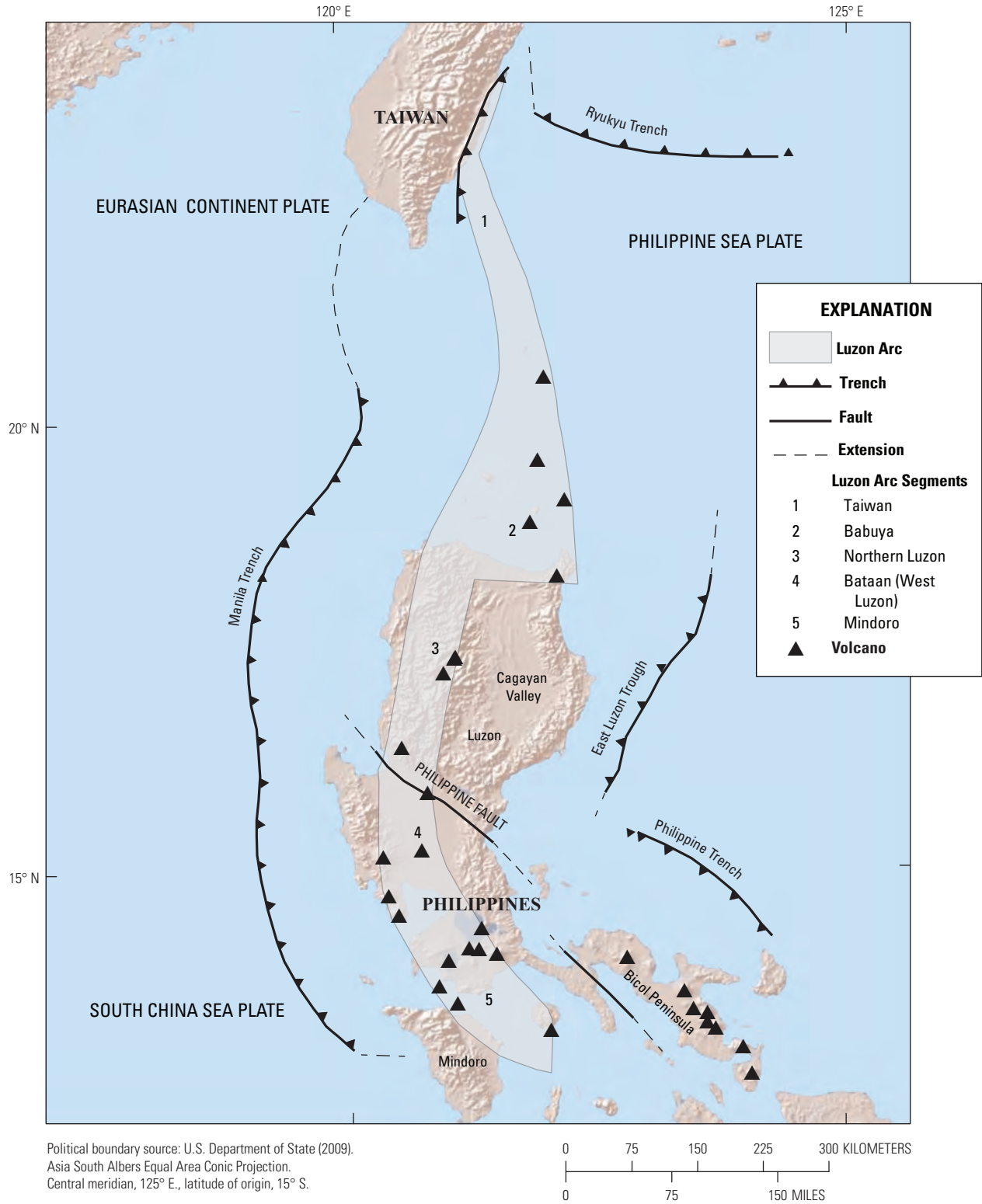
The Neogene Luzon composite arc system extends from the Coastal Range of eastern Taiwan southward for a distance

of 1,200 km to Mindoro in the Philippines (fig. 7). The arc became active in the early Miocene and is now underlain by an east-dipping Benioff zone related to the Manila Trench. In northern Luzon, an early to middle Miocene reversal in arc polarity may have shifted the locus of arc activity from east to west as the geodynamics switched from subduction of the proto-Philippine Sea Plate along the proto-East Luzon Trough to subduction of the South China Sea Plate along the Manila Trench (Yumul and others, 2008a). The 900-km-long Manila Trench marks Plio-Pleistocene eastward subduction of the South China Sea on the Eurasian Plate beneath the Luzon Arc of the Philippine Mobile Belt (figs. 5B, 7). The trench trends approximately north-south from the Taiwan collision zone in the north to Mindoro in the south, where the Palawan block collides with southwestern Luzon. Subduction of the Scarborough seamounts, the aseismic mid-ocean ridge of the South China Sea (fig. 5B), at 5–4 Ma may have caused a change in subduction angle (buoyancy) that interrupted subduction, caused regional uplift and erosion, and led to a gap in magmatic activity expressed as an approximately 50-km-wide gap between the western and eastern volcanic zones of the double island arc between Luzon and Taiwan to the north.

The Luzon Arc is a chain of active and extinct stratovolcanoes and volcanic necks that erupted tholeiitic through calc-alkalic to shoshonitic and adakitic rocks (Yumul and others, 2008a). The oldest rocks associated with the Luzon Arc occur in the north (30–9 Ma on Taiwan); south of Taiwan, the arc is made up of several Miocene to Holocene segments (Yang and others, 1996; Garwin and others, 2005). The Luzon Central Cordillera segment contains 13 porphyry copper deposits, including the 1.5-Ma Far Southeast deposit, with more than 4 Mt contained copper and the 3.5–1-Ma Baguio district, the most important gold-producing area in the Philippines (fig. 4B). The Baguio district hosts the Black Mountain and Santo Tomas II porphyry copper-gold deposits and at least eight porphyry copper-gold prospects (fig. 4B), as well as copper-gold skarns skarn and giant epithermal gold and base-metal vein deposits (Waters and others, 2011).

Permissive Tract 142pCu7301 (Luzon)

The 1,200-km-long Luzon Arc was assessed as a single tract (fig. 3A), but is described as four geographically separate segments. The northernmost segment of the Luzon Arc delineates permissive rocks along the Coastal Range of eastern Taiwan and adjacent islands, and includes the Chimei porphyry copper prospect. The Luzon Central Cordillera segment contains 13 copper-gold porphyry deposits that range in age from 11–1 Ma, including the world class Baguio and Mankayan mining districts (fig. 4B). The 657-Mt Far Southeast-Bato



**Figure 7.** Map showing the Luzon Arc segments (after Defant and others, 1989; Yang and others, 1996). The Northern Luzon segment includes the Luzon Central Cordillera.



Tabio deposit in the Mankayan district contains more than 4 Mt of copper (Lepanto Consolidated Mining Company, 2008). The deposit was discovered in 1980 by drilling beneath the Lepanto epithermal deposit. Recognition of coupled, coeval K-silicate alteration in the Far Southeast porphyry deposit and advanced argillic (quartz-alunite) alteration in the spatially associated Lepanto high-sulfidation epithermal veins established a genetic relation between porphyry and epithermal deposit types (Sillitoe, 1983; Arribas and others, 1995; Hedenquist and others, 1998). Further studies in the Mankayan district showed that the presence of a lithocap, such as the one at Lepanto, indicated a level of erosion characteristic of the epithermal zone and that detailed alteration mapping can provide vectors to causative intrusions as an exploration tool for concealed porphyry and epithermal deposits (Chang and others, 2011).

The Western Luzon segment of the arc contains three copper-gold porphyry deposits (7–2 Ma), including the Taysan deposit (fig. 4C) with 968 Mt of ore and 2.1 Mt contained copper. The Babuyan arc segment (number 2 on fig. 7) includes the northeasternmost tip of Luzon Island and offshore islands to the north; no deposits are known.

### **East Asia (South Korea and Japan)**

The complete absence of known economic porphyry copper deposits associated with magmatic arcs in South Korea and Japan is in stark contrast to the arcs of Southeast Asia, though these countries do have significant mineralized belts of copper-tungsten and lead-zinc-molybdenum, as well as gold-silver and polymetallic deposits. Mesozoic arcs may be too deeply exhumed to preserve porphyry deposits, or arc magmas may have been insufficiently copper-rich or insufficiently oxidized to result in porphyry copper formation. Neogene arcs may be too immature or insufficiently eroded to expose porphyry copper systems subaerially. The following discussion includes an overview of the geologic setting of the East Asia magmatic arcs, descriptions of permissive tracts for porphyry copper deposits, and discussion of possible explanations for the apparent lack of porphyry copper deposits in the region. Locations of prospects in South Korea are plotted in figure 8, along with physiographic features mentioned in this report.

### **Mesozoic to Holocene Evolution of the East Asian Continental Margin**

Following the Late Triassic collision and suturing of the North and South China cratons along the Qinling-Dabie suture (fig. 9), westward subduction of Paleopacific oceanic plates along the eastern margin of the amalgamated continent produced large volumes of Mesozoic granitic intrusions and volcanic rocks. Subduction of mid-ocean ridges, northward (along arc) migration of triple junctions, acceleration in plate velocities, and shifts in sea plate orientation produced the belts of Jurassic and Cretaceous continental arc magmas that

characterize the Korean Peninsula and Japan (fig. 9). Figure 10A shows a paleogeographic reconstruction of the Late Cretaceous Eurasian margin. During the Cretaceous, southern Korea was part of an active, Andean-type continental margin along East Asia that encompassed what is now southeastern China, western Japan, and the Sikhote-Alin area of Russia (fig. 9). Northward passage of the Pacific-Izanagi mid-ocean ridge along the Asian margin formed the fore-arc Ryoke granitoid belt and the Sanbagawa metamorphic belt (fig. 10A, based on Maruyama and others, 1997). Paleogene clockwise rotation of about 23 degrees affected both Korean and Japan (Lee, 2008). By the Eocene, the Izanagi Plate was completely subducted and the Pacific Plate came into contact with proto-Japan. An extensional regime developed along the northern Asian continental margin in Eocene time as the convergence rate decreased. Continued extension led to the Miocene opening of the Japan Sea as a back-arc basin and resulted in the separation of Japan from the continent. Further clockwise rotation of southwestern Japan and counterclockwise rotation of the northeastern Japan in the Miocene led to the modern configuration of the archipelago (fig. 10B), parts of which are situated on four different tectonic plates—Eurasia, Okhotsk (North America), the Philippine Sea Plate, and the Pacific Sea Plate (Maruyama and others, 1997). The Japan Arc evolved from a Cretaceous Eurasian continental margin arc through a continental rifting stage (approximately 24 Ma), followed by an arc rifting stage (16–13 Ma), and then to the modern island arc (less than 14 Ma).

Quaternary volcanic fronts parallel the trenches that mark present-day subduction of the Pacific and Philippine Sea Plates. The Philippine Sea Plate is moving towards the northwest and subducting beneath the Southwest Japan and Ryukyu Arcs; the Pacific Plate is moving west-northwest and subducting beneath the Kurile and Izu-Bonin Arcs (fig. 10B). For a more detailed overview of the tectonic setting and evolution of Japan, see Maruyama and others (1997) and NUMO (2004).

### **Korean Peninsula**

The Korean Peninsula is a collage of continental blocks that amalgamated in the late Paleozoic to early Triassic. Basement rocks include Precambrian massifs of high-grade schists and gneisses that are unconformably overlain by younger rocks and intervening belts of mainly Paleozoic metasedimentary and metavolcanic rocks (fig. 11A). Correlations among the major pre-Mesozoic tectonic provinces in Korea with those in China vary. For example, the entire Korean Peninsula historically has been interpreted to be part of the North China (Sino-Korea) crustal block, but some studies link the Gyeongii and Yeongnam Massifs (fig. 11A) to the South China Craton (Oh, 2006; Ernst and Liou, 1995; Zhang and others, 2012) and regard the Imjingang Belt (fig. 11A) as an extension of the Qinling-Dabie suture belt (fig. 9) between the North China (Sino-Korea) Craton and the South China Craton in China (Chough and others, 2000; Kim, 1996).

Phanerozoic magmatism in the Korean Peninsula is associated with three major tectonic events—(1) the Late Permian to Triassic Songnim orogeny that marked the collision between the North and South China Cratons (Qinling-Dabie-Sulu Indosinian orogeny in China), (2) the Jurassic Daebo orogeny, and (3) the Late Cretaceous to early Tertiary magmatism associated with the Bulguksa (Bulgugsa)<sup>15</sup> orogeny (Kim, 1996). The Songnim magmatism mainly is preserved in North Korea as deeply eroded batholiths with no coeval volcanic rocks. The Daebo orogeny ended with intrusion of S-type granites.

Jurassic granites are widespread in southern Korea as deep-seated batholiths; deeply exhumed Triassic stocks are less common, and coeval volcanic rocks are absent (fig. 11B). Cretaceous, calc-alkalic I-type magnetite-series granites are preserved mainly as volcano-plutonic complexes in the Gyeongsang Basin (fig. 11B), the largest of the northeast-southwest-oriented strike-slip basins that developed as a result of oblique subduction of the Paleopacific Plate beneath the Eurasian Plate (Choi and Lee, 2011). No plutonic rocks younger than Paleogene are known in South Korea.

No porphyry copper deposits are known on the Korean Peninsula. Porphyry-type mineralization has been recognized at a few prospects in the Gyeongsang Basin associated with Cretaceous to early Tertiary calc-alkalic rocks, and some exploration was done in the 1970s (Sillitoe, 1980). Intrusion-related copper-tungsten skarn and polymetallic vein and carbonate replacement deposits are aligned with a series of northeast-southwest-striking metallogenic zones recognized within the Gyeongsang Basin. From southeast to northwest across the basin, the zones define belts of copper, iron, copper-zinc-lead, tungsten-molybdenum, and lead-zinc mineralization. Yang and Bodnar (1994) concluded that although the geodynamic setting and lithologies in the basin are similar to productive porphyry settings elsewhere in the circum-Pacific region, the exposed permissive rocks represent the root zones of porphyry copper systems where any ore deposit that existed higher in the system has eroded off. Their study of silicate melt and fluid inclusions in granitoid intrusions in the Gyeongsang Basin showed that the high pressure of emplacement (1.9–2.5 kilobars, kbar), very late-stage attainment of magma water saturation, lack of veining and fracturing, and shapes of intrusions are characteristics of low-grade, deeper parts of porphyry systems.

The assessment team delineated one qualitative permissive tract in South Korea on the basis of distributions of permissive rocks for porphyry copper deposits. Yanshanian (Jurassic and Cretaceous) igneous rocks in North Korea are included in the Manchuride tract (142pCu8509) in the porphyry copper assessment of the Mesozoic of East Asia by Ludington and others (2012).

<sup>15</sup>The South Korean Ministry of Culture adopted a revised Romanization of the Korean language in 2000. As a result, many place names appear with slightly different spellings depending on the date of the publication. For example, the city of Busan formerly was known as Pusan.

## Gyeongsang Basin

### Tectonic Setting

Before the opening of the Sea of Japan in the Miocene, southeastern Korea and Japan were joined and formed an active continental margin on the Eurasian Plate. The Gyeongsang Basin preserves Late Cretaceous volcano-sedimentary complexes and calc-alkalic I-type subvolcanic intrusions (Bulguksa magmatism) that have been interpreted as marking the trace of a subduction-related continental arc system that extends from eastern China through southeastern Korea to the Japan Arc (Zhang and others, 2012).

### Permissive Tract 142pCu7313 (Gyeongsang Basin)

The Late Cretaceous igneous and volcanic rocks of South Korea were delineated as permissive tract 142pCu7313 (fig. 3B). Most of these rocks are preserved in the Gyeongsang Basin and along the Ogcheon Belt (fig. 11A). Rocks of the Gyeongsang Supergroup, a 9-km-thick sequence of volcanic and sedimentary rocks, including the 2,000–3,000-m-thick volcanic-dominant Yucheon Group, fill the basin. The Yucheon Group is comprised of andesitic and rhyolitic subgroups of high-K calc-alkalic volcanic rocks. The granitoids in the basin range in age from 120–40 Ma. Zhang and others (2012) described volcanic rocks (94.4–78.4 Ma) and associated intrusions (72 Ma) in an area in the southern part of the basin. Small stocks and volcano-plutonic complexes are predominantly porphyritic, I-type diorites to granodiorites that have textures and miarolitic cavities indicative of a shallow level of emplacement (Zhang and others, 2012). The deeply eroded intrusions studied by Yang and Bodnar (1994) lie to the east of the area studied by Zhang and others (2012). These two study areas are on opposite sides of a major north-northeast-trending strike-slip fault system and may record different ages or different tectonic histories. The tract includes porphyry copper prospects (Sillitoe, 1980), copper-tungsten breccia-pipe deposits (Yang and Bodnar, 2004), skarns, and polymetallic deposits as well as copper occurrences, but no economic porphyry copper deposits have been documented to date.

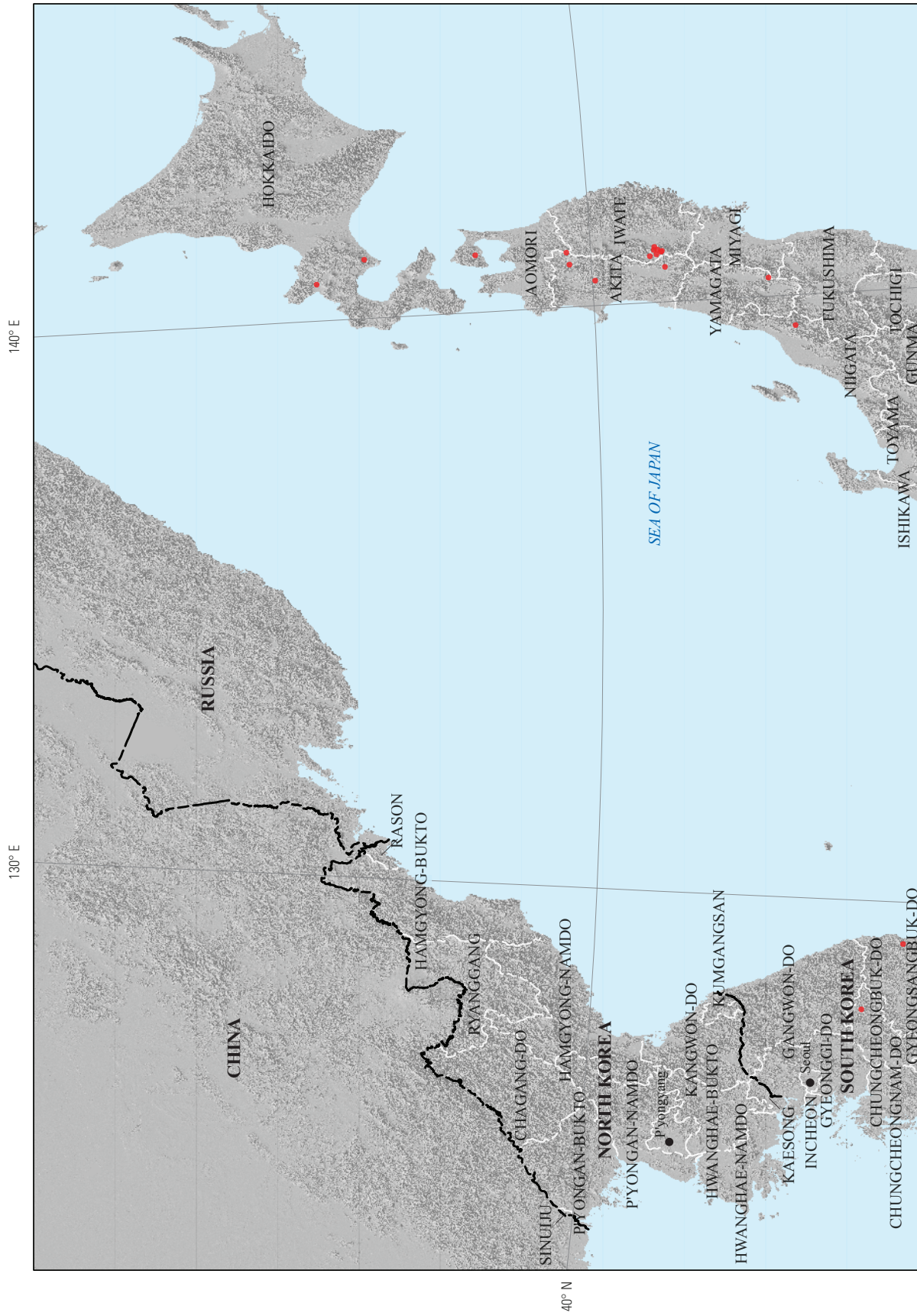
## The Japan Arc

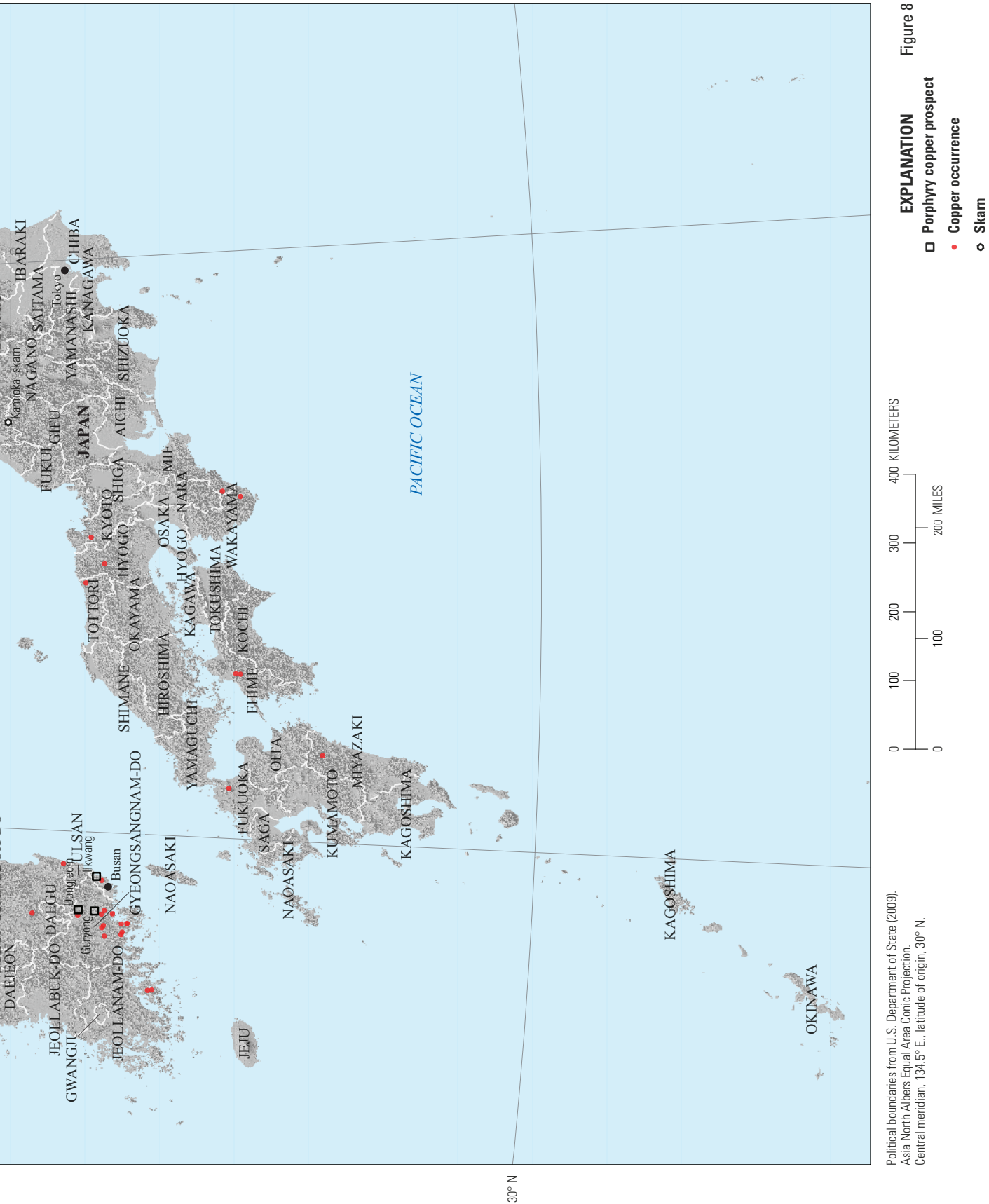
### Tectonic Setting

The 1,800-km-long Japan Arc records a long and complex geodynamic history. Cretaceous and Paleogene I-type granitoids intruded Permian-Triassic gneiss, schist, and Jurassic accretionary complexes on the Eurasian continental margin before Miocene separation of Japan from the craton as the Sea of Japan opened as a back-arc spreading center (Garwin and others, 2005).

Mesozoic granitoids formed during the continental-arc stage are present in western Honshu in the Inner Zone of southwest Japan along the eastern margin of the Sea of Japan



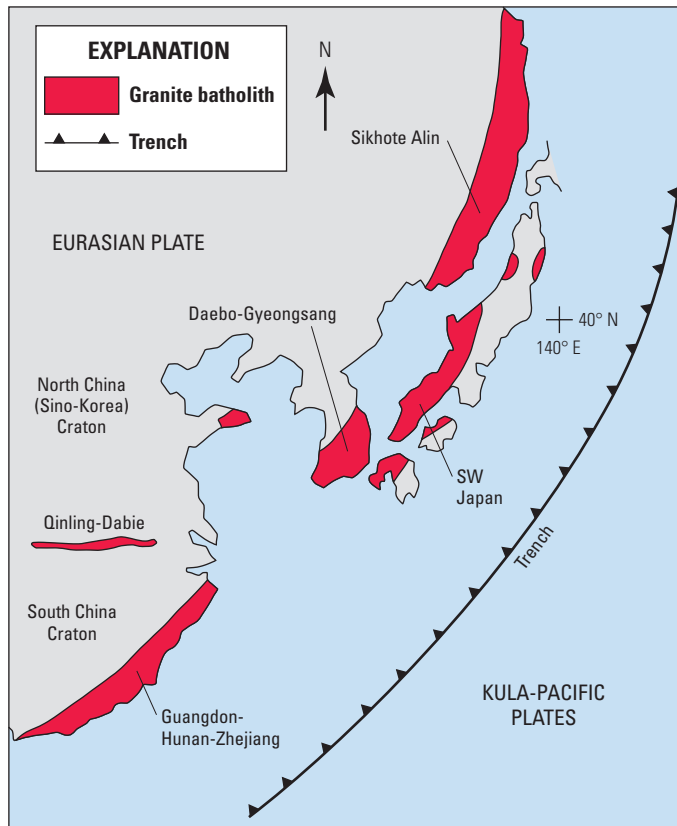




Political boundaries from U.S. Department of State (2009). Asia North Albers Equal Area Conic Projection. Central meridian, 134.5° E., latitude of origin, 30° N.

Figure 8

**Figure 8.** Map showing physiographic features and locations of porphyry copper prospects (open squares) and copper occurrences (filled red circles) in the Republic of Korea (South Korea) and Japan, along with province boundaries for North and South Korea and prefecture boundaries for Japan. The location of the Kamioka zinc-lead skarn district in central Japan is shown for reference.



**Figure 9.** Simplified map showing the distribution of Cretaceous granitoids of the northern Eurasian continental margin, modified from Takagi (2004). SW, southwest.

and in northeast Japan (fig. 12A, B). Jurassic to Quaternary granitoids occur in narrow (80–100 km wide) belts in southern Japan (Ishihara, 1998), where back-arc magnetite series rocks characterize the Sanin Belt and fore-arc ilmenite series rocks characterize the Sanyo-Ryoke Belts (fig. 12A).

#### Permissive Tract 142pCu7314 (Western Honshu)

The Late Cretaceous to Paleogene calc-alkalic magnetite-series igneous and volcanic rocks of Western Honshu were delineated as permissive tract 142pCu7314 (fig. 3B), which includes the western Sanin segment and the Hida segment to the northeast. Molybdenum quartz vein deposits and skarns are found in the Sanin molybdenum province (fig. 12A), but no economic porphyry copper deposits have ever been found. The Kamioka zinc-lead skarn deposits (fig. 8), Japan's largest zinc-lead producer, lies within the Hida tract segment. In a study that documented hydrothermal alteration patterns associated with igneous rocks in Japan, Utada (1980) defined alteration zones as acidic (alunite-rich), intermediate (approximately propylitic), and alkaline (Ca- and Na-zeolites). Propylitic and acidic alteration are most common; the potassic alteration stage typical of porphyry copper systems was not observed.

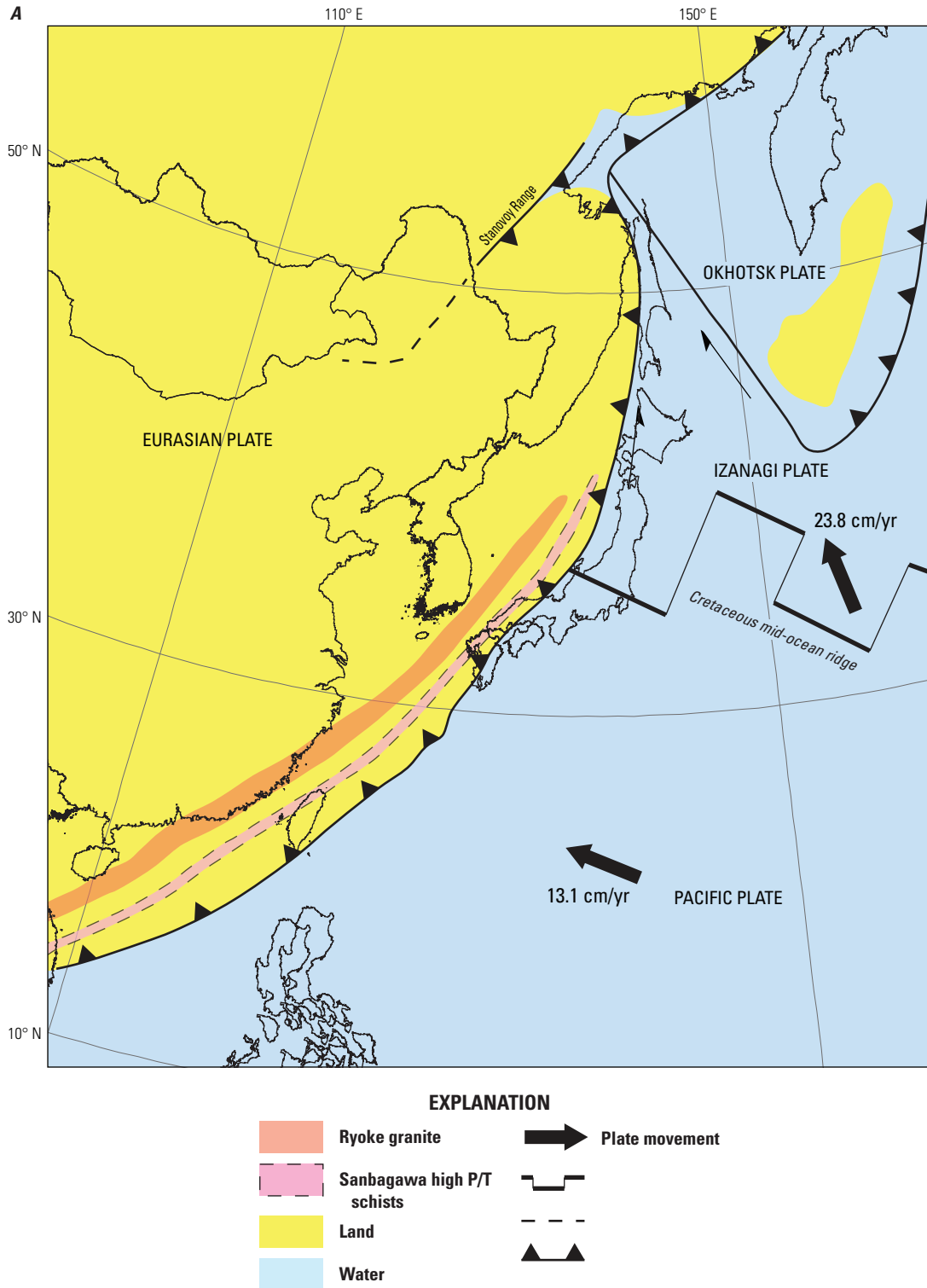
The absence of porphyry copper deposits in the magnetite-series rocks of Japan has been a subject of extensive study and speculation; negative factors put forth include absence of thick crust, an extensional setting that produced volcanogenic massive sulfide deposits rather than a compressional setting that would favor porphyry formation, low copper abundance in granitoids, a low percentage of magnetite-series relative to ilmenite-series granitoids, and insufficient erosion to expose tops of porphyry systems (Qin and Ishihara, 1998). The lack of porphyry copper deposits most likely reflects the fact the oxygen and sulfur fugacities of magnetite-series magmas in Japan were not high enough to form porphyry copper deposits; that is, the magmas were less oxidized than those that formed deposits in the porphyry-rich areas elsewhere, such as in North and South America (Takagi and Tsukimura, 1997; Takagi, 2004). Differences in source magma  $\text{SO}_2$  and  $\text{H}_2\text{S}$  content and redox effects of assimilation of subducted sediment (promoted by increasing subduction-erosion accompanying increasing plate convergence rates) can explain the origin of the two series in Japan; contamination of granitic magmas with 15 percent subducted sediment or more could have produced the ilmenite-series rocks (Takagi, 2004). Both Utada (1980) and Qin and Ishihara (1998) suggested that porphyry copper deposits might lie at depth below acid-sulfate alteration.

## Japan and South Korea

In Japan, Cretaceous granitoids are more abundant than older Mesozoic granitoids, in contrast to South Korea, where, with the exception of the Cretaceous magmatism preserved in the Gyeongsang Basin, Jurassic granitoids are more abundant (compare figs. 11B and 12B). The 50-million-year magmatic gap from Late Jurassic to Early Cretaceous in both Japan and South Korea might have resulted from changes in subduction angle or changes in plate convergence rates (Sagong and others, 2005).

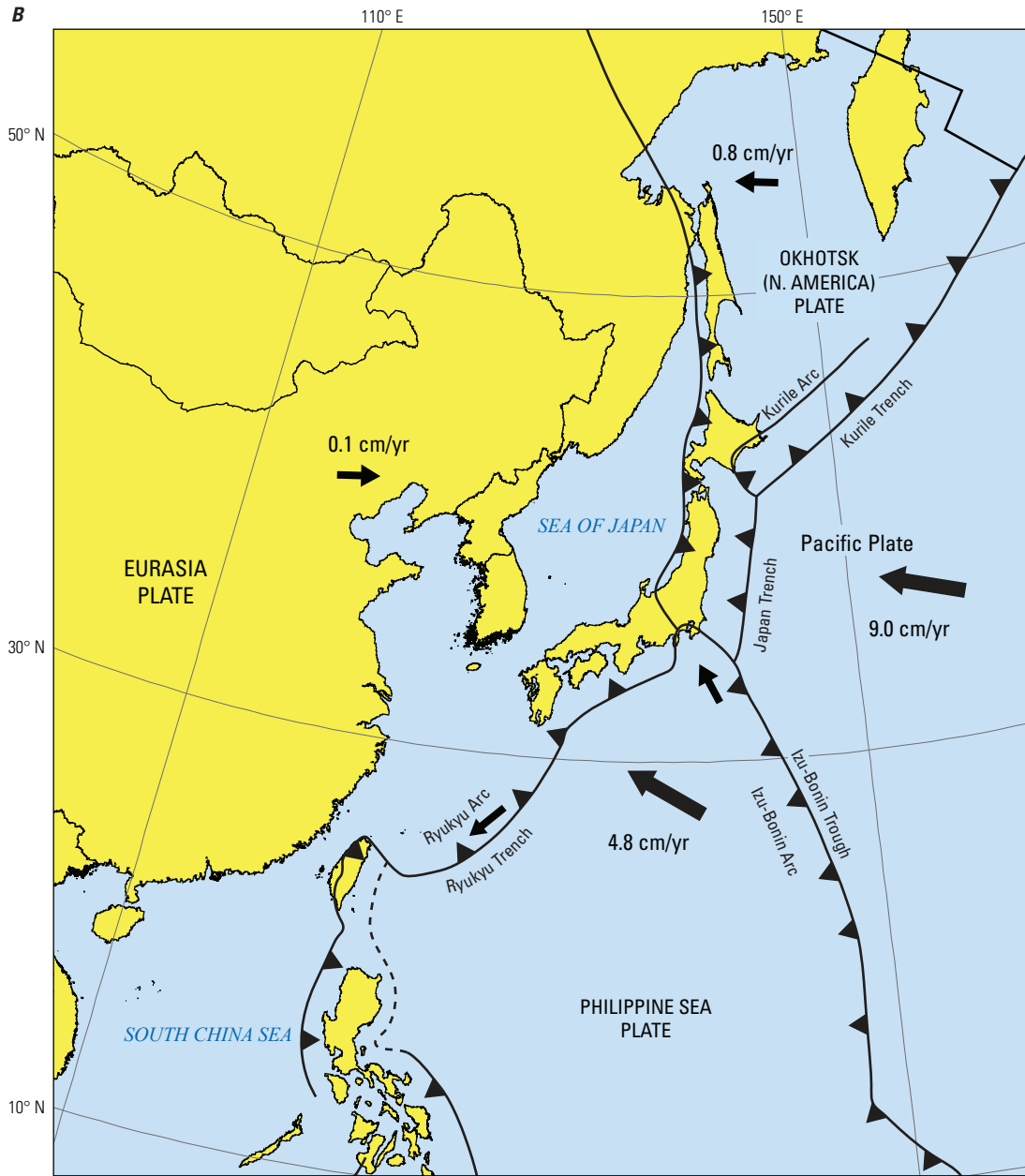
A number of authors have compared the Cretaceous igneous rocks of the Gyeongsang Basin of South Korean with the Sanin Belt rocks, given that they formed along the same continental margin (Ishihara, 1981; Sillitoe, 1980; Jwa, 1998; Koh and others, 2003; Sagong and others, 2005). Intrusive rocks in both areas were emplaced mainly between 100 and 50 Ma, have similar  $^{87}\text{Sr}/^{86}\text{Sr}$  values of about 0.706, and lead isotopes for galena from ore deposits in both areas have similar ranges. Intrusions were emplaced at high levels in the crust with coeval volcanism in both areas. Jwa's (2004) comparison of Cretaceous to Paleogene granitoids of the Gyeongsang Basin with those in Japan indicated that the South Korean rocks are more oxidized and richer in alkali elements.

Major differences are observed in the arrangement of age trends, metal zones, and the distributions of Cretaceous to Paleogene magnetite and ilmenite series rocks. In general,



**Figure 10.** Map showing tectonic setting of the Eurasian continental margin (modified from Maruyama and others, 1997). *A*, Late Cretaceous. *B*, present day. Dark yellow, land areas; blue, sea areas; white, Okhotsk Plate. Arrows show directions and speed of plate motions. Thin black lines show country boundaries. cm/yr, centimeters per year; N., North; P/T, pressure/temperature.

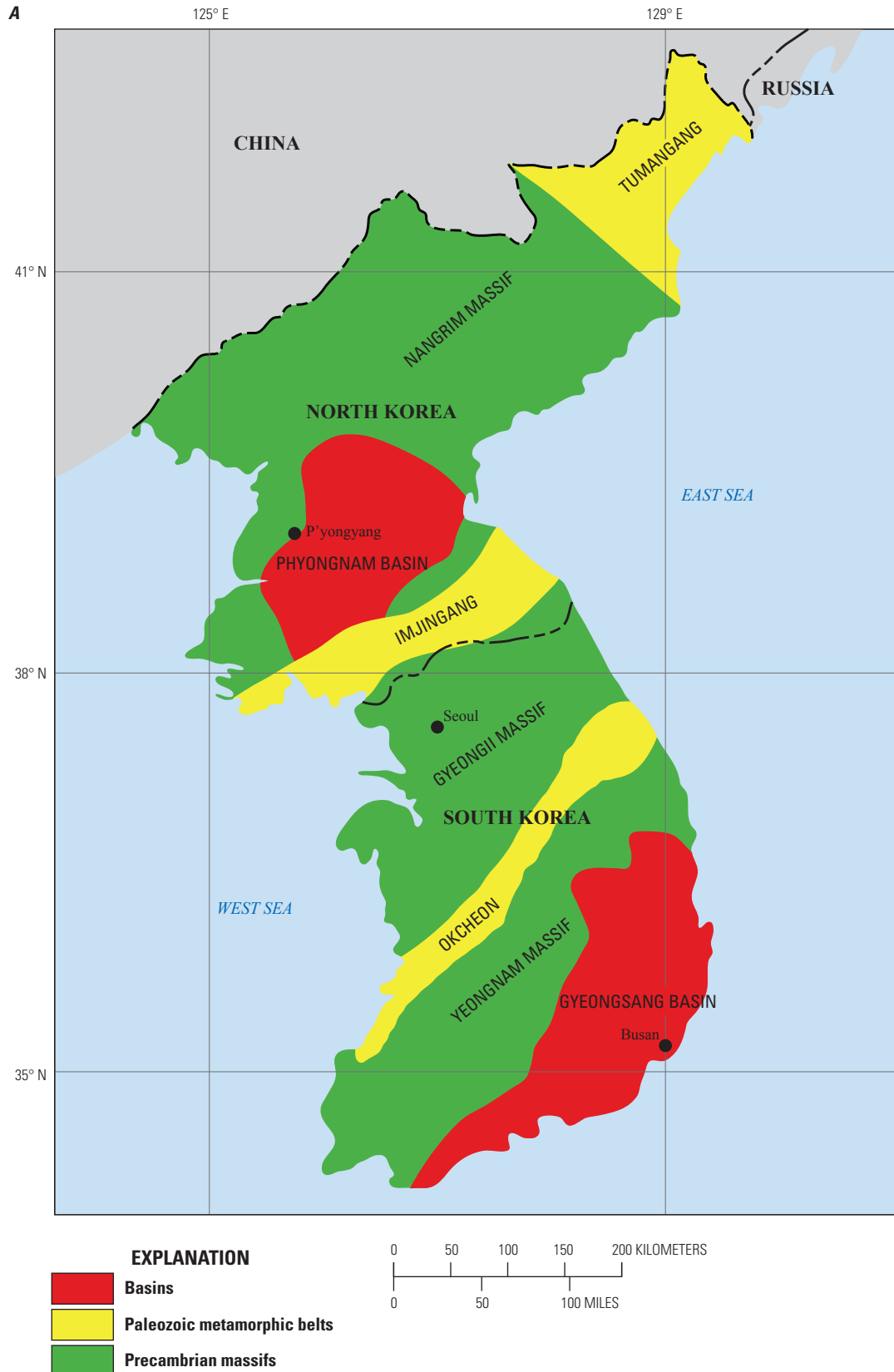




**EXPLANATION**

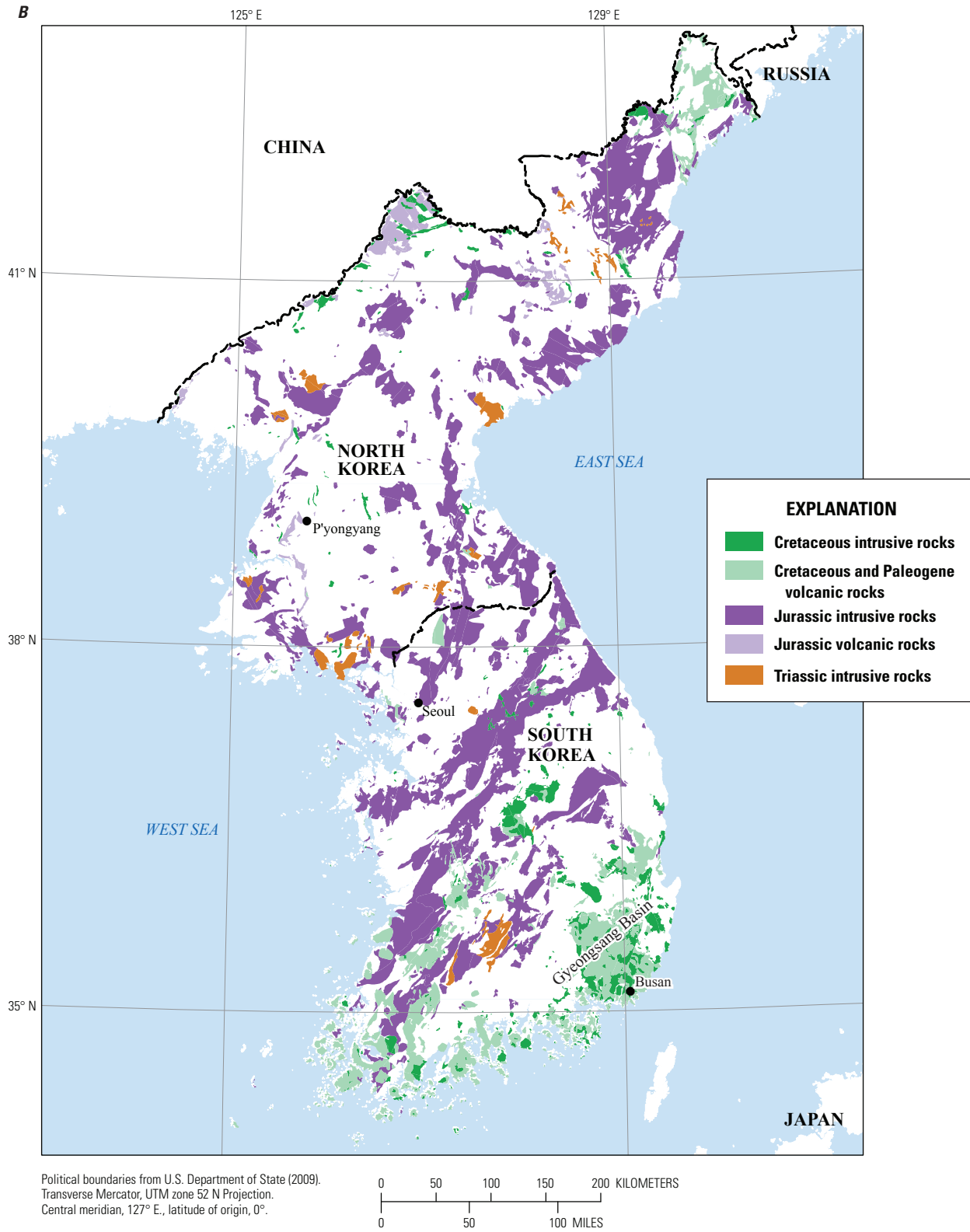
- Land
- Water
- Plate movement
- Trench
- Fault
- Extension (approximate)

Figure 10.—Continued

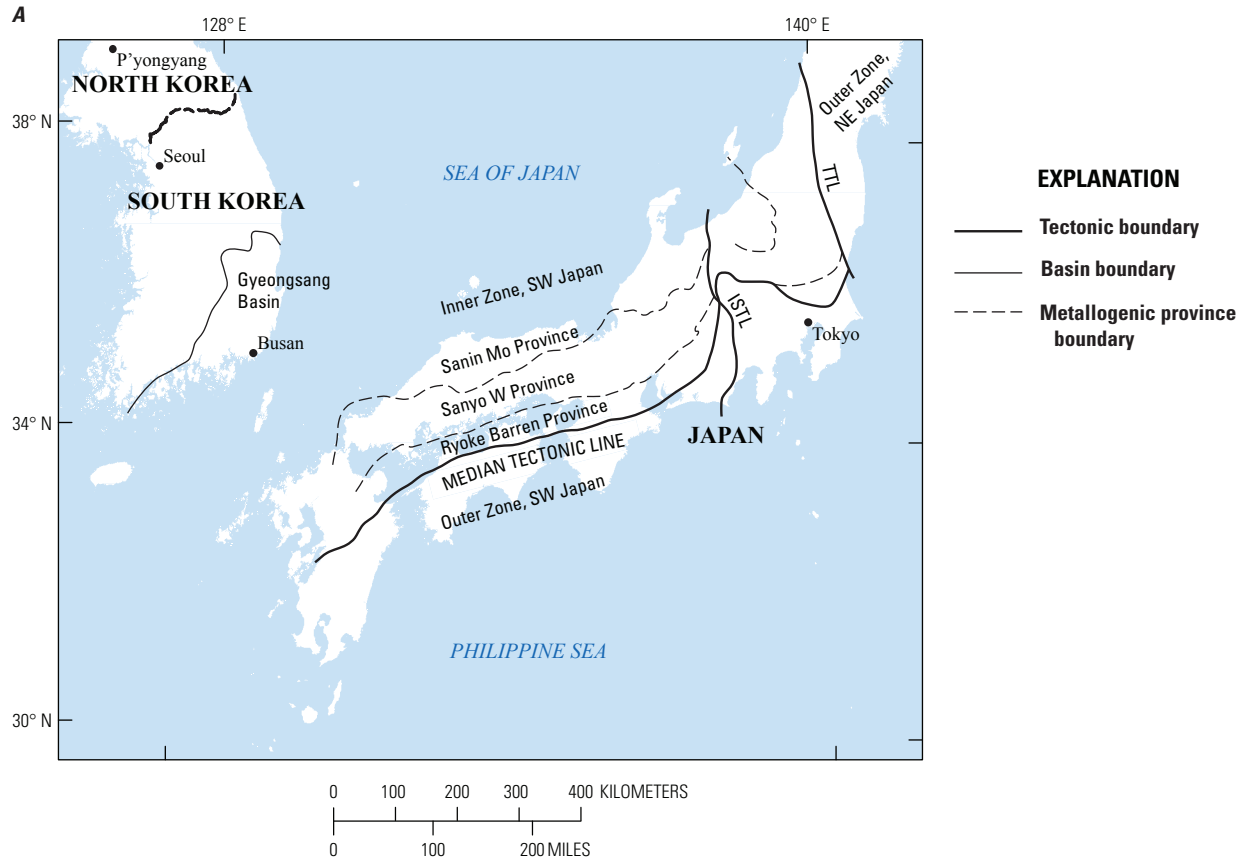


**Figure 11.** Maps showing tectonic divisions and Mesozoic igneous rocks of the Korean Peninsula. *A*, Major tectonic divisions of the Korean Peninsula, based on Paek and others (1996). *B*, Distribution of Mesozoic igneous rocks in the Korean Peninsula, based on the 1:1,000,000-scale geologic map of Korea (Korea Institute of Geology, Mining and Materials (KIGAM), 1995a).

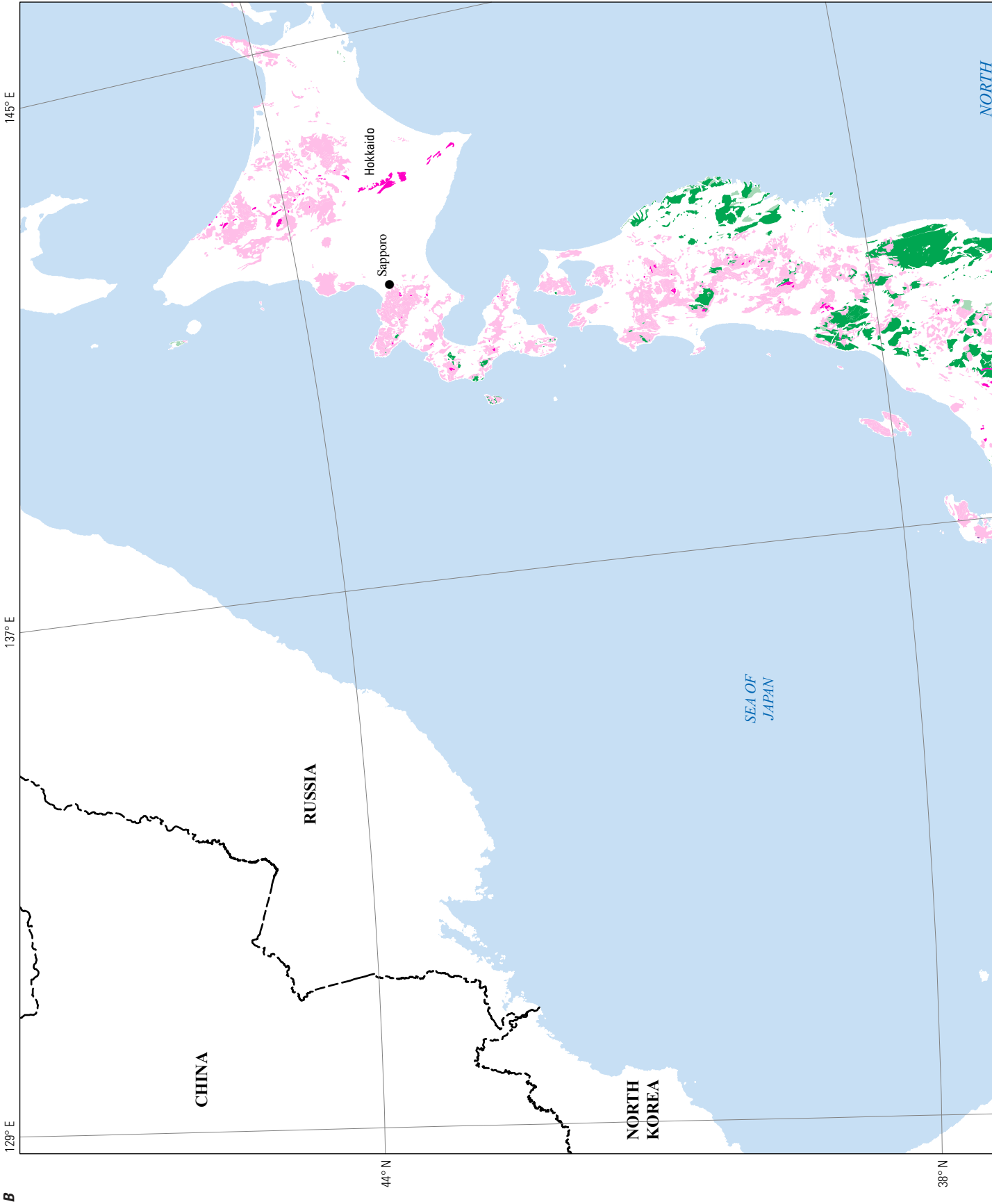




**Figure 11.—Continued**



**Figure 12.** Maps showing metallogenetic provinces and igneous rocks of Japan. *A*, Cretaceous to Paleogene metallogenetic provinces of southwest Japan (Mo, molybdenum; W, tungsten). The Median Tectonic Line separates the Inner (Sea of Japan side) and Outer (Pacific Ocean side) Zones of southwest Japan. The Itoigawa-Shizuoka Tectonic Line (ISTL) separates the southwest (SW) and northeast (NE) segments of the Japan Arc and marks the western boundary of a depression along the Eurasian and North American Plate boundaries. The Tanakuru Tectonic Line (TTL) separates pre-Cretaceous basement terranes of northeast and southwest Japan. *B*, Distribution of Mesozoic and Tertiary igneous rocks in Japan, based on the 1:1,000,000-scale geologic map of Japan (Geological Survey of Japan, 2003).



B

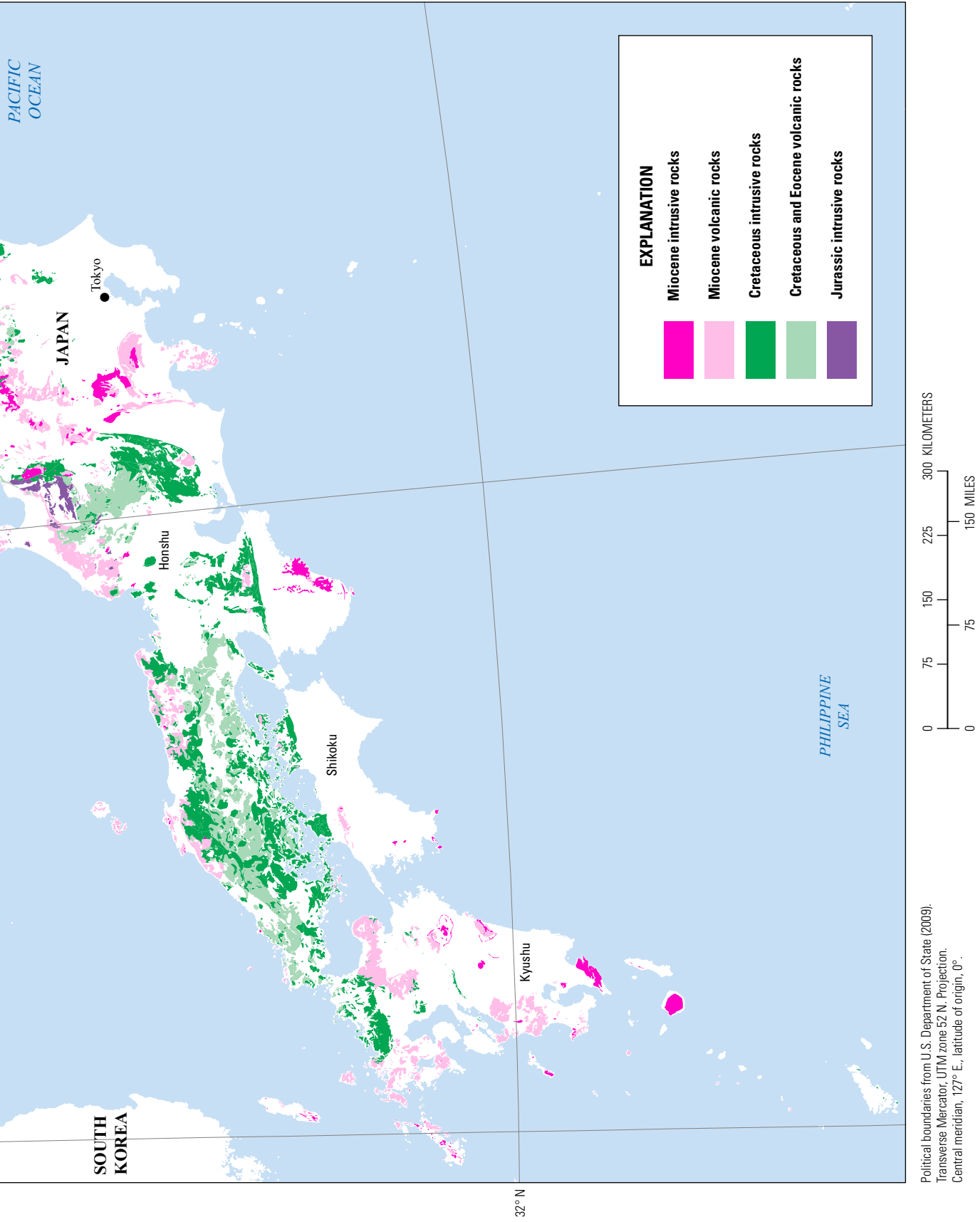


Figure 12.—Continued

ages of mineralized zones decrease across the Gyeongsang Basin from 100–80 in the northwest to 60–40 Ma in the southeast (Koh and others, 2003). Magnetic susceptibility increases from the interior towards the coast across the basin and nearly all of the intrusions are magnetite-series rocks (Jin and others, 2001). From northwest to southeast across the Gyeongsang Basin, metallogenic subprovinces include the following zones: lead-zinc, tungsten-molybdenum, copper-zinc-lead, iron and copper; the most common deposits are tungsten-molybdenum skarns and polymetallic veins (Jwa, 2004). In Japan, the Sanin Belt (magnetite series) along the east coast of the Sea of Japan is a Tertiary (65–46 Ma) molybdenum-lead-zinc province, whereas copper is present in the tungsten-tin province of the 96–64 Ma Sanyo Belt (ilmenite > magnetite series). It was originally postulated that South Korean rocks were correlative with the molybdenum-lead-zinc Sanin Province of Japan, based on distributions of magnetite-rich rocks (Sillitoe, 1980). Any porphyry copper systems would likely be associated with the younger magnetite-series rocks in both areas; the Gyeongsang Basin has more evidence of porphyry-type mineralization, albeit at deep levels, as noted above. The Sanin Belt rocks, like the rocks in South Korea, may be too deeply eroded to preserve any porphyry systems that may have formed. The occurrence of copper with lead-zinc skarns in both areas suggests that depth may be a factor. Alternatively, exploration for concealed porphyry systems beneath volcanic cover has not been extensive or optimum redox conditions for development of porphyry systems may never have obtained along this particular continental margin.

## Neogene Volcanic Arcs

### Tectonic Setting

Japan lies at a crossroads of a number of active arc systems that produced volcanogenic massive sulfide deposits and epithermal deposits from the middle Miocene through the Pliocene and into the Pleistocene. No porphyry copper deposits are known within these arcs. The Neogene arcs include the Japan Arc, the Ryukyu Arc, the Izu-Bonin Arc, and the Kurile Arc (figs. 2 and 10B). Rift-related bi-modal arc volcanism (opening of the Sea of Japan) continued in the southwestern Japan Arc through the early and middle Miocene, followed by subduction-related andesite-dacite volcanism starting in the late Miocene (Garwin and others, 2005). The northeastern and southwestern segments of the Japan Arc are separated by a fault zone (Itoigawa-Shizuoka tectonic line, ISTL on fig. 12A) that forms the boundary between the North American and Eurasian Plates (Garwin and others, 2005; Uyeda, 1991). The northeastern Japan Arc is related to subduction of the Pacific Plate beneath the North America Plate along the Japan Trench. The 1,800-km-long modern continental Japan Arc connects the Ryukyu Arc to the south with the Kurile Arc to the north (figs. 2 and 10B). The Ryukyu Arc, an island chain related to subduction of the Philippine Sea Plate beneath Eurasia, extends from southern Japan to Taiwan. The Kurile Arc is formed by subduction of the Pacific Plate beneath the Okhotsk Plate along the Kurile Trench. The oceanic Izu-Bonin Arc results from northwestward subduction of the Pacific Plate along the

Philippine Sea Plate (fig. 10B). During the middle Miocene, the Okhotsk (North America) continental block and the Izu-Bonin Arc collided with the Japan Arc. Most of the Izu-Bonin Arc is submerged.

### Permissive Tract 142pCu7315 (Subaerial Neogene Arcs of Western Japan)

The tract delineates subaerial parts of the Miocene (fig. 12B) and younger-age Kurile (Chishma) volcanic arc and the subaerial parts of the Northeast Japan, Izu, Southwest Japan, and Ryukyu volcanic arcs. All of these arc systems contain Miocene to Quaternary volcanic rocks, including calc-alkalic andesite and dacite with minor rhyolite and basalt. Miocene and Pliocene shallow-level intrusions are variable in size, ranging from a few meters to several kilometers in diameter. The Miocene to Quaternary volcanic rocks in the Inner Zone of southwestern Japan (fig. 12A), known as the Green Tuff region, typically are more than 1 km thick; this area is the type locality for kuroko-type massive sulfide deposits. Although no porphyry copper deposits or occurrences are known in the tract, abundant advanced argillic alteration occurs around late Miocene and Pliocene shallow intrusions in some areas suggesting that the porphyry granitoid systems may occur beneath the epithermal deposits. High-sulfidation epithermal gold provinces associated with Tertiary volcanic rocks, such as in southern Kyushu and central Honshu, are the most likely target areas for concealed porphyry copper deposits (T. Takagi, contributor to this report, written commun., 2004).

A submerged porphyry-copper type system associated with a 7-Ma back-arc seamount chain in the Izu-Bonin Arc in the Pacific Ocean off the coast of Honshu is the first documentation of this deposit type in the arc (Ishizuka and others, 2002). The evidence for a porphyry system includes chalcopyrite-bearing altered tonalite porphyry (potassic and propylitic alteration) with stockwork quartz-magnetite veins containing hypersaline high-temperature (600 °C) fluid inclusions in quartz. Although offshore occurrences are not included in the assessment tract, the occurrence demonstrates that processes that produced porphyry systems were active in the back-arc region before the present rift setting.

## Exploration History

Porphyry copper exploration in the Philippines has been cyclic, driven largely by global metal prices, government policies, and accessibility of the region. Although the area is considered among the most copper- and gold-endowed regions on Earth, parts of the area remain relatively underexplored (Feebrey, 1999). As noted by Waters and others (2011), despite the interest in gold and the long history of mining in the Luzon Central Cordillera, the area has not been thoroughly evaluated for porphyry potential. Political, social, cultural, and environmental issues as well as mining laws affect exploration in the region. Downturns in copper prices led to mine closures in the



Philippines in the 1990s. In addition, steep topography, lack of infrastructure, tropical climate and vegetation, and natural hazards, such as earthquakes, tsunamis, and volcanic eruptions, complicate exploration and development in the region. An example of porphyry copper exploration cycles for the Philippines is described below, based on information provided in country reports presented at the 2010 CCOP-USGS Workshop in Busan, South Korea, by coauthors of this assessment.

## Philippines

The Philippine copper industry dates back to the country's pre-Spanish period. In the 1800s, during the Spanish period, the Cariwisán Mine in Antique Province in western Panay (fig. 4A) opened in 1842, followed by work on the Mankayan Mine in the Mankayan district in western Luzon (fig. 4B) in 1865. The Mankayan Mine reopened in 1936 during the American period, and the Atlas Mine on Cebu (fig. 1), the Sipalay Mine on Negros (fig. 1), and Santo Tomas II in the Baguio district of Luzon (fig. 4B) opened in the 1950s. A boom period in copper exploration and mine development in the 1960s and 1970s was followed by a period of declining production and mine closures from the early 1980s to 1990s. Factors that contributed to the decline of the copper industry were ore depletion; global economics, including decreasing metal prices and demand; inflation; the Gulf War crisis; and domestic problems, including labor problems, power shortages, natural disasters, the mine tailings spill on Marinduque Island (Plumlee and others, 2000; Wnuk and others, 2006), and heightened local resistance to mining. The decline has continued into the 2000s. Passage of the Mining Act of 1995, which was challenged but upheld in 2004, resulted in a policy shift to the promotion of mining. Since 1990, several new discoveries were made, and some mining projects were expanded. As of 2009, four porphyry copper projects were producing in the Philippines, four porphyry copper-gold projects were in the feasibility stage, and at least eight other base- and precious-metal projects were in exploration for massive sulfide and epithermal gold deposits.

## South Korea

The few porphyry copper, copper-molybdenum, and molybdenum prospects identified in South Korea were discovered during exploration programs of the Korea Mining Promotion Corporation and other groups in the 1970s (Sillitoe, 1980). A few prospects were drilled, and geophysical and geochemical surveys were done. Anomalous copper and molybdenum concentrations associated with advanced argillic alteration apparently are stratigraphically controlled and are not clearly related to plutons.

In 2009, the Korea Institute of Geoscience and Mineral Resources (KIGAM) initiated a 3-year domestic exploration project for epithermal gold deposits in hydrothermally altered Cretaceous volcanic rocks in the Haenam area, which hosts the Moisan Mine, an epithermal gold-silver vein system (Korea Institute of Geoscience and Mineral Resources,

2011). KIGAM is also assessing domestic metallic resources; their work includes stream-sediment surveys and drilling for extension of tungsten skarns in the Gangweon Province (KIGAM, 2011).

## Japan

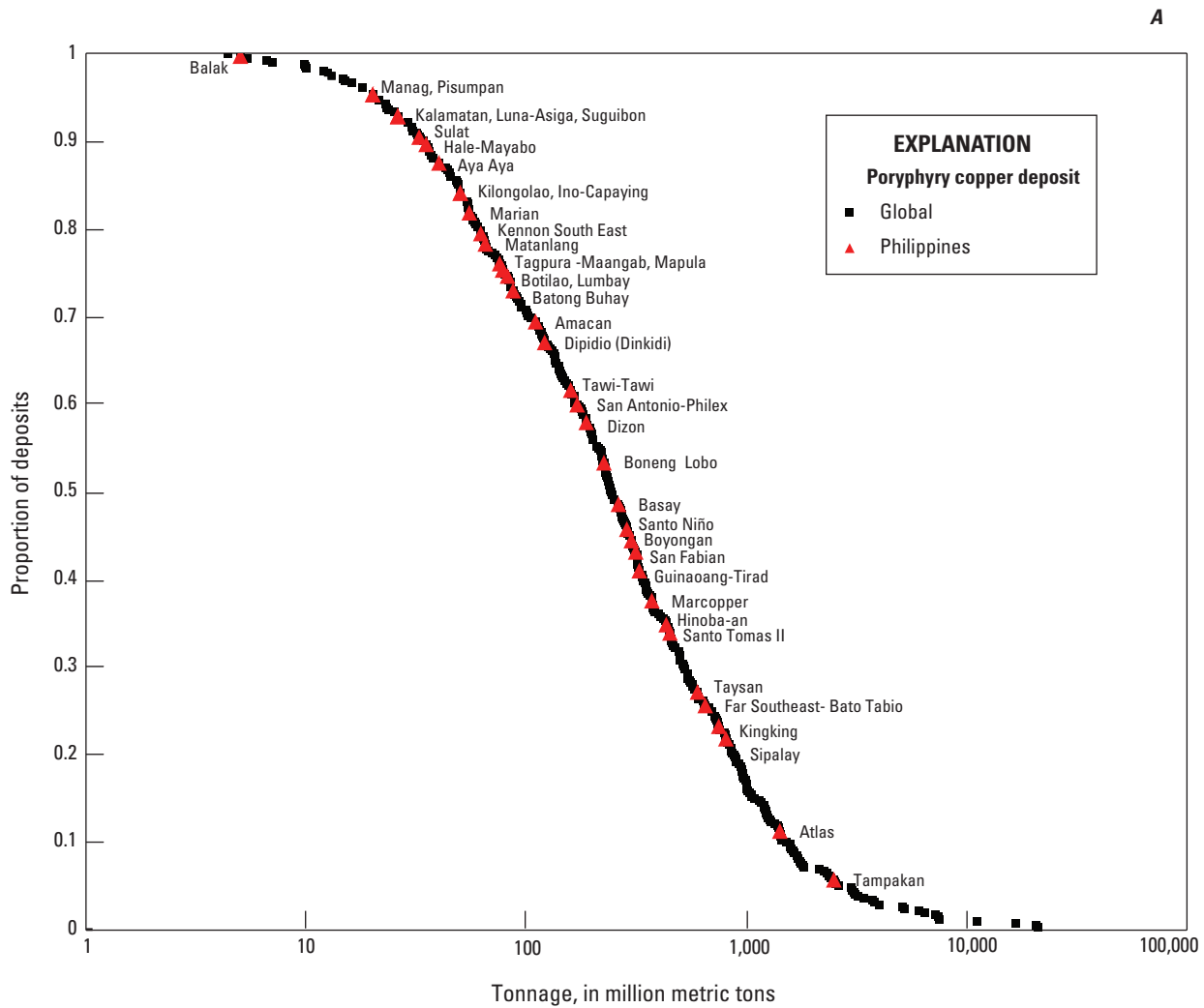
Japan has been explored for minerals for well over 100 years. Various epithermal gold-silver deposits have been drilled at depths of hundreds to thousands of meters. Small volcanic islands in the middle and northeastern parts of the Kurile Arc have not been well explored.

Japan explores and invests in mining internationally, but there is no domestic copper exploration, and Japan is the one of the world's largest importers of copper. Very little copper is produced domestically; the Kamioka lead-zinc-copper skarn produced copper until 2001, when operations ceased owing to low grade and high mining costs (Wu, 2001).

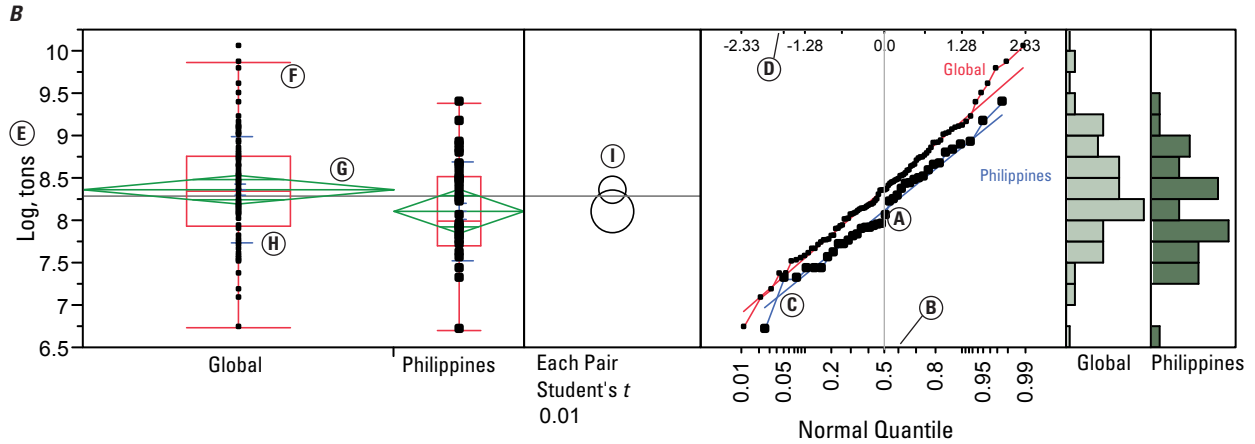
## Grade and Tonnage Models

The global porphyry copper grade and tonnage models of Singer and others (2008) were used for the simulation of undiscovered resources. Available models include a copper-gold subtype model based on data for 115 deposits, a copper-molybdenum subtype model based on data for 51 deposits, a copper subtype model based on data for 256 deposits, and a general porphyry copper-gold-molybdenum model based on all 422 deposits. The subtypes are based on grade criteria defined by Singer and others (2008). Deposits are classified as the copper-gold subtype if (1) the gold (in g/t) to molybdenum (in percent) ratio is greater than or equal to 30 or (2) if no molybdenum grade is reported and the gold grade is greater than 0.2 g/t. Deposits are classified as the copper-molybdenum subtype if (1) the gold (in g/t) to molybdenum (in percent) ratio is less than or equal to 3 or (2) if no gold grade is reported and the molybdenum grade is greater than 0.03 percent. Otherwise, the deposits are classified as the porphyry copper subtype. The general model that includes all subtypes is recommended for most settings, in particular where no deposits are known (Singer and others, 2008).

The tonnages for the 38 deposits in the Philippines are plotted on the global general model of Singer and others (2008) in figure 13A. Most (29 out of 38) of the deposits in the Philippines (table 4) meet the criteria for the copper-gold subtype. No gold grades are available for four of the deposits and no molybdenum grades are reported for 16 of the deposits. Four deposits that have both gold and molybdenum grades reported meet the criteria for the copper subtype (that is, gold to molybdenum ratios between 3 and 30). The tracts that host three of those four deposits (Ino-Capayang in the Southern Sierra Madre Arc; Aya Aya, and Sipalay in the Masbate-Western Negros Arc) also host copper-gold deposits. The fourth deposit, the Atlas deposit on Cebu, is the oldest, and before the Tampakan discovery was the largest, porphyry deposit in the Philippines. The Atlas deposit historically produced both molybdenum and gold.



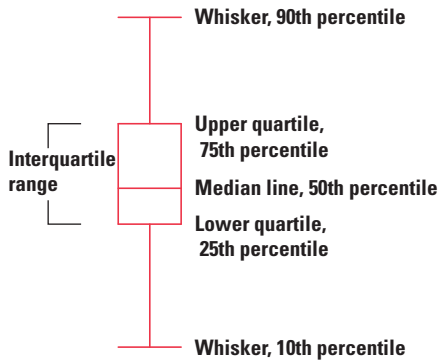
**Figure 13.** Tonnage model analysis for the Philippines. *A*, Global porphyry copper tonnage model of Singer and others (2008). Philippine porphyry copper deposits (red triangles) are labeled. *B*, *t*-test comparison of the tonnages of the 38 porphyry copper deposits in the Philippines with tonnages of deposits in the global porphyry copper-molybdenum-gold model of Singer and others (2008). *C*, Explanation of the elements of the graphs shown in *B*.



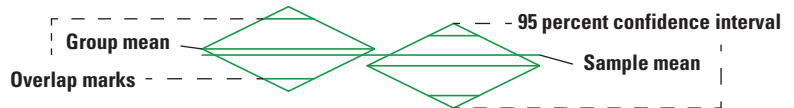
C

- A. Mean is intersection of line with normal quantile score = zero
- B. Probability score
- C. Slope is standard deviation
- D. Normal quantile score
- E. Data values

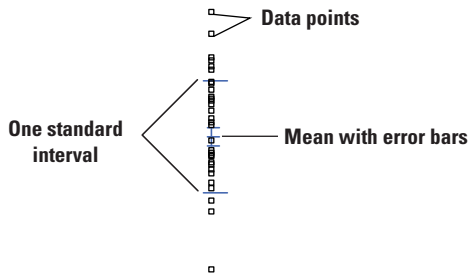
F. Box plots are schematics that illustrate how data are distributed as measured by percentiles.



G. The means diamonds are a graphical illustration of the t test. If the overlap marks do not vertically separate the groups, the groups are probably not significantly different. The groups appear separated if there is vertical space between the top overlap mark of one diamond and the bottom overlap mark of the other.



H. Graph that illustrates how data are distributed using estimates of the measured standard deviation.



I. Comparison circles are a graphical technique that illustrate significant separation among means in terms of how circles intersect.

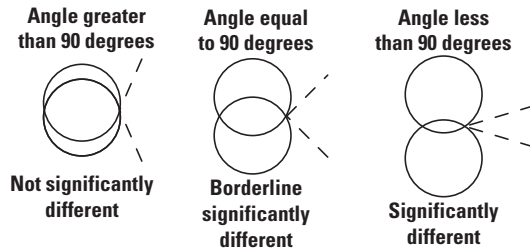


Figure 13.—Continued

**Table 4.** Grade and tonnage model selections for simulations of undiscovered resources.

[Pooled *t*-test results assuming equal variances; analysis of variance (ANOVA) tests used for tracts with a single deposit;  $p > 0.01$  indicates that the deposits in the tract are not significantly different from those in the model at the 1-percent level;  $p < 0.01$  indicates that the deposits in the tract are significantly different from those in the model at the 1-percent level, and therefore, the tract fails the selected test (as indicated by an asterisk (\*)) and the model is inappropriate for the assessment. n.d., no data; tests for silver, where reported, were not rejected for either model. Model selected, refers to the Cu-Au subtype and the general Cu-Au-Mo (includes all subtypes) grade and tonnage models of Singer and others (2008)]

Coded_ID	Tract name	$N_{\text{known}}$	Porphyry Cu-Au-Mo model						Porphyry Cu-Au subtype model						Model selected	Basis for selection
			Tons	Cu	Mo	Ag	Au	Contained Cu	Tons	Cu	Mo	Ag	Au	Contained Cu		
142pCu7312	Cotabato Arc	1	0.12	0.82	n.d.	n.d.	0.85	0.13	0.06	0.72	n.d.	n.d.	0.14	0.09	Cu-Au-Mo	deposit grades
142pCu7311	Mindoro-Tablas-West Panay Area	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	Cu-Au subtype	possible continuation of West Luzon Arc
142pCu7309	Philippine Arc	8	0.1	0.46	0.4	0.15	0.03	0.07	0.13	0.45	0.16	0.18	0.55	0.09	Cu-Au subtype	statistical tests, deposit grades
142pCu7308	Central Mindanao Volcanic Province	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	Cu-Au subtype	geologic rationale
142pCu7307	Sulu-Zamboanga Arc	0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	Cu-Au subtype	geologic rationale
142pCu7306	Bohol-Cebu Area	2	0.33	0.32	0.69	0.89	0.74	0.54	0.41	0.33	0.14	0.83	0.52	0.63	Cu-Au-Mo	deposit grades
142pCu7305	Masbate-Negros Arc System	5	0.54	0.53	0.79	0.1	0.62	0.46	0.74	0.5	0.01	0.04	0.0002*	0.6	Cu-Au-Mo	statistical tests
142pCu7304	Sierra Madre Arc	3	0.4	0.7	0.005*	0.22	0.11	0.5	0.5	0.71	0.26	0.15	<0.001*	0.61	Cu-Au-Mo	default to general model
142pCu7302	Cordon Alkalic Complex	3	0.48	0.46	n.d.	n.d.	0.26	0.39	0.55	0.45	n.d.	n.d.	0.81	0.43	Cu-Au subtype	geologic rationale
142pCu7301	Luzon Arc	16	0.12	0.66	<0.001*	0.72	0.01	0.12	0.23	0.6	0.61	0.27	0.44	0.2	Cu-Au subtype	statistical tests
	All	38	0.01	0.51	<0.001*	0.47	0.01	0.01	0.05	0.38	0.39	0.16	<0.001*	0.03		

A *t*-test or analysis of variance (ANOVA) was done for each assessed permissive tract to compare the log-transformed tonnages and grades of any known deposits in the tract with the global models using a *p*-value (significance probability) of 0.01 to test for significant differences in the means of the two groups. Results of these tests on a tract by tract basis for the deposits in the Philippines are listed in table 4.

As a group, the 38 deposits in the Philippines have lower tonnages than those in all the global models but do not fail the *t*-test for the porphyry copper-gold subtype model at the 1-percent screening level, although the *p*-value of 0.03 for the test indicates that the test would barely pass at a 3-percent screening level and would fail at a 5-percent level (fig. 13B). In a previous analysis of appropriate model selection for Southeast Asia, Drew and Singer (2005) used a slightly older dataset (2005) to conclude that a copper-gold model might be appropriate for assessing the Philippines region. The general model was used for the tracts that failed the *t*-test for gold using the copper-gold model.

## Estimates of Numbers of Undiscovered Deposits

The assessment team evaluated the available data and, using expert judgment, made individual, subjective estimates of the numbers of undiscovered porphyry copper deposits. The distribution of known deposits, prospects, related deposit types, alteration, depth of erosion, thickness of cover, and level of exploration were factors considered in making estimates. Sites were ranked informally using the following numeric scale:

- 5=deposit (identified resources)
- 4=prospect in Singer and others (2008) or less than 16,000 t of ore established by drilling
- 3=drilled, with greater than 20 m of 0.2-percent copper or more
- 2=drilled, or trenched, with less than 20 m of 0.2 percent copper; past or ongoing exploration
- 1=stream sediment, magnetic anomaly, or mineralized structural trend

Sites ranked at 3 or 4 typically were considered to represent significant prospects that, if fully explored, might have grades and tonnages represented by the deposit model. Sites ranked as 2 may or may not be significant, and sites ranked as 1 generally were considered as occurrences that could be compatible with, although not necessarily indicative of, porphyry copper formation.

In addition, the distribution of reported copper and gold occurrences of unknown type and placer gold workings were considered. Other considerations included the fact that some

areas are heavily vegetated and have been inaccessible for exploration for 20 years or more because of environmental concerns and local opposition to mineral development. Particular weight was given to sites classified as porphyry copper-related in published literature and recent exploration reports. The location, number, deposit type, and relative importance of other prospects, such as skarns and epithermal deposits, were also considered. Recent literature, company Web sites, and technical reports for exploration projects were reviewed for descriptions of geology, mineralogy, deposit type, rock alteration, and sampling results to evaluate the likelihood that a particular prospect might be associated with a porphyry copper system similar to those in the grade and tonnage models. In some cases, team members provided information about prospects based on personal observations from site visits. The rationales for individual tract estimates are discussed in the appendixes.

Estimates are expressed in terms of different levels of certainty. Estimators are asked for the least number of deposits of a given type that they believe could be present at three levels of certainty (90 percent, 50 percent, and 10 percent). For example, on the basis of all the available data, a team member might estimate that there was a 90-percent chance (or better) of the presence of at least one deposit, a 50-percent chance of at least three deposits, and a 10-percent chance of at least five undiscovered deposits in a permissive tract. In some cases, the number and characteristics of porphyry copper prospects within a tract were the primary basis for estimates at the 90th and 50th quantiles. The individual estimates were discussed as a group, and a single team estimate was agreed upon for each tract. The estimates are converted to a mean number of deposits and standard deviation based on an algorithm developed by Singer and Menzie (2005). The algorithm can be described by the following general equations to calculate an expected (mean) number of deposits ( $\lambda$ ) and a standard deviation ( $s_x$ ) based on estimates of numbers of undiscovered deposits predicted at different quantile levels<sup>16</sup> ( $N_{90}$  = 90 percent level,  $N_{50}$  = 50 percent level, etc.):

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

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

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

<sup>16</sup>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  $N_{01}$ .



uncertainty associated with an estimate is the coefficient of variation ( $C_v$ ), defined as:

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

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

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

Team estimates reflect both the uncertainty in what may exist and the favorability of the tract (Singer, 1993). Final team estimates of numbers of undiscovered deposits are summarized in table 5, 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 implied deposit density for each tract.

## Simulation of Undiscovered Resources in Southeast Asia

Estimates of numbers of undiscovered deposits for each permissive tract (table 5) are combined with the selected grade and tonnage models (table 4) 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.

Simulation results for mean and median<sup>17</sup> estimates of contained copper and gold in undiscovered deposits are reported in table 6 along with total identified resources in known deposits in each tract. Identified resources (table 1) are based on total production, if any, and published data for measured, indicated, and inferred reserves and resources at the lowest cutoff grade reported. Identified resources may include substantial amounts of metal that have already been produced.

Three of the assessed permissive tracts contain no identified resources. Some tracts may contain porphyry copper systems that are currently, or have been, explored, but no

<sup>17</sup> Amount of metal at the 0.5 quantile; 50-percent chance of occurrence of that amount of metal or more, based on simulation for the estimated numbers of undiscovered deposits.

**Table 5.** Estimates of numbers of undiscovered porphyry copper deposits in East and Southeast Asia.

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

Appendix	Coded_id	Tract name	Consensus undiscovered deposit estimates					Summary statistics				Tract area ( $\text{km}^2$ )	Deposit density ( $N_{total}/100,000 \text{ km}^2$ )	
			$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$			$N_{total}$
A	142pCu7312	Cotabato Arc	1	1	2	2	2	1.2	0.55	45	1	2.2	9,700	23
B	142pCu7308	Central Mindanao Volcanic Province	0	1	5	5	5	1.9	1.9	100	0	1.9	29,320	6
C	142pCu7307	Sulu-Zamboanga Arc	0	1	1	2	3	0.8	0.7	90	0	0.8	10,180	8
D	142pCu7305	Masbate-Negros Arc System	0	2	4	4	4	2	1.5	73	5	7	12,230	57
E	142pCu7309	Philippine Arc	3	7	14	14	14	7.7	4.1	53	8	15.7	23,700	66
F	142pCu7302	Cordon Alkalic Complex	0	1	4	5	5	1.7	1.7	100	3	4.7	4,860	97
G	142pCu7304	Sierra Madre Arc	0	0	1	1	3	0.36	0.75	210	1	1.36	14,000	10
H	142pCu7311	Mindoro-Tablas-West Panay Area	0	1	2	3	3	1.1	0.98	91	0	1.1	9,170	12
I	142pCu7306	Bohol-Cebu Area	0	1	3	3	3	1.3	1.2	90	2	3.3	2,600	127
J	142pCu7301	Luzon Arc	2	9	20	20	20	10	6.4	63	18	28	23,700	118

**Table 6.** Summary of simulations of undiscovered resources in porphyry copper deposits in East and Southeast Asia.

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

Appendix	Coded_id	Tract name	Identified copper resources (t)	Mean undiscovered copper resources (t)	Median undiscovered copper resources (t)	Identified gold resources (t)	Mean undiscovered gold resources (t)	Median undiscovered gold resources (t)	Mean undiscovered molybdenum resources (t)	Mean undiscovered silver resources (t)	Mean rock (Mt)
Philippine Archipelago											
A	142pCu7312	Cotabato Arc	15,000,000	4,600,000	1,300,000	480	110	18	120,000	1,400	930
B	142pCu7308	Central Mindanao Volcanic Province	0	5,900,000	1,400,000	0	430	130	35,000	2,000	1,200
C	142pCu7307	Sulu-Zamboanga Arc	0	2,500,000	410,000	0	180	43	13,000	850	490
D	142pCu7305	Masbate-Negros Arc System	6,800,000	7,800,000	2,800,000	180	200	44	210,000	2,600	1,600
E	142pCu7309	Philippine Arc	6,300,000	24,000,000	15,000,000	720	1,800	1,300	140,000	8,000	4,900
F	142pCu7302	Cordon Alkalic Complex	1,400,000	4,900,000	1,200,000	160	370	110	28,000	1,600	990
G	142pCu7304	Sierra Madre Arc	310,000	1,400,000	0	2	36	0	35,000	420	290
H	142pCu7311	Mindoro-Tablas-West Panay Area	0	3,200,000	670,000	0	230	66	17,000	1,000	630
I	142pCu7306	Bohol-Cebu Area	6,400,000	5,000,000	1,000,000	340	130	9	140,000	1,600	1,000
J	142pCu7301	Luzon Arc	17,000,000	31,000,000	22,000,000	1,700	2,300	1,700	180,000	10,000	6,300
Total for Philippines Area			53,000,000	90,000,000	NA	3,600	5,800	NA	920,000	29,000	18,000

reliable grade and tonnage estimates are yet available; these were considered as significant prospects with a high probability of representing deposits like those in the grade and tonnage models.

The amounts of metal reported at different quantiles are included in the appendix tables, along with the mean value, the probability associated with the mean, and a cumulative graph of the results. Note that the probability associated with the mean typically is on the order of 30 percent or more and that the median value is less than the mean. 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.

## Discussion

This probabilistic assessment of the metal resources associated with undiscovered porphyry copper deposits in the Philippines indicates that additional resources may be present (table 6). The mean estimate of undiscovered copper resources in the study area (90 Mt) is about twice the amount of copper present in identified resources (52 Mt). If present, however, these resources may be either inaccessible or otherwise uneconomic to develop. Results should be interpreted with due caution pending application of economic filters to evaluate what portion of the estimated undiscovered resources might be economic under various conditions such as mining method, metal prices, capital development costs, and so forth. Identified resources are compared with mean and median estimates of undiscovered copper resources by area, and by tract, in figure 14.

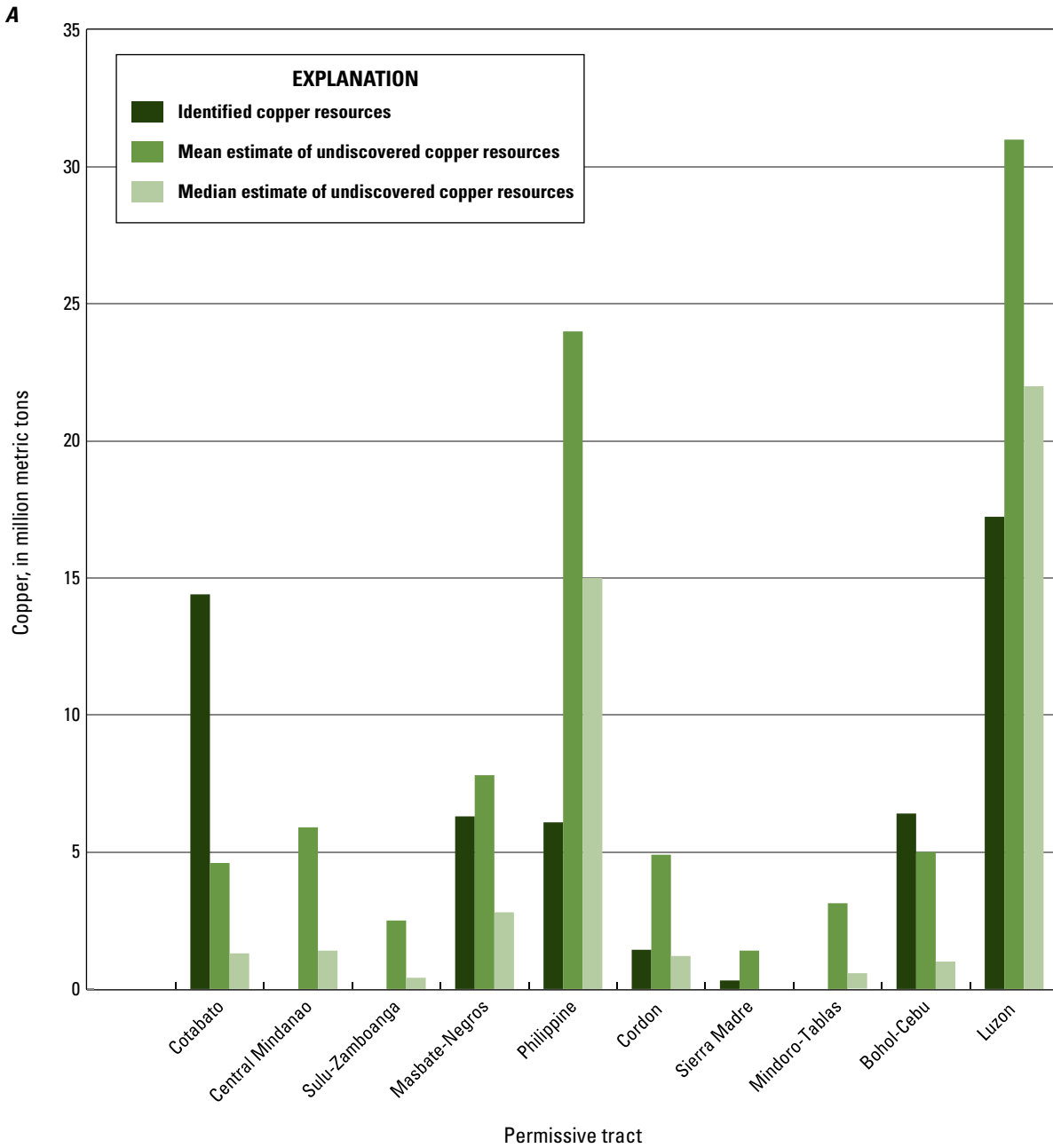
Cases in which the mean estimates of undiscovered copper resources in a permissive tract far exceed the identified resources in that tract, such as for the Luzon Arc and Philippine Arc permissive tracts (table 6), raise concerns about the appropriateness of the global models used for the simulation. As noted in the discussion on grade and tonnage models, the deposits in the Philippines as a group appear to have smaller tonnages than most of the deposits in global models, which may be attributed to the underlying resource estimates or to some geologic factors. Much of the tonnage and grade data for the Philippines deposits represents 1980s-era historical estimates with unspecified cutoff grades and cannot be considered compliant with modern reporting standards. Renewed exploration in the Philippines in the 21st century, with a focus on more extensive and deeper drilling than was done in past, is providing updated resource information for some deposits. Table 1 includes updates to the tonnage and grade data

reported by Singer and others (2008) for five deposits in the Philippines. For example, the 2008 data for the Tawi Tawi deposit listed historical data of 159 Mt at 0.39 percent copper, whereas Solfotara Mining Corporation (2012) reported 225 Mt at 0.4 percent copper, an approximately 50-percent increase in contained copper. The 159 Mt estimate is from Sillitoe and Gappe (1984); the larger estimate (non-JORC compliant) was calculated in 1975 based on 58 drill holes, and a 2006 computer-generated block model estimates resources of 261 Mt at 0.4 percent copper. These data illustrate the difficulties in combining older and more recent data in models, which ideally should capture information on cutoff grade and meet modern reporting standards where possible. In many cases, the recent exploration and development focus is on copper and gold, and molybdenum and silver grades are not always reported. Most of the known deposits in the Philippines are considered to be open in one or more directions indicating that further exploration is likely to increase identified resources.

The broader question of whether there are important regional differences in size and quality of deposits remains open. No geologic explanations for the apparent differences in the Philippines are obvious; the deposits formed in multiple geodynamic settings on oceanic, continental, and accreted arc basement.

The Philippines Mines and Geosciences Bureau's 2009 resource estimates for the country include 7.1 billion metric tons at 1.00 weight percent copper (approximately 71 Mt contained copper) and 4.3 billion metric tons at 0.94 g/t gold (approximately 4,000 t), in addition to chromite, nickel, iron, and manganese (L.A. Rollan, a coauthor of this report, written commun., 2010). Porphyry copper deposits represent more than 97 percent of the identified copper reserves, and 26 percent of the annual gold production as a byproduct. The remaining copper resources are present in volcanogenic massive sulfide deposits, copper veins, and skarns. The predicted mean amounts of copper in undiscovered porphyry copper deposits from this assessment (approximately 90 Mt copper) and gold (5,800 t gold) are somewhat higher than the Bureau's estimates for copper, although much of the Philippine gold production is likely to come from epithermal deposits which may, or may not, be associated with a porphyry deposit at depth.

The magmatic arc systems preserved in South Korea and Japan lack known porphyry copper deposits, although a few partly explored prospects are present in South Korea. Although the possible occurrence of porphyry copper deposits in these settings is of academic interest, no exploration has occurred in recent years and the likelihood of near-surface porphyry discoveries large enough to warrant development in the foreseeable future is negligible.



**Figure 14.** Graphical summary of results as bar charts comparing identified copper resources with mean and median estimated copper in undiscovered porphyry copper deposits on a tract by tract basis for the Philippines. *A*, Copper. *B*, Gold.

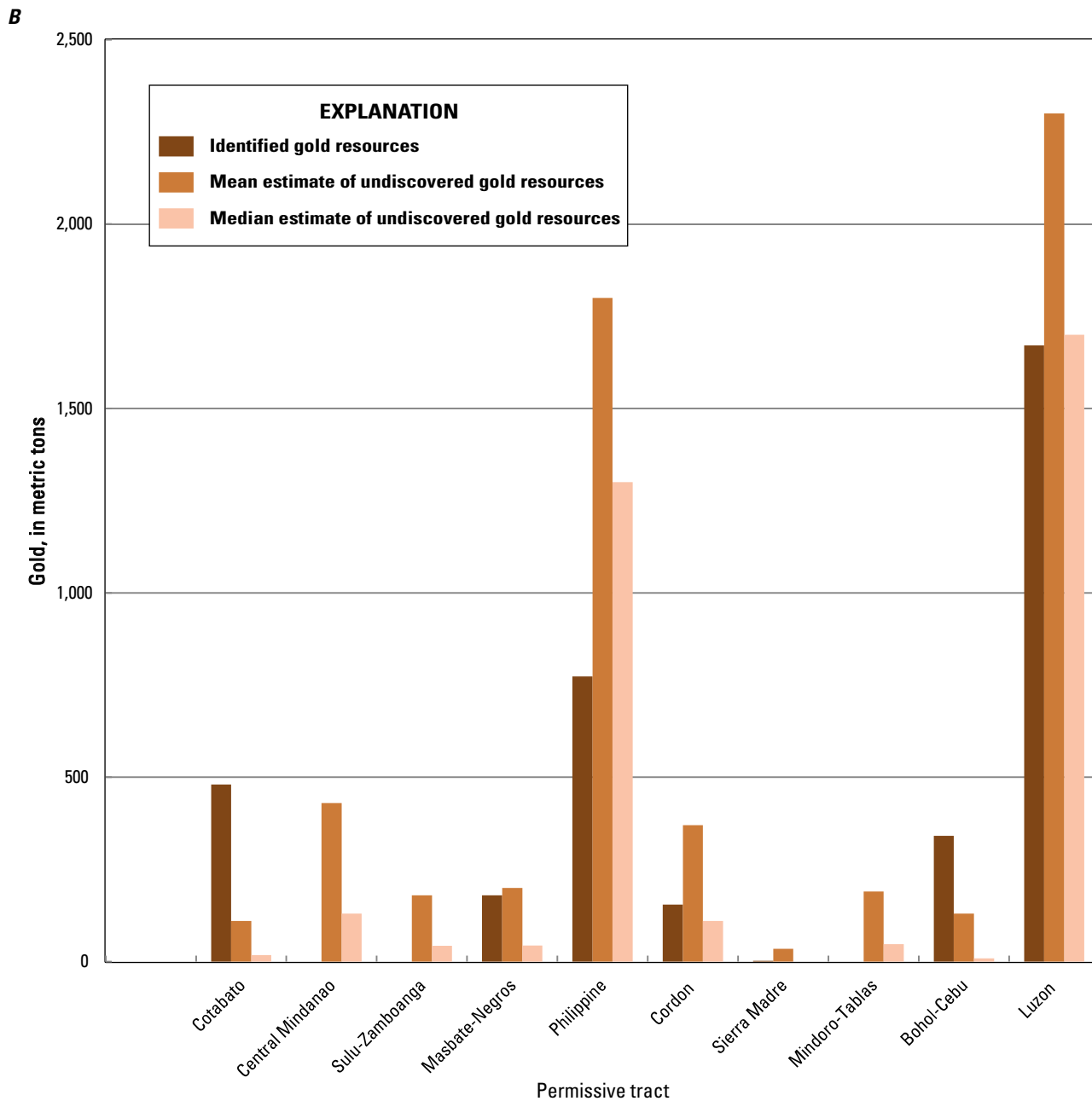


Figure 14.—Continued



## Considerations for Users of this Assessment

GMRAP products represent a synthesis of current, readily available information. Ideally, assessments are made on a recurring basis, at a variety of scales, because available data change over time. This assessment is based on the descriptive and grade-tonnage data contained in published mineral deposit models. Data in the grade and tonnage models represent average grades of each commodity of possible economic interest and tonnages based on the total of production, reserves, and resources at the lowest cutoff grade for which data were available when the model was constructed. The present-day economic viability of the deposits used to construct the models varies widely, so care must be exercised when using the results of this assessment to answer questions that involve economics. Furthermore, these estimates are for numbers of deposits that are likely to exist, not necessarily those likely to be discovered (Singer, 2007b). Prospects, revealed by past or current exploration efforts, may become deposits when further drilling and characterization takes place. These probable deposits are treated here as undiscovered deposits, albeit ones with a high degree of certainty of existence. The mineral industry explores for extensions of identified resources, as well as for greenfields projects in new exploration areas. Extensions of identified resources are not considered in this assessment. This assessment addresses the potential for concealed deposits that have upper parts within 1 km of the surface. Very high-grade deposits may be exploited at greater depths. However, exploration for, and exploitation of such deposits may be so expensive that deposits, if present, may not be discovered in the near term. If they are discovered, the costs and logistics related to mining a deeply buried porphyry deposit might prohibit their development into mines given current or near-term metal prices and technology.

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

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## Appendix A. Porphyry Copper Assessment for Tract 142pCu7312, Cotabato Arc—Philippines

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### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper (Singer and others, 2008)

Table A1 summarizes selected assessment results.

**Table A1.** Summary of selected resource assessment results for tract 142pCu7312, Cotabato Arc—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified copper rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	9,700	15,000,000	4,600,000	1,300,000

### Location

Southwestern Mindanao (fig. A1).

### Geologic Feature Assessed

Miocene to Holocene Cotabato Arc.

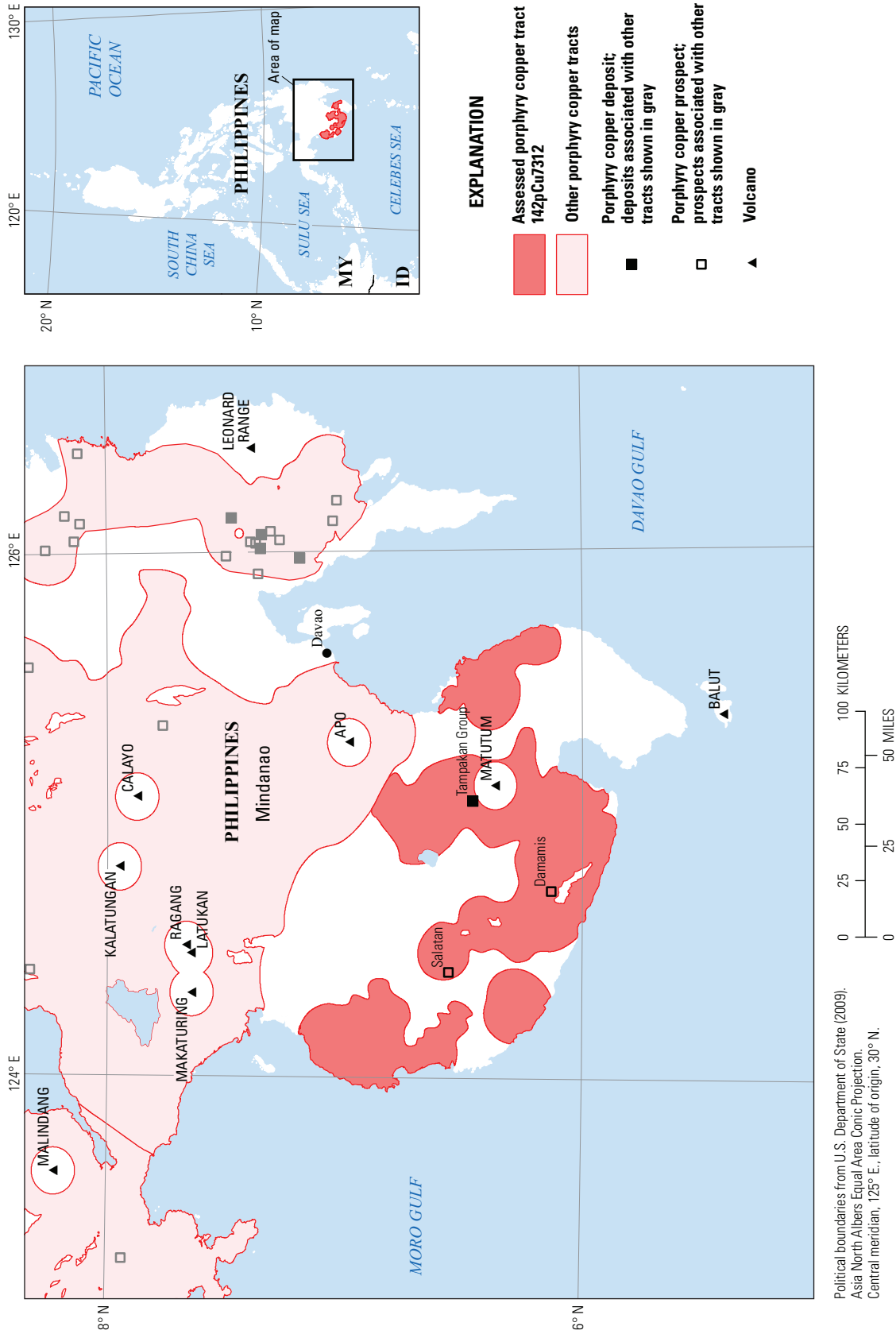
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure A1.** Map showing tract location, known deposits, and significant prospects and occurrences for tract 142pCu7312, Cotabato Arc—Philippines. MY, Malaysia; ID, Indonesia.



## Delineation of the Permissive Tract

### Tectonic Setting

The tract delineates calc-alkalic intrusive rocks within the 300-km-long Miocene to Holocene Cotabato Arc in southwestern Mindanao (fig. 2A<sup>6</sup>) as outlined by Garwin and others (2005) and Mitchell and Leach (1991). The arc formed by northeast-directed subduction of oceanic crust in the Cotabato Trench (fig. 5B). The Cotabato Arc is built on a Paleogene (50–30 Ma) basement of volcanic rocks characterized by island-arc tholeiitic compositions; these rocks are attributed to an older arc (Daguma) related to subduction of a proto-Molucca Sea along a proto-Sangihe trench (Sajona and others, 1997). The Cotabato Arc may be coextensive with the Masbate-Negros Arc to the north and with the North Sulawesi-Sangihe Arc to the south (fig. 2A); its continuation across the intervening Sulu-Zamboanga Arc has not been established (Garwin and others, 2005).

### Geologic Criteria

The permissive tracts were constructed by selecting igneous rocks from a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a). Map units were classified by age groups, and subdivided into intrusive and volcanic subgroups. Lithologies were examined, and rock types that are not considered permissive for porphyry copper deposits, such as pillow basalts, ultramafic rocks, and rhyolites were excluded. Permissive rocks used to delineate the tract are shown in figure A2 and listed in table A2. A 10-km buffer was created around intrusive rocks, and a 2-km buffer was created around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand to honor fault boundaries and to include known prospects and permissive igneous rocks shown on larger scale maps (fig. 7 of Sajona and others, 1997; Middleton and others, 2004).

The tract primarily is based on the pre-Pleistocene intrusive and volcanic rocks shown on the 1:1,000,000-scale geologic map of the Philippines. Site locations for dated and classified igneous rocks were also used to ensure that permissive rocks that did not appear on the map were included within the tract (Malaihollo and others, 2002). Calc-alkalic and high-K calc-alkalic andesite and dacite flows, andesitic necks, and intrusions within the tract area are dated at 23.6 Ma to Holocene (Sajona and others, 1997). The Cotabato Fault bounds the tract on the north and separates it from the Central Mindanao Volcanic Province (tract 142pCu7308). A circular cutout in

the tract represents a 10-km area around the 8.4-Ma Mount Matutum active stratovolcano (fig. A1); other excluded areas within the tract outline ophiolite complexes along the Daguma Range (fig. 4E). Tract boundaries were clipped to shorelines based on political boundaries established by the U.S. Department of State (2009).

### Known Deposits

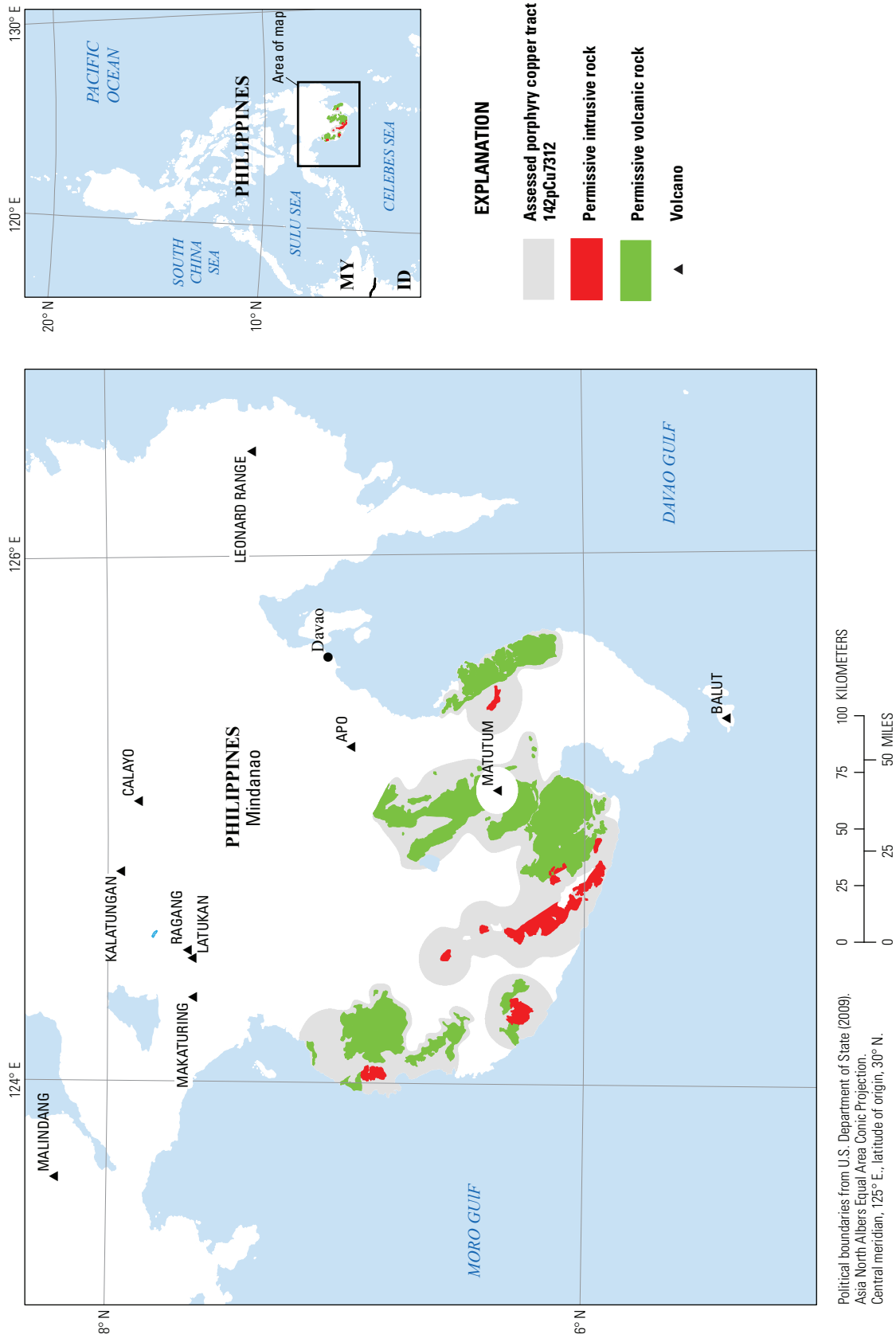
The Tampakan Group (fig. A1) include the Tampakan deposits and the adjacent Sodaco exploration project. The 3.5-Ma Tampakan deposit in southern Mindanao has been described as the largest undeveloped copper-gold deposit in Southeast Asia (Middleton and others, 2004). As of January 2012, resources were reported to be 2,940 Mt of ore having an average grade of 0.52 percent copper and 0.17 g/t gold (table A3). The porphyry system underlies a high-sulfidation epithermal deposit and is associated with intermediate argillic alteration (sericite-chlorite-clay (SCC) type alteration) of andesite and diorite. The andesite overlies early to middle Miocene basaltic basement intruded by hornblende diorite porphyry stocks. The main copper mineral in the porphyry is chalcopyrite, which occurs as disseminations and stringers. In the epithermal system, the main copper mineral is enargite (Philippine Mines and Geosciences Bureau, 2005). Feasibility studies were completed with plans for open-pit mining and production to begin approximately 2016, with a 20–40 year mine life. However, a ban on open-pit mining in South Cotabato was enacted in July of 2010, which may affect mine development (Aguiba, 2010).

Tampakan is near intersections of faults that strike west-northwest and north-northeast. The Sodaco exploration project, 900 m from Tampakan, lies within the 90-km<sup>2</sup> lithocap of advanced argillically altered volcanic rocks and is considered as an extension of the Tampakan deposit. Drilling 400 m south of the Sodaco project intercepted 158 m of rock containing 0.52 g/t gold and 0.41 percent copper.

### Prospects, Mineral Occurrences, and Related Deposit Types.

Two porphyry copper prospects are known within the tract area: Salatan and Damamis (fig. A1, table A4). The main ore-bearing intrusive rock at the Salatan prospect is an argillically altered biotite-hornblende dacite porphyry and associated dikes (Sillitoe and Gappe, 1984). The maximum depth of oxidation at Salatan is less than 10 m, and supergene enrichment is minor. Little is known about the Damamis copper prospect, a reported porphyry-type copper-gold occurrence (C. Manipon, a coauthor of this report, written commun., 2004). Several iron and copper occurrences are associated with Miocene quartz diorite in the Daguma Range (fig. 4E).

<sup>6</sup>Refer to figures and tables in main report.



**Figure A2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7312, Cotabato Arc—Philippines. MY, Malaysia; ID, Indonesia.

**Table A2.** Map units that define tract 142pCu7312, Cotabato Arc—Philippines.

[Map unit, age range, and principal lithologies are based on a digital compilation of maps listed in table A5]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Include granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene rock sequences.	Neogene
Volcanic rocks			
Pliocene-Quaternary volcanic rocks	QVP	Volcanic plain or volcanic piedmont deposits. Chiefly pyroclastic rocks and (or) volcanic debris at foot of volcanoes.	Pliocene-Quaternary
Pliocene-Quaternary volcanic rocks	QV	Non-active cones (generally pyroxene andesite); also dacitic and (or) andesitic plugs.	Pliocene-Quaternary
Neogene volcanic rocks	IN2	Principally dacite and/or andesite flows, generally with pyroclastics.	Late Miocene-Pliocene
Neogene volcanic rocks	IN1	Mostly submarine andesite and/or basalt flows. Intercalated with pyroclastics and clastic sedimentary rocks and (or) reef limestone lenses. Largely confined within the axial zone of Luzon, Visayas, and Mindanao.	Oligocene-Miocene

**Table A3.** Porphyry copper deposits in tract 142pCu7312, Cotabato Arc—Philippines.[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as  $(Mt \times 1,000,000) \times (Cu \text{ grade, } \% \div 100)$ ]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Tampakan Group	6.467	125.050	NA	4.25	2,940	0.52	0.006	0.17	n.d.	15,288,000	Middleton and others (2004), Mills (2007), Mitchell and Leach (1991), Rohrlach (2002), Rohrlach and others (1999), Singer and others (2008), WMC (1999, 2000)

**Table A4.** Significant prospects and occurrences in tract 142pCu7312, Cotabato Arc—Philippines.

[Ma, million years. Rank 4=prospect listed in global database of Singer and others (2008) or &lt;16,000 metric tons (t) of ore established by drilling. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Damamis	6.133	124.708	Early Miocene (~19.5)	South Cotabato copper prospect. Chalcopyrite, bornite.	U.S. Geological Survey (2012)	1
Salatan	6.567	124.400	Early Miocene (~19.5)	Prospect explored by Gold Fields Asia, Ltd. in 1982.	Almogela (1974), Sillitoe and Gappe (1984), Singer and others (2008)	4

## Exploration History

In the 1960s–1980s, a minor amount of gold prospecting was done and small alluvial gold deposits were worked within the tract area. The Salatan prospect was explored in 1982 by Gold Fields Asia, Ltd. (Sillitoe and Gappe, 1984). Reconnaissance exploration within the district began in 1990, and Tampakan was discovered in 1992 (Indophil Resources, Ltd., 2010). Geochemical and geophysical surveys followed, and the deposit was characterized by 85 drill holes that led to geological resource estimates and plans for development. The May 2012 mining tenement map for Central Mindanao showed more than 25 exploration permit applications, permits, or mineral protection sharing agreements for copper and gold that overlap parts of the tract area (<http://www.mgb.gov.ph/lmtp.aspx>).

## Sources of Information

Principal sources of information for the Tampakan deposit are listed in table A5.

## Grade and Tonnage Model Selection

The gold to molybdenum ratio of reported grades for the Tampakan deposit is 28, which categorizes the deposit as a porphyry copper subtype deposit according to the model criteria of Singer and others (2008). An analysis of variance (ANOVA) test for the deposit (table 4) also supports selection of general global porphyry copper model.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The small size of the tract (less than 10,000 km<sup>2</sup>) limits the numbers of undiscovered deposits that could be present.

The project area for Tampakan, the one known deposit in the tract, is about 300 km<sup>2</sup>. The tract contains two porphyry copper prospects, one of which (Salatan) was explored in the past. A favorable structural setting, epithermal gold deposits associated with the Tampakan deposit, alluvial gold occurrences, and alteration of diorites in the Daguma Range (Philippine Mines and Geosciences Bureau, 2010) are all positive indications for additional deposits. Also, the extensive Quaternary volcanic cover could conceal deposits. On the basis of these factors, the assessment team estimated a 90-percent chance for one or more additional deposits and a 10-percent chance of two or more deposits within the tract. The mean number of undiscovered deposits is  $1.2 \pm 0.5$  (table A6).

## 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 A7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. A3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of undiscovered copper within the tract, 4.6 Mt, represents about a third of the amount of copper identified at Tampakan (15.3 Mt).

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**Table A5.** Principal sources of information used for tract 142pCu7312, Cotabato Arc—Philippines.

[NA, not applicable]

Theme	Name or Title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geology and mineral distribution map of the Philippines	1:1,400,000	Philippine Bureau of Mines (undated)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Mineral distribution map of the Philippines	1:2,500,000	Philippine Geological Survey Division (1964)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Mining places in the Philippines (kml file)	NA	GoogleEarth® (2013)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984); Philippine Mines and Geosciences Bureau (2005)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites and technical reports	NA	Indophil Resources (2010), WMC (1999, 2000)

**Table 6.** Undiscovered deposit estimates, deposit numbers, and tract area for tract 142pCu7312, Cotabato Arc—Philippines.

[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model;  $N_{total}$ , total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers ( $km^2$ ); 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)]

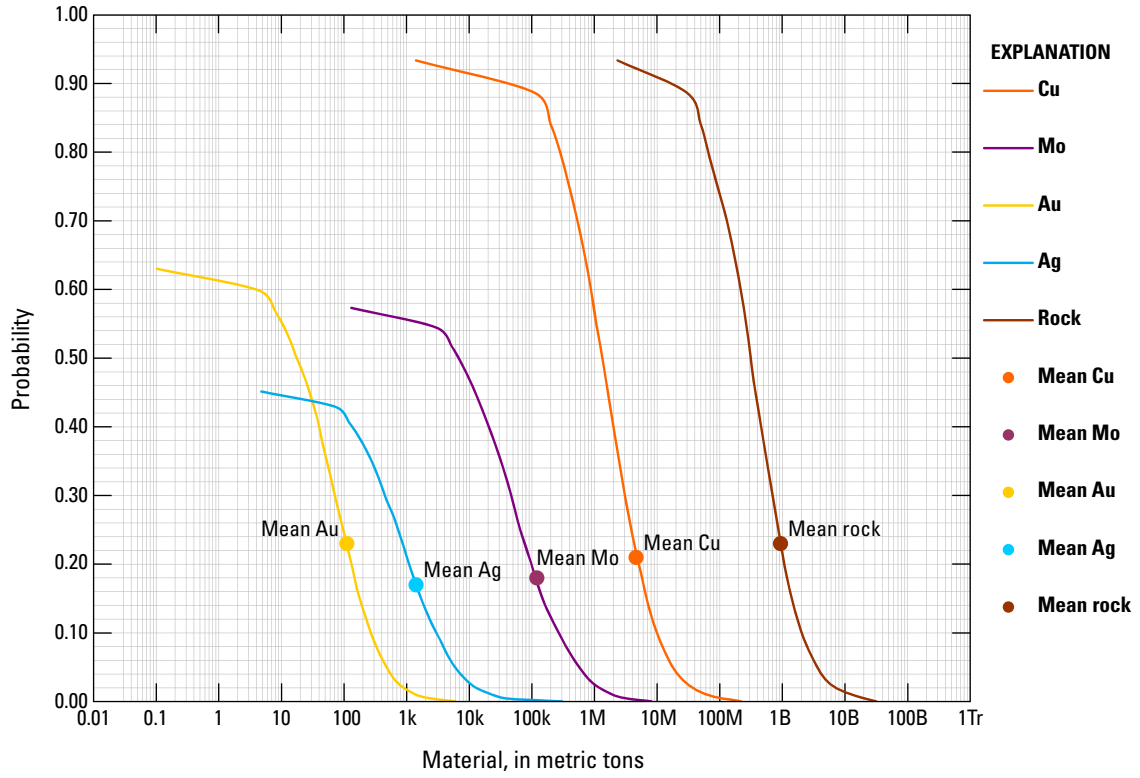
Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $km^2$ )	Deposit density ( $N_{total}/100,000 km^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
1	1	2	2	2	1.2	0.55	45	1	2.2	9,700	23

**Table A7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7312, Cotabato Arc—Philippines.

[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	88,000	1,300,000	9,900,000	18,000,000	4,600,000	0.21	0.07	
Mo	0	0	6,800	270,000	550,000	120,000	0.18	0.43	
Au	0	0	18	270	470	110	0.23	0.37	
Ag	0	0	0	3,000	6,000	1,400	0.17	0.55	
Rock	0	24	310	2,000	3,700	930	0.23	0.07	





**Figure A3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7312, Cotabato Arc—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix B. Porphyry Copper Assessment for Tract 142pCu7308, Central Mindanao—Philippines

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### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table B1 summarizes selected assessment results.

**Table B1. Summary of selected resource assessment results for tract 142pCu7308, Central Mindanao—Philippines.**

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	29,320	0	5,900,000	1,400,000

### Location

Central part of Mindanao Island (fig. B1).

### Geologic Feature Assessed

Central Mindanao Volcanic Province.

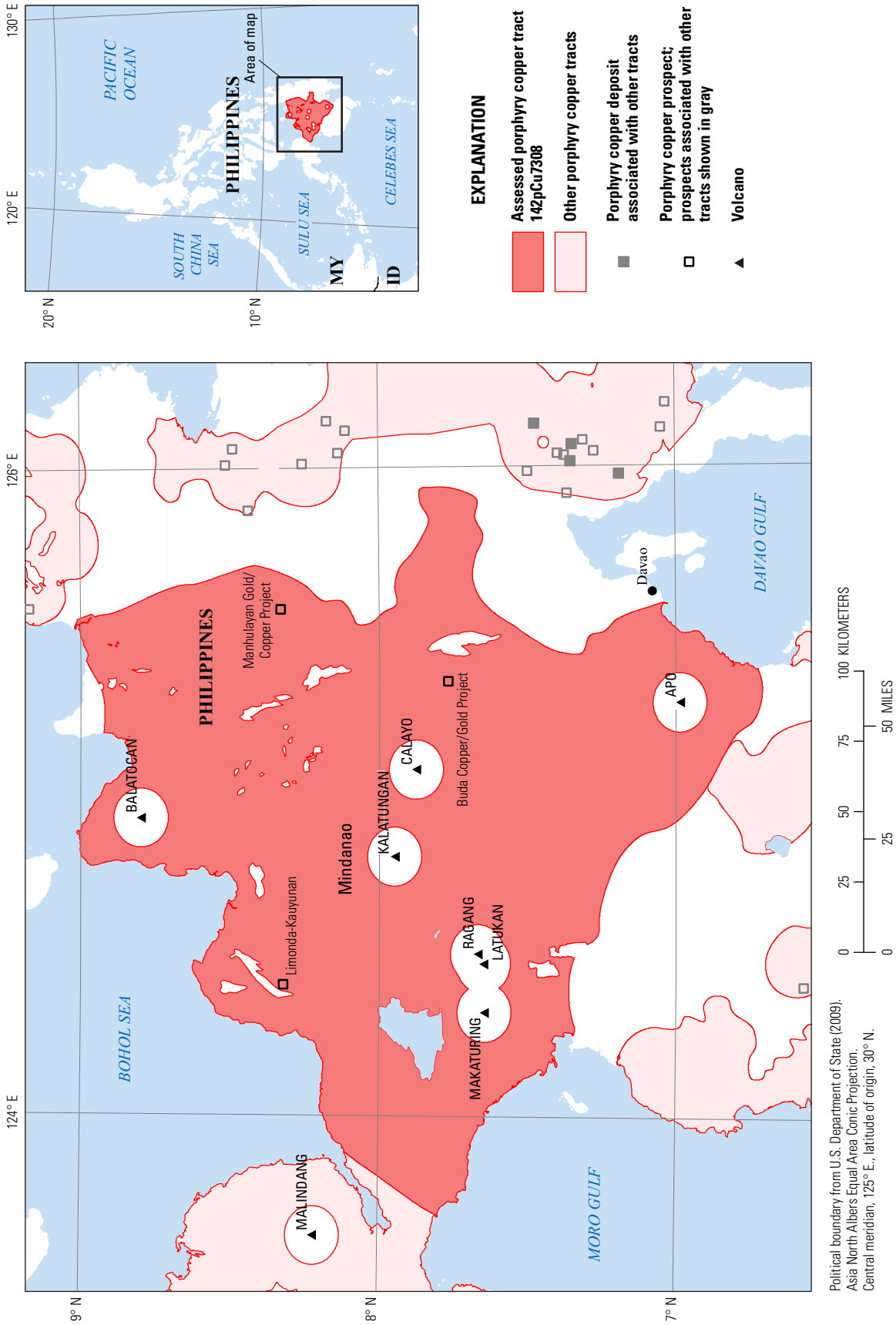
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure B1.** Map showing tract location and significant porphyry copper prospects for tract 142pCu7308, Central Mindanao—Philippines. MY, Malaysia; ID, Indonesia.



## Delineation of the Permissive Tract

### Tectonic Setting

The Central Mindanao Volcanic Province (fig. 2A<sup>6</sup>) represents an area of soft collision of two arcs in the Pliocene (4–5 Ma), followed by postcollisional calc-alkalic to shoshonitic magmatism (2–3 Ma) that produced the largest volcanic field in the Philippines (Pubellier and others, 1991, 1996; Sajona and others, 1997, 2000). Sajona and others (2000) noted that deep seismic studies refute a linkage with subduction along any of the trenches that surround Mindanao (Philippine Trench to the east, Sulu Trench to the west, or Cotabato Trench to the southwest, fig. 5B). They describe the island arcs that collided as northern continuations of the Neogene Sulawesi-Sangihe (western Mindanao) and Halmahera Arcs (eastern Mindanao) (fig. 2A). Other studies ascribed Quaternary volcanism to a Central Mindanao Volcanic Arc, an arc parallel to, and related to, subduction along the Philippine Trench, or to a detached slab; the volcanoes in western Mindanao were probably related to east-dipping subduction along the extension of the Sulawesi-Sangihe Arc (Corpuz, 1992 and references therein).

### Geologic Criteria

The tract is based on the distribution of Neogene intrusive and volcanic rocks (fig. B2, table B2) in the highlands of Central Mindanao, as shown on the 1:1,000,000-scale geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a). Much of the area is covered by Pliocene-Quaternary andesitic volcanic rocks and pyroclastic rocks. Permissive rock units were selected from the digital geologic map using GIS tools, and 10- and 2-km buffers were created around intrusive and volcanic rocks, respectively. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The map-unit polygons were buffered, aggregated, smoothed, and edited by hand to honor fault boundaries and include known prospects and permissive igneous rocks shown on maps included in topical studies (Sajona and others, 1997; Corpuz, 1992; Malaihollo and others, 2002). Pliocene-Quaternary volcanic rocks were not used to delineate the tract, but comprise cover that could conceal deposits. Areas within approximately 10 km of Quaternary volcanic centers are excluded from the tract because the volcanic cover is likely to be greater than 1 km thick.

The northern boundary of the tract follows the Cotabato Fault (fig. 5B). The northeastern boundary of tract parallels the Philippine Fault (fig. 5B), which is a Neogene feature that cuts through the Agusan-Davao Basin (fig. 4E). The basin is underlain by at least 5 km of Cenozoic clastic rocks. Therefore, the

basin is excluded from the tract because any buried porphyry systems in that area are likely to be deeper than the 1-km depth limit chosen for this study. The final tract boundary was clipped to the Mindanao shoreline (U.S. Department of State, 2009).

Miocene andesites in Central Mindanao are dated at 20–16 Ma. Pliocene volcanic rocks include calc-alkalic basalts and basaltic andesites. Postcollisional volcanic rocks vary from calc-alkalic (2.3–0.6 Ma) to shoshonitic (0.5–0.4 Ma) to calc-alkalic (0.3 to the present). The geochemistry of these rocks (OIB<sup>7</sup>-like enrichments in niobium (Nb), high La/Nb ratios) include typical arc as well as adakite-like compositions and may reflect contributions of upwelled mantle (Sajona and others, 1997, 2000), possibly related to sinking of a detached slab of the Molucca Sea Plate<sup>8</sup>. Any porphyry systems are likely to be related to the pre-collisional rocks. Although collisional and postcollisional settings are known for porphyry copper deposits elsewhere in the world, any deposits associated with the younger rocks are likely to lie below 1 km of the surface under the thick volcanic cover.

### Known Deposits

None.

### Prospects, Mineral Occurrences, and Related Deposit Types

Two porphyry copper prospects are being explored in the eastern part of the tract (fig. B1, table B3). At the Manhulayan prospect, drilling intercepted a potassically altered porphyry stock (185 m of 0.33 percent copper, 0.16 g/t gold) associated with a magnetic anomaly and adjacent to epithermal veins (Oceana Gold Corporation, 2010). The Buda copper-gold prospect is part of Indophil Resources NL (2010) Central Mindanao project area. Copper and gold are reported in veins in andesite at the Limonda-Kauyunan occurrence in the northwestern part of the tract.

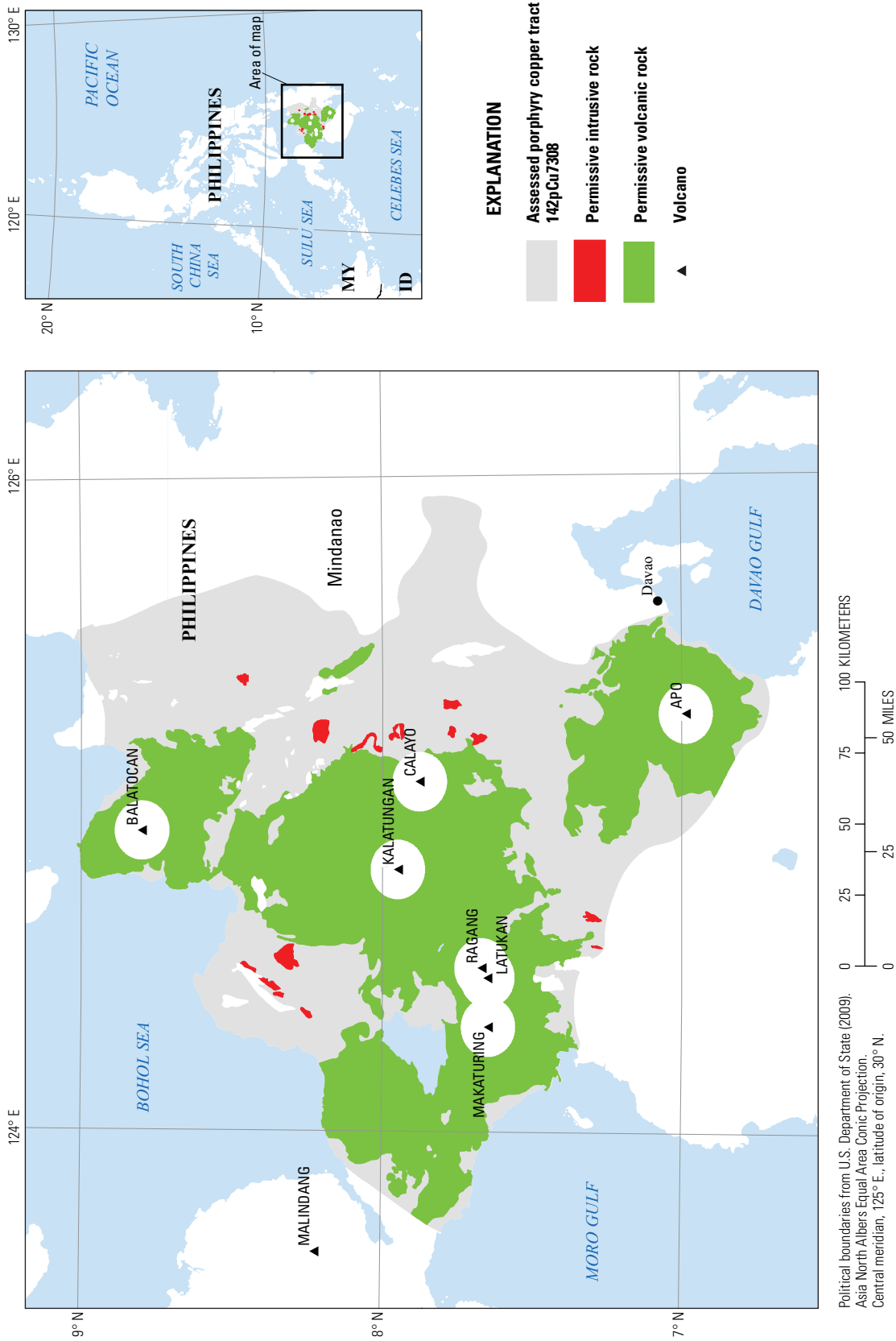
### Exploration History

The eastern side of the tract area, to the west of the Philippine Fault, recently has been explored for porphyry copper (table B3). Porphyry copper deposits and larger prospects are known to the east of fault zone (within tract 142pCu7309). Recent exploration data collected within the tract (aeromagnetic and radiometric surveys, regional geologic mapping, and geochemical sampling) were interpreted as surface expressions of buried porphyry systems overprinted by epithermal gold and base-metal veins (Oceana Gold Corporation, 2010; Indophil Resources NL, 2010). Paleogene volcanic rocks and

<sup>6</sup>Refer to figures and tables in main report.

<sup>7</sup>OIB, oceanic island basalt.

<sup>8</sup>Molucca Sea Plate: a microplate in Indonesia that is subducting to the west under the Eurasian Plate and to the east under the Philippine Sea Plate.



**Figure B2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7308, Central Mindanao—Philippines. MY, Malaysia; ID, Indonesia.

**Table B2.** Map units that define tract 142pCu7308, Central Mindanao—Philippines.

[Map unit, age range, and principal lithologies are based on a digital geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene sequences.	Neogene
Volcanic rocks			
Neogene volcanic rocks	IN <sub>2</sub>	Principally dacite and/or andesite flows, generally with pyroclastics.	Late Miocene-Pliocene
Neogene volcanic rocks	IN <sub>1</sub>	Mostly submarine andesite and (or) basalt flows. Intercalated with pyroclastics and clastic sedimentary rocks and/or reef limestone lenses. Largely confined within the axial zone of Luzon, Visayas, and Mindanao.	Oligocene-Miocene

**Table B3.** Significant prospects and occurrences in tract 142pCu7308, Central Mindanao—Philippines.

[Ma, million years; n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. Rank 3=drilled prospect, with &gt;20 m of 0.2% or more Cu]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Buda Copper/Gold Project	7.770	125.340	n.d.	Southern block of Indophil's Central Mindanao Project area. Porphyry Cu-Au target area; Au, Cu, and Ag in sulfide outcrop along a major fault at Bangan prospect within the project area.	Indophil Resources NL (2010)	1
Limonda-Kauyunan	8.324	124.403	n.d.	Cu and Au veins in andesite	U.S. Geological Survey (2012)	1
Manhulayan Gold/Copper Project	8.331	125.564	n.d.	Cu-Au porphyry prospect adjacent to low sulfidation epithermal gold and base-metal sulfide veins. Drilling (4 holes) intercepted K- altered porphyry (185 m of 0.33% Cu, 0.16 ppm Au and 300 m of 0.32% Cu, 0.15 ppm Au). Prospect is associated with a 900 by 200 m mineralized porphyry stock within a 2.5 by 0.8 km positive magnetic anomaly.	Oceana Gold Corporation (2010)	3

Neogene andesites and intrusions are mapped within 25 km of the prospects on the east side of Mount Kalatungan volcano (fig. 4E). Mining tenement maps for northern Mindanao (Philippine Bureau of Mines and Geosciences, 2009) show that recent exploration activity is concentrated along a 140-km-long belt in the eastern part of the tract that trends north-south and includes both the Manhulayan and Buda prospects.

## Sources of Information

Table B4 lists the principal sources of information used for the assessment.

## Grade and Tonnage Model Selection

No deposits are known within the tract. The copper-gold subtype model was selected for the assessment on the basis of characteristics of the partially explored prospects and the model selected for the permissive tracts in the southern arc

counterparts—the Halmahera and Sulawesi-Sangihe Arcs (fig. 2A; Hammarstrom and others, 2012).

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

On the basis of the facts that the tract has not been thoroughly explored, the possibility that if fully explored, the Mahulayan project could represent undiscovered resources, the possibilities for buried deposits, and the occurrence of porphyry copper deposits in the Sangihe and Halmahera Arcs to the south, the assessment team estimated a 50-percent chance for one or more undiscovered deposits and a 10-percent chance for 5 or more deposits (table B5). The expected number of deposits based on this distribution of estimates is 1.9 deposits, with a relatively high uncertainty ( $C_v=100$  percent).

**Table B4.** Principal sources of information used for tract 142pCu7308, Central Mindanao—Philippines.

[NA, not applicable]

Theme	Name or Title	Scale	Citation
Geology	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Neotectonic map of Mindanao	1:800,000	Pubellier and others (1993)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites and technical reports	NA	Oceana Gold (2010), Indophil Resources NL (2010)

## Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and

Spanski, 2012). Selected simulation results are reported in table B6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. B3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. See table 6 for comparisons with other tracts.

**Table B5.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7308, Central Mindanao—Philippines.

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

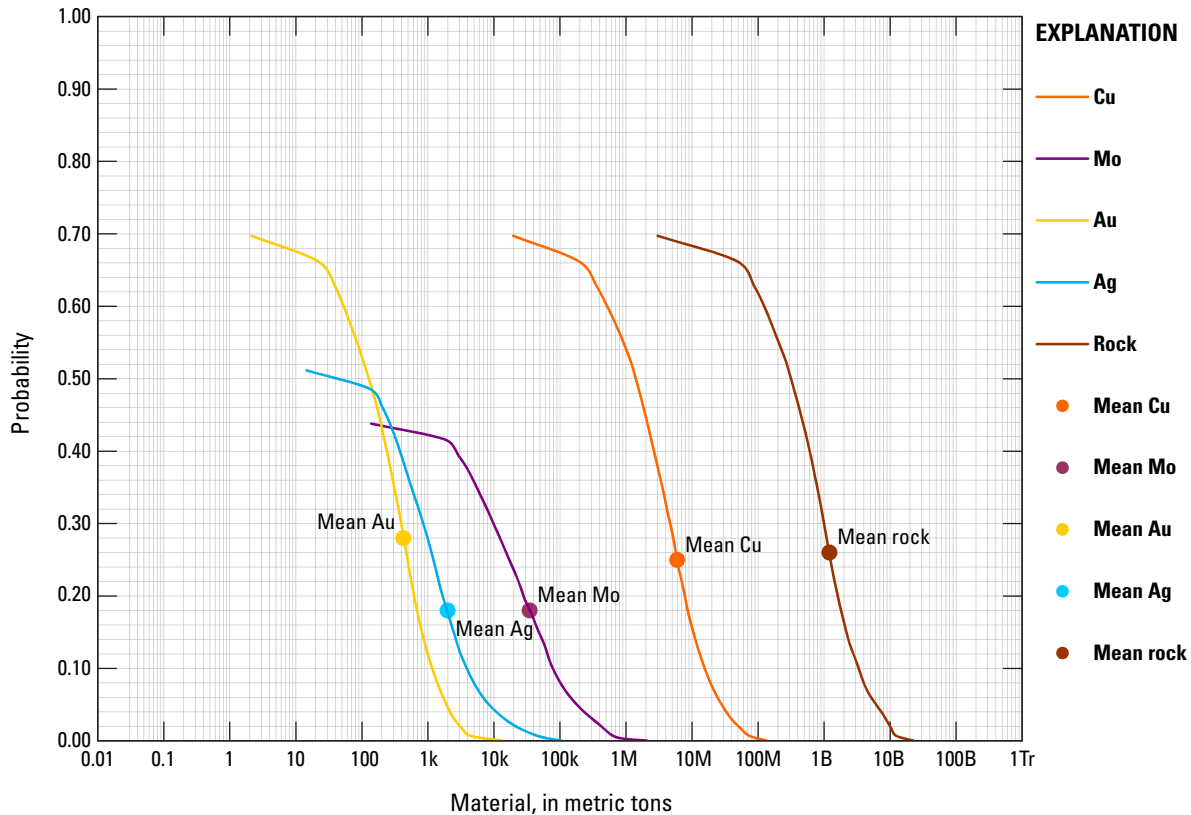
Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $\text{km}^2$ )	Deposit density ( $N_{total}/100,000 \text{ km}^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
0	1	5	5	5	1.9	1.9	100	0	1.9	29,320	6

**Table B6.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7308, Central Mindanao—Philippines.

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

Material	Probability of at least the indicated amount					Probability of		
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	1,400,000	16,000,000	27,000,000	5,900,000	0.25	0.30
Mo	0	0	0	77,000	190,000	35,000	0.18	0.56
Au	0	0	130	1,200	1,900	430	0.28	0.30
Ag	0	0	67	3,900	8,300	2,000	0.18	0.49
Rock	0	0	310	3,300	5,900	1,200	0.26	0.30





**Figure B3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7308, Central Mindanao—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix C. Porphyry Copper Assessment for Tract 142pCu7307, Sulu-Zamboanga—Philippines

By Jane M. Hammarstrom<sup>1</sup>, Arthur A. Bookstrom<sup>2</sup>, Connie L. Dicken<sup>1</sup>, Steve Ludington<sup>3</sup>, Gilpin R. Robinson, Jr.<sup>1</sup>, and Michael L. Zientek<sup>2</sup> with contributions from Sevillo (Bill) D. David, Jr.<sup>4</sup>, Claro J. Manipon<sup>4</sup>, Lilian A. Rollan<sup>4</sup>, and Yasushi Watanabe<sup>5</sup>

### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Cox, 1986; Cooke and others, 1998; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table C1 summarizes selected assessment results.

**Table C1.** Summary of selected resource assessment results for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	10,180	0	2,500,000	410,000

### Location

Zamboanga Peninsula, Western Mindanao (fig. C1).

### Geologic Feature Assessed

Northeastern (oceanic arc) part of the Miocene to Holocene Sulu-Zamboanga Arc.

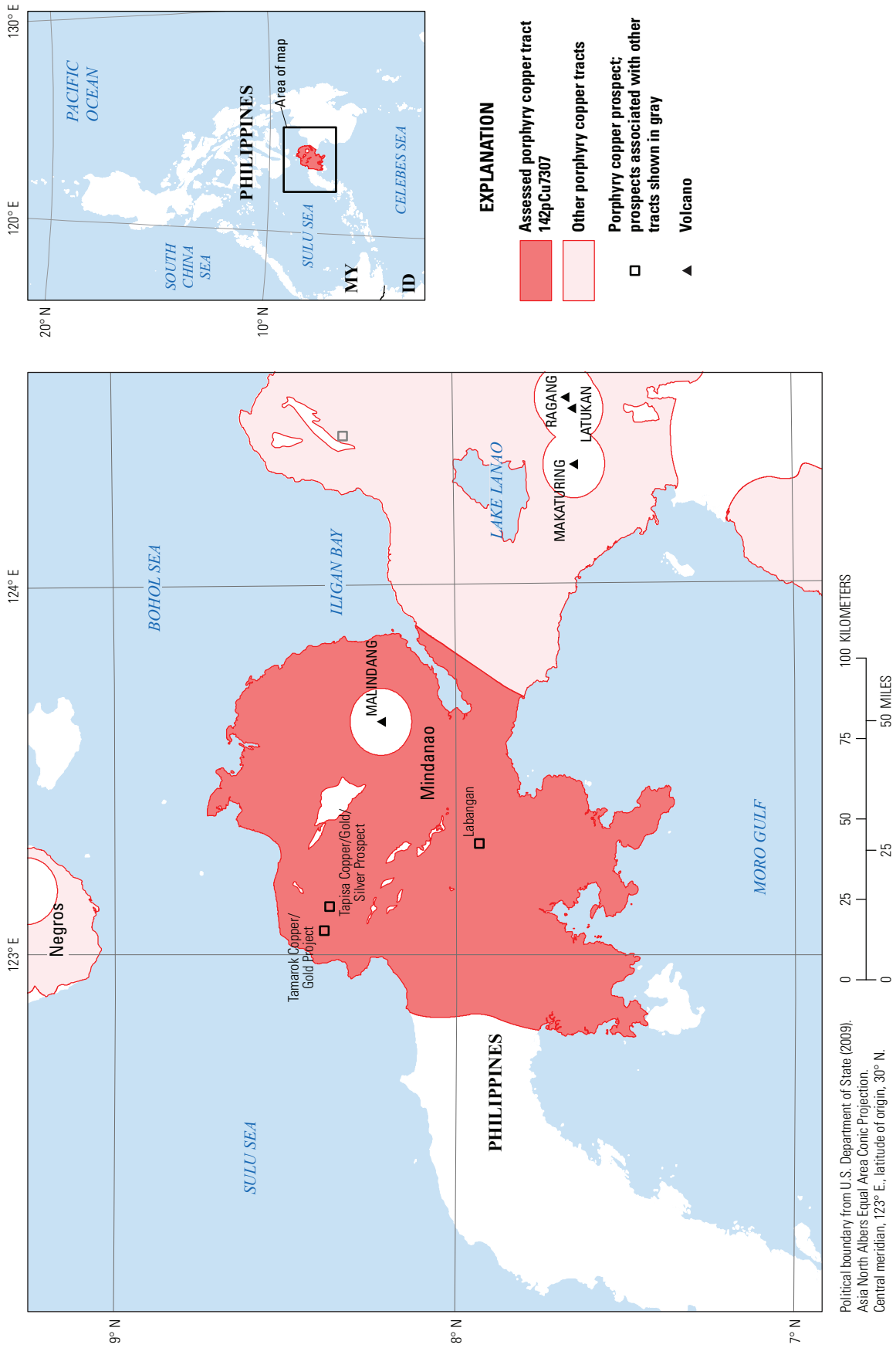
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure C1.** Map showing tract location and significant porphyry copper prospects for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines. MY, Malaysia; ID, Indonesia.



## Delineation of the Permissive Tract

### Tectonic Setting

The tract is the northern part of the late Miocene to Holocene, 400-km-long Sulu-Zamboanga Arc that extends from eastern Sabah to the Zamboanga Peninsula of the Philippines (fig. 2A). The arc was formed by subduction at the Sulu Trench (fig. 5B<sup>6</sup>). The Celebes Sea Basin (fig. 5B), located southeast of the Sulu-Zamboanga Arc, consists of Eocene oceanic crust (Weissel, 1980; 1981; Lee and McCabe, 1986). The Sulu-Zamboanga Arc separates the Sulu Sea Basin from the Celebes Sea Basin (fig. 5B) and includes a group of Quaternary islands with one active volcano (Cruz, 1987). Subduction beneath the arc is from the Sulu Trench to the northwest. Although there is no well-defined seismic zone along the Sulu Trench, the volcanic arc is considered to be in a waning (fumarolic) stage (Pubellier and others, 1991).

The northern part of the arc lies north of a mid-Miocene collisional boundary (Siayan-Sindangan Suture Zone and its continuation as the tectonically active Sindangan-Cotabato-Daguma Lineament on fig. C2) that separates island-arc rocks to the north and continental rocks related to Sundaland on the south (Anonymous, 1995; Pubellier and others, 1993). The Sulu-Zamboanga Peninsula collided with central Mindanao in the middle Miocene; subduction gave way to strike-slip motion along the suture zone (Yumul and others, 2008). The Cotabato and Masbate-Negros arc systems (fig. 2A) cut off the Sulu-Zamboanga Arc at its northern end (Garwin and others, 2005).

### Geologic Criteria

The tract (fig. C1) is based on the distribution of Paleogene and Neogene intrusions and late Miocene to Pliocene volcanic rocks as shown on the 1:1,000,000-scale geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a). Plio-Pleistocene volcanic rocks in the northeastern part of the Zamboanga Peninsula at Maundang volcano, where volcanic cover is likely to be greater than 1 km thick, are excluded from the tract.

Permissive rock units (fig. C2, table C2) were selected from the digital geologic map using GIS tools, and 10- and

2-km buffers were created around intrusive and volcanic rocks, respectively. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand to honor fault boundaries and include known prospects and permissive igneous rocks shown on maps included in topical studies (Pubellier and others, 1993; Malaihollo and others, 2002). Quaternary volcanic rocks were not used as criteria to delineate the tract but are included as cover that could conceal deposits. A northwest-striking belt of ophiolitic complexes was excluded from the tract; these appear as irregularly shaped holes in the tract (fig. C1). The western boundary of the tract is based on a series of north-striking faults; no permissive rocks are mapped south of the faults.

### Known Deposits

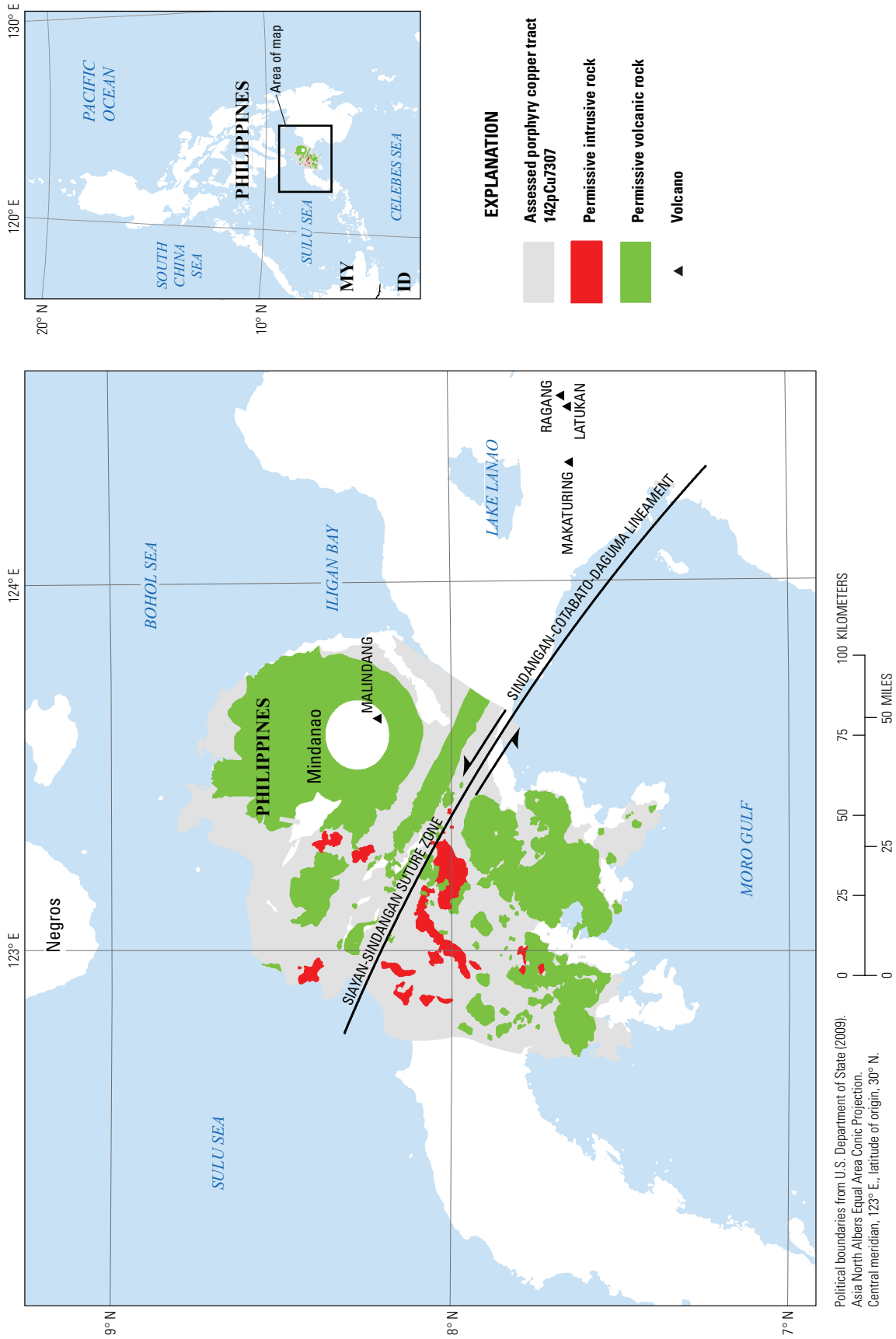
None.

### Prospects, Mineral Occurrences, and Related Deposit Types

The tract includes three significant porphyry copper prospect areas (fig. C1, table C3). Labangan is an undrilled, abandoned porphyry copper-gold prospect associated with diorite porphyry, andesitic to basaltic flows, and northwesterly faults. Pleistocene volcanic cover is present at Labangan (Sillitoe and Gappe, 1984). Tamarok and Tapisa are part of an ongoing exploration program; initial channel sampling for Tamarok, characterized as chalcopyrite and bornite disseminations and in sheeted quartz veins in altered hornblende diorite, indicate grades compatible with the porphyry copper system (table C3). A porphyry copper outcrop (Malachite Hill), described as a 50-m exposure of altered hornblende diorite (chlorite-clay-sericite overprinting magnetite-biotite-K-feldspar-silica alteration), was drilled in 2011. Drilling was suspended pending further structural analysis (TVI Pacific, Inc., 2012).

Porphyry copper prospects are associated with andesitic to basaltic lava flows, diorite porphyry, and northwest-striking faults. Other deposit types on the peninsula include epithermal gold veins, copper-iron skarn, and volcanogenic massive sulfides.

<sup>6</sup>Refer to figures and tables in main report.



**Figure C2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines. MY, Malaysia; ID, Indonesia.

**Table C2.** Map units that define tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geological map of the Philippines (Philippine Bureau of Mines, 1963).

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Include granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene sequences.	Neogene
Paleogene intrusive rocks	Pg <sub>1</sub>	Mostly quartz diorite.	Paleogene
Volcanic rocks			
Neogene volcanic rocks	IN <sub>2</sub>	Principally dacite and (or) andesite flows, generally with pyroclastics. Locally thick and associated with reef limestone lenses in southern Zamboanga.	Late Miocene-Pliocene

**Table C3.** Significant prospects and occurrences in tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

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

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Labangan	7.933	123.300	Late Miocene to early Pliocene (?)	Porphyry Cu-Au prospect associated with diorite porphyry, andesitic to basaltic flows, northwest-southeast faults. Chalcopyrite, bornite, sphalerite, galena (+gold), silver, covellite, chalcocite, azurite, malachite. Alteration: silicification.	Jimenez and others (2002), Mercado (1975), Sillitoe and Gappe (1984), Singer and others (2008)	4
Tamarok Copper/Gold Project	8.388	123.066	Miocene	Part of TVI's Zamboanga regional exploration (2008): initial results showed 38 m of 0.71% Cu and 0.35 g/t Au from a continuous channel sample. Chalcopyrite and bornite in sheeted quartz veins, stockworks, and disseminations in altered hornblende diorite.	TVI Pacific, Inc. (2010, 2012)	2
Tapisa Copper/Gold/Silver Prospect	8.372	123.131	n.d.	Part of TVI's Zamboanga regional exploration (2008); target area adjacent to Tamarok area.	TVI Pacific, Inc. (2010)	1

## Exploration History

The Labangan prospect (fig. C1) was explored by the Marcopper Mining Corp. in the 1970s (Sillitoe and Gappe, 1984). A resurgence in exploration activity starting about 2000 in the northern part of the Zamboanga Peninsula led to discovery of the other two prospect areas. Airborne magnetic surveys, mapping, and channel and rock sampling at Tamarok were completed in 2011; drilling was scheduled to resume in 2012 (TVI Pacific, Inc., 2012).

## Sources of Information

Table C4 lists the principal sources of information used for assessment of the tract.

## Grade and Tonnage Model Selection

Based on the gold-rich character of porphyry deposits in the Philippines, associations of epithermal gold in the

region, and recommendations of a regional analysis (Drew and Singer, 2005), the copper-gold subtype model was used for the assessment of the tract.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The assessment team considered the Labangan, and Tamarok-Tapisa porphyry prospects as potential deposits. Preliminary results from recent exploration support the likelihood of additional targets in the tract area. Sillitoe and Gappe (1984) speculated that areas along strike from the Labangan prospect in the northern part of the Sulu-Zamboanga Arc have significant potential for discoveries. In addition, the numerous gold prospects, general lack of thorough exploration and volume of Quaternary cover were considered favorable for

**Table C4.** Principal sources of information used for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

[NA, not applicable; n.d., no data]

Theme	Name or Title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Digital geologic map of the East and Southeast Asia	1:2,000,000	Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP) and Geological Survey of Japan (1997)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Philippine porphyry copper deposits and prospects	NA	Database (C. Manipon, 2004, written commun., compiled from Philippine Mines and Geosciences Bureau records)
	Mineral resource map of Asia	1:35,000,000	Kamitani and Naito (1998)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Commercial databases	NA	<a href="http://www.infomine.com/">http://www.infomine.com/</a>
	Company Web sites and technical reports	NA	TVI Pacific, Inc. (2010)

the occurrence of undiscovered porphyry copper deposits. The Labangan and Tamarok-Tapisa prospect areas lie along the northwest-striking Sindangan-Cotabato-Daguma Lineament (fault system), which may represent a mineralized corridor. The area is poorly explored relative to more thoroughly explored parts of the Philippines such as western Luzon.

The team estimated a 50-percent chance of one or more undiscovered deposits, a 5-percent chance of two or more and a 1-percent chance of three or more deposits based on the occurrence of three known prospect areas. The mean result is 0.8 deposits with a high degree ( $C_v=90$  percent) of uncertainty (table C5). One consideration is that although near-surface epithermal systems may be present, porphyry copper deposits may be present at depths greater than the 1-km maximum depth for undiscovered deposits specified for the assessment.

## Probabilistic Assessment Simulation Results

Estimates of undiscovered resources for the tract were made by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table C6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. C3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. See table 6 in the main text of this report for comparisons with other tracts.

**Table C5.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

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

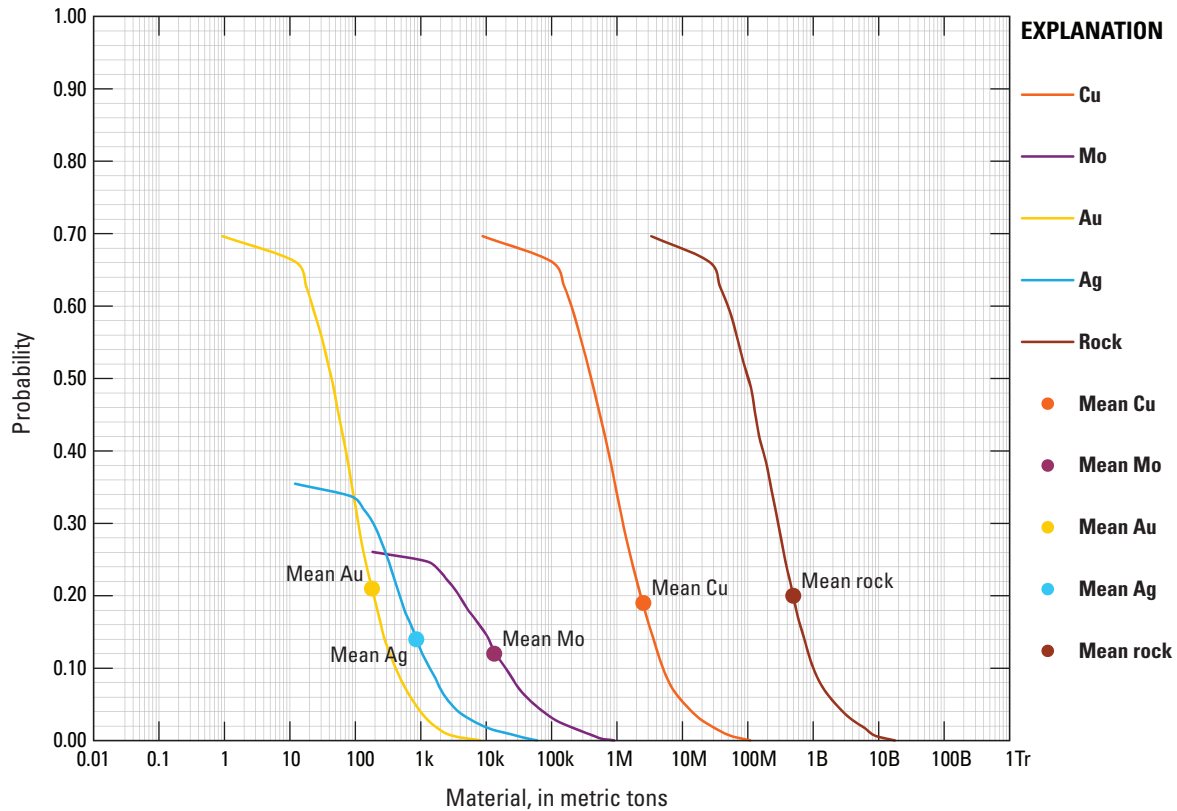
Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $\text{km}^2$ )	Deposit density ( $N_{total}/$ 100,000 $\text{km}^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
0	1	1	2	3	0.81	0.73	90	0	0.81	10,180	8

**Table C6.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7307, Sulu-Zamboanga Arc—Philippines.

[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	410,000	5,000,000	11,000,000	2,500,000	0.19	0.30
Mo	0	0	0	20,000	54,000	13,000	0.12	0.74
Au	0	0	43	410	780	180	0.21	0.30
Ag	0	0	0	1,400	2,900	850	0.14	0.65
Rock	0	0	100	1,000	2,300	490	0.20	0.30





**Figure C3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7307, Sulu-Zamboanga Arc—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix D. Porphyry Copper Assessment for Tract 142pCu7305, Masbate-Negros Arc—Philippines

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### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper (Singer and others, 2008)

Table D1 summarizes selected assessment results.

**Table D1.** Summary of selected resource assessment results for tract 142pCu7305, Masbate-Negros Arc—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified copper rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	12,230	6,800,000	7,800,000	2,800,000

### Location

Central and Western Visayas region, including the islands of Negros, Masbate, and Panay, Philippines (fig. D1).

### Geologic Feature Assessed

Masbate-Negros Arc.

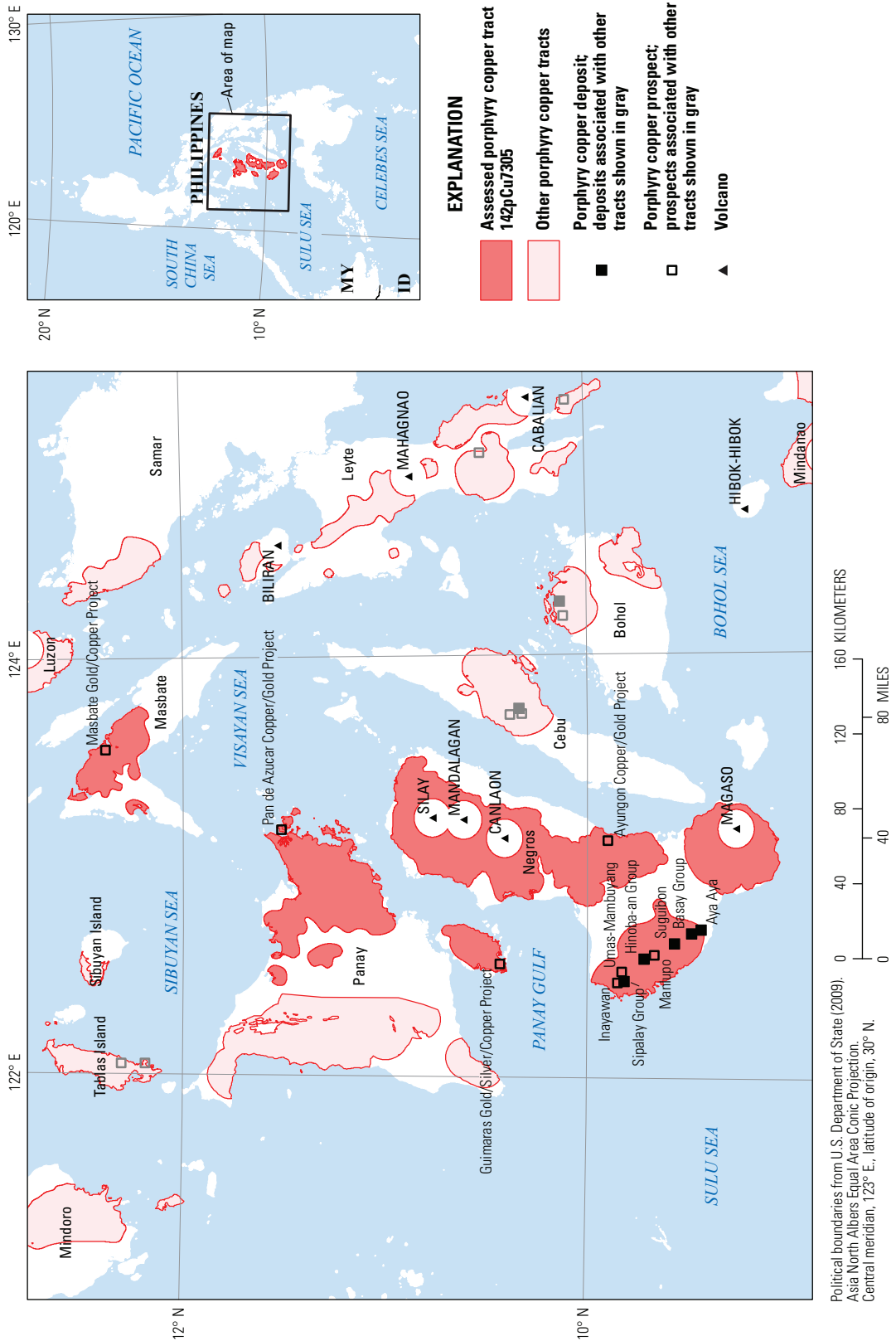
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

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<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure D1.** Map showing tract location, porphyry copper deposits, and porphyry copper prospects for tract 142pCu7305, Masbate-Negros Arc—Philippines. MY, Malaysia; ID, Indonesia.



## Delineation of the Permissive Tract

### Tectonic Setting

The 400-km-long Masbate-Negros composite arc system (fig. 2A<sup>6</sup>) includes an Eocene to Miocene western arc and a Miocene to Holocene eastern arc, both a result of subduction beneath Negros (Garwin and others, 2005). The older western arc, which was built on oceanic and accretionary basement, extends across several islands from southwestern Negros through east Panay to Masbate (fig. 5B). The polarity of subduction (west or east dipping) for the older arc is unknown, but it may be a northern extension of the Daguma Arc, which forms the older basement for the Cotabato Arc (appendix A) in Mindanao (Pubellier and others, 1991; Sajona and others, 1997, 2000). The younger arc overprints the older arc and is also related to east-dipping subduction at the Negros Trench (fig. 5B). The Masbate-Negros arc system is bounded by the Philippine Fault (fig. 5B) on the north, and by the Sulu-Zamboanga Arc (fig. 2A) on the south.

### Geologic Criteria

The tract was delineated by selecting Neogene intrusions, including mid-Miocene dacite porphyry stocks and dikes and Eocene to Oligocene diorite stocks and andesitic to dacitic volcanic rocks (fig. D2, table D2) that lie within the Masbate-Negros Arc as defined by Garwin and others (2005). These permissive rock units were selected from a digital version of the 1:1,000,000-scale geologic map of the Philippine (Philippine Mines and Geosciences Bureau, 2004a) using GIS tools. and 10- and 2-km buffers were created around intrusive and volcanic rocks, respectively. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand and tract boundaries were checked to include known prospects and permissive igneous rocks shown on maps included in topical studies (Malaihollo and others, 2002). Circular cutouts in the tract represents 10-km areas around the Quaternary stratovolcanoes, where the volcanic cover is likely to be about 1 km thick above any undiscovered porphyry systems. Final tract boundaries were edited by hand to honor fault boundaries and include prospects and dated igneous-rock localities (Malaihollo and others, 2002). As a last step, the tracts were clipped to coastlines (U.S. Department of State, 2009).

In this composite arc system, the mid-Miocene arc rocks intruded and overprinted the Oligocene arc. The Oligocene arc rocks on Negros include the Pagatban Batholith (38.4 and 34.4 Ma ages of diorite) that intrudes andesitic and dacitic rocks (Mitchell and Leach, 1991). On eastern Panay, the pre-Miocene arc rocks include diorites that have intruded andesites (Mitchell and Leach, 1991). The mid-Miocene arc is defined by dacite porphyry stocks and dikes that intrude Oligocene porphyry-copper-related diorites in southwestern Negros and andesites in eastern Panay (Mitchell and Leach, 1991).

### Known Deposits

Five porphyry copper deposits are known within the tract area (fig. D1, table D3). The deposits are aligned along the Southwest Negros mineral district, a mineralized corridor that extends for about 60 km from the Sipalay Group in the northwest to the Basay Group in the southeast (fig. D1). Intersections of two major faults in the district, north-northwest arc-parallel faults and northeast arc-normal faults, may control deposit locations (Vigar and others, 2011). The Aya Aya and Suguibo deposits are relatively small ( $\leq 120,000$  t contained copper) and the authors are unaware of any recent activity at these sites.

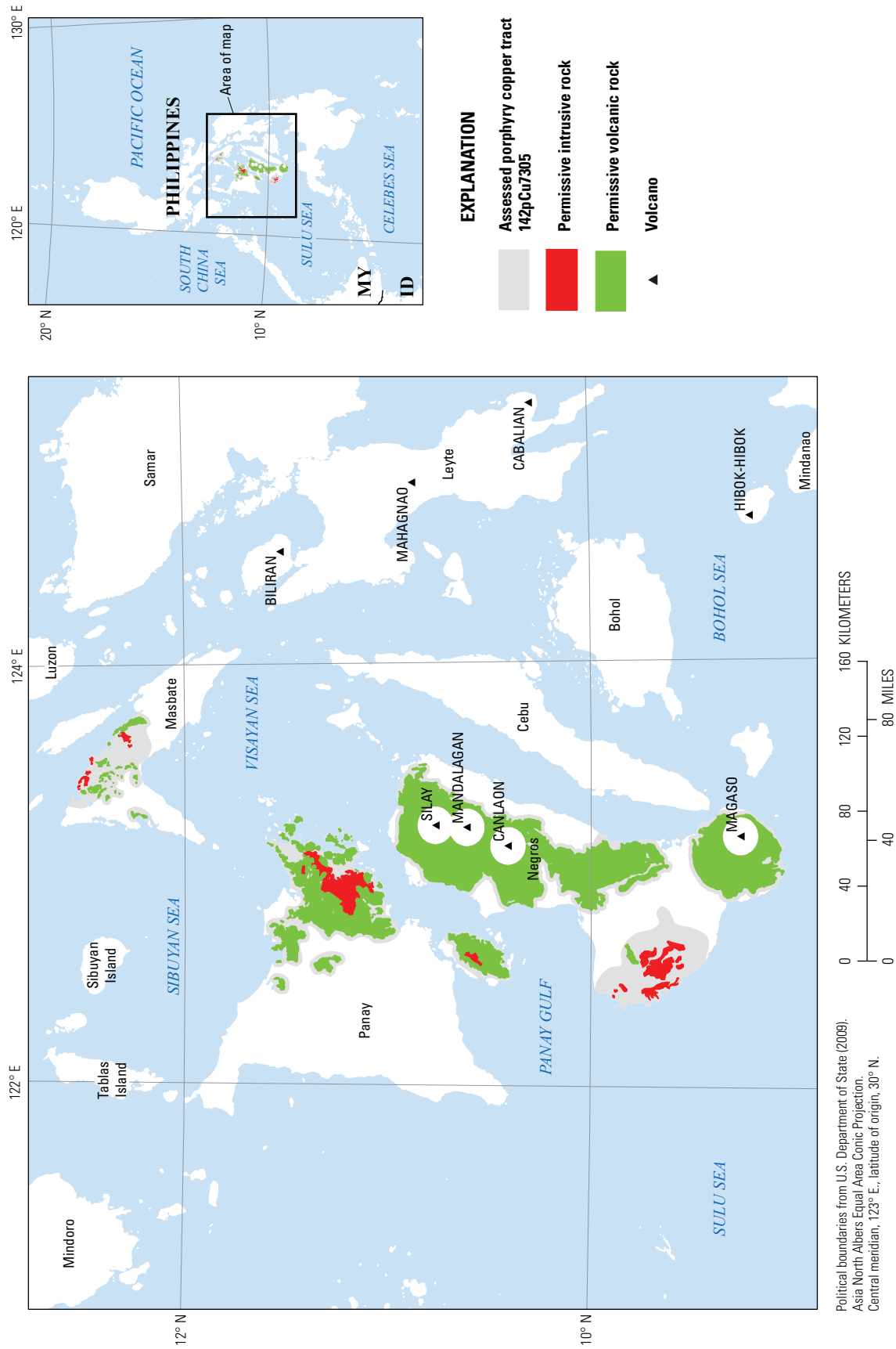
#### Sipalay Group

The largest deposit in the tract is the 30 Ma Sipalay deposit (807 Mt, 0.473 percent copper). Sipalay was discovered in 1936; production started in 1957. The mine was closed in 2002, leaving in-place resources of 642 Mt at 0.41 percent copper (Vigar and others, 2011). In the mine area, multiphase Eocene-Oligocene diorite intrudes metavolcanic rocks. The mine pit area is at the intersection of nearly perpendicular faults. Ore minerals are disseminated in diorite; supergene enrichment is variable within the three ore bodies at Sipalay (Philippines Bureau of Mines and Geosciences, 1986). The Sipalay Group includes Baciao and Cansibat-Bunuliog and also is known as Colet or Maracalum.

#### Hinoba-an Group

The 17.5 Ma Hinoba-an deposit lies about 25 km north of Basay (fig. D1). The Hinoba-an project includes the Colet area that was explored as one of 23 National Priority Projects under the Philippines Revitalization Program of the Minerals Industry. Singer and others (2008) reported resources for the Hinoba-an deposit as 432 Mt at 0.367 percent copper,

<sup>6</sup>Refer to figures and tables in main report.



**Figure D2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7305, Masbate-Negros Arc—Philippines. MY, Malaysia; ID, Indonesia.

**Table D2.** Map units that define tract 142pCu7305, Masbate-Negros Arc—Philippines.

[Map unit, age range, and principal lithologies are based on a digital compilation of the 1963 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene rock sequences. Neogene	Neogene
Volcanic rocks			
Pliocene-Quaternary volcanic rocks	QV	Nonactive cones (generally pyroxene andesite); also dacitic and (or) andesitic plugs.	Pliocene-Quaternary
Neogene volcanic rocks	IN <sub>2</sub>	Principally dacite and/or andesite flows, generally with pyroclastics.	Late Miocene-Pliocene
Paleogene volcanic rocks	IP <sub>g</sub>	Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin. Undifferentiated from early Miocene sedimentary rocks in some areas.	Oligocene

**Table D3.** Porphyry copper deposits in tract 142pCu7305, Masbate-Negros Arc—Philippines.

[\*, See text for discussion of other resource estimates for these deposits. Ma, million years; Mt, million metric tons; %, percent; t, metric ton; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data; NA, not applicable. Contained Cu in metric tons is computed as (Mt × 1,000,000) × (Cu grade, % ÷ 100). Age, based on midpoint of age range reported by Singer and others (2008)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Aya Aya	9.433	122.700	NA	19.5	40	0.30	0.022	0.08	1.5	120,000	Divis (1983), Sillitoe and Gappe (1984), Singer and others (2008)
Basay Group*	9.481	122.682	Cu-Au	30.0	262	0.44	0.008	0.29	1.5	1,152,800	Jacinto and Hofilena (1981), Motton (2009), Saegert and Lewis (1976), Sevillano and Fernando (1981), Singer and others (2008), Vigar and others (2011)
					131.1	0.48	n.d.	n.d.	n.d.	629,280	Copper Development Corporation (2012)
Hinoba-an Group*	9.719	122.562	NA	17.5	432	0.367	n.d.	0.14	0.34	1,585,440	Border and others (2003), Copper Resources Corp. (2005), Divis (1983), Malicdem (1974), Motegi (1977), Sillitoe and Gappe (1984), Singer and others (2008)
					339	0.35	n.d.	n.d.	n.d.	1,186,500	Copper Development Corporation (2012)

**Table D3.** Porphyry copper deposits in tract 142pCu7305, Masbate-Negros Arc—Philippines.—Continued

[\*, See text for discussion of other resource estimates for these deposits. Ma, million years; Mt, million metric tons; %, percent; t, metric ton; g/t, gram per metric ton; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data; NA, not applicable. Contained Cu in metric tons is computed as  $(Mt \times 1,000,000) \times (Cu \text{ grade, \%} \div 100)$ . Age, based on midpoint of age range reported by Singer and others (2008)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Sipalay-Group	9.818	122.456	NA	30.0	807	0.473	0.0139	0.05	1.5	3,817,110	Divis (1983), Domingo (1980), Kinkel and others (1956), Philippine Mines and Geosciences Bureau (2007), Motegi (1977), Philippine Mines and Geosciences Bureau (1986), Sillitoe and Gappe (1984), Singer and others (2008,) Walther and others (1981)
Suguibon	9.567	122.633	NA	n.d.	26	0.35	0.015	n.d.	n.d.	91,000	Divis (1983), Sillitoe and Gappe (1984), Singer and others (2008)

0.14 g/t gold, and 0.34 g/t silver based on a 0.2 percent copper cutoff grade. JORC-compliant total resources announced by Copper Development Corporation (2012) in June 2012 are 339.0 Mt at 0.35 percent copper (also based on a 0.2 percent copper cutoff grade). Table D3 lists the data of Singer and others (2008), because those data include byproduct grades that are not available for the new resource estimates and because of uncertainties in the comparing the areas included in the two different resource estimates. The deposit, which was at the prefeasibility stage of development in 2005, was held by Copper Development Corporation in 2012 and was proposed for development as an open-pit mine with a conventional flotation plant.

The Hinoba-an project area includes two deposits within 1 km of each other (Don Jose, also known as DJ, and A1, also known as Mantoboy) that are both along a north-northwest fault zone and within a large alteration zone (mainly phyllic and argillic) in quartz diorite of the Pagatban Intrusive Complex. The main ore minerals are disseminated chalcopyrite and minor amounts of bornite and chalcocite (Border and others, 2003). The Luz porphyry, about 2 km from Hinoba-an, was drilled in 2009 by Vulcan Industrial and Mining Corporation resulting in an announcement of inferred resources of 33.4 Mt at 0.38 percent copper; further exploration may expand this area as a separate development project (Vigar and others, 2011).

### Basay Group

The Basay porphyry copper deposit produced ore from 1979 to 1983. The property currently (2012) is part of an 18 km<sup>2</sup> exploration project by Copper Development Corporation and Solfotara Mining Company. Singer and others (2008)

reported the total resources for Basay, including Nabuangan and Bunkville, as 262 Mt at 0.44 percent copper, 0.008 percent molybdenum, 0.29 g/t gold, and 1.5 g/t silver, citing 1980s-era data (table D3). Historical noncompliant resources estimates for the period 1975–1983 compiled by Vigar and others (2011) vary and do not include data for molybdenum, gold, silver, or rhenium; for example, historical resources of 230 Mt at an average grade of 0.44 percent copper and reserves of 129 Mt of 0.48 percent copper were reported in 1983. Initial JORC-compliant gross inferred mineral resources of 131.1 Mt at 0.48 percent copper (0.25 percent copper cutoff grade) were announced in March 2012 for four deposit areas in and around the historical open pit, based on historical and new drilling (Copper Development Corporation, 2012). All four areas are open along strike and at depth, and step-out and deeper work was planned to update resource statements. According to Vigar and others (2011), the areas within the current Basay project area may represent only part of a much larger porphyry system. Table D3 lists of data of Singer and others (2008), with the caveat that the deposit is open and that resource estimates are likely to change.

The Basay deposit(s) are in hornblende diorite, quartz diorite, and monzonite stocks that have intruded andesitic to dacitic volcanic rocks. The primary ore minerals are chalcopyrite and molybdenite. A supergene zone estimated to be about 40 m thick and containing about 4 Mt of 0.69 percent copper is present at one of the four target areas, the Nabore deposit, which is on an uneroded plateau about 1 km south of the open pit. The other areas are proximal to the open pit within eroded valleys and apparently lack supergene enrichment zones (Vigar and others, 2011).

## Prospects, Mineral Occurrences, and Related Deposit Types

The tract includes 7 prospects, some of which have been recently explored (fig. D1, table D4). The Manlupo prospect lies along a northwest trend between the Aya Aya and Basay copper deposit to the south and the Hinoba-an and Sipalay deposits to the north on Negros (fig. D1). The Ayungon and Masbate prospects on Negros are being explored to develop drill targets (Geograce Resources Philippines, Inc., 2010). The Pan de Azucar project area includes a polymetallic target (Valderama) and a potential porphyry copper-gold target at depth at (Asparin Hill); most of the drilling has focused on the Valderama massive pyritic sulfide target (Mindoro Resources, Ltd., 2012; Abrasaldo and Climie, 2003).

## Exploration History

The tract area was explored in the 1980–1990s time-frame. Recent changes in Philippine mining law have encouraged new exploration and reevaluation of previously explored areas. Although there have been several exploration projects in the area, no large-scale mines have been developed. Yumul and others (2008) mention Panay as an attractive exploration area for copper and gold, and a need for further studies and reevaluations in the area. Garwin and others (2005) suggested that there may be potential for buried porphyry copper deposits in the eastern Masbate-Negros Arc where there are indications of upper parts of high-sulfidation epithermal systems. A number of companies were reevaluating properties and drilling the tract area 2010–2012.

## Sources of Information

Table D5 list the principal sources of information used in the assessment.

## Grade and Tonnage Model Selection

The Basay deposit is classified as a copper-gold porphyry deposit (gold greater than 0.2 g/t and gold:molybdenum greater than 30). The other four deposits are less gold-rich and could be classified as the general porphyry type using reported grades (Singer and others, 2008). Garwin and others (2005)

referred to Sipalay and Hinoba-an as gold-poor, copper-molybdenum deposits. Statistical tests based on the grades and tonnages for the known deposits supported a general model and failed the copper-gold subtype model for both molybdenum and gold grade (table 5). As a result, the general porphyry model was adopted for the simulation of undiscovered resources in the tract.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

On the basis of the northwest-trending distribution of the five known deposits in the southern part of Negros (fig. D1), the occurrence of additional prospects there, and along the trend of the arc to the north, the assessment team estimated a 50-percent chance of two or more deposits, a 10-percent chance of four or more deposits, and a 5-percent chance of five or more deposits (table D6). The tract includes the partially explored Ayungon and Manlupo porphyry prospects and five additional known project areas (table D4). Buried deposits may be present under volcanic cover, especially in the younger, eastern parts of the tract.

## Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the general porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Span-ski, 2012). Selected simulation results are reported in table D7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. D3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. Mean estimated copper resources (7.8 Mt) are about 1 Mt greater than the identified copper resources (approximately 6.8 Mt) in the tract. See table 6 of the main report for comparisons with identified copper and gold resources and with other tracts.

**Table D4.** Significant prospects and occurrences in tract 142pCu7305, Masbate-Negros Arc—Philippines.

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

<b>Name</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Age</b>	<b>Comments</b>	<b>Reference</b>	<b>Rank</b>
Ayungon Copper/ Gold Project	9.900	123.120	Oligocene-early Miocene (?)	Explored 1989–1991; 2008 re-evaluation for potential large, low- to medium-grade porphyry system at depth beneath hydrothermally-altered andesite.	Geograce Resources Philippines, Inc. (2010)	2
Pan de Azucar Copper/Gold Project	11.516	123.174	Oligocene-early Miocene (?)	Volcanic caldera. Asparin Hill porphyry copper-gold prospect. Exploration results (including drilling) suggest potential buried porphyry system, but not proven. Propylitized andesite with disseminated chalcopyrite, quartz-magnetite alteration, positive magnetic anomaly.	Abrasaldo and Climie (2003), Mindoro Resources, Ltd. (2010, 2012), Rusina Mining NL (2010)	2
Manlupo	9.667	122.583	Oligocene-early Miocene (?)	Porphyry copper prospect 25 km north of Basay; resource estimate of 81.5 Mt at 0.42% Cu	Vigar and others (2011)	4
Guimaras Gold/ Silver/Copper Project	10.436	122.535	Oligocene-early Miocene (?)	Low-sulfidation epithermal Au-Ag and porphyry copper prospect area.	Rusina Mining NL (2010)	1
Inayawan	9.850	122.450	Oligocene-early Miocene (?)	Porphyry copper prospect associated with volcanoclastic sedimentary rocks.	Philippines Mines and Geosciences Bureau (2004, written commun.)	1
Masbate Gold/ Copper Project	12.380	123.560	Oligocene-early Miocene (?)	Cretaceous to early Miocene volcanic and sedimentary units intruded by dioritic to andesitic porphyry intrusions west of the Philippine Fault. Cu hosted in dioritic intrusions; alteration halos (silicification).	Geograce Resources, Philippines, Inc. (2010)	1
Umas-Mambuyang	9.831	122.500	Oligocene-early Miocene (?)	Au, Cu vein occurrence in diorite	U.S. Geological Survey (2012)	1



**Table D5.** Principal sources of information used for tract 142pCu7305, Masbate-Negros Arc—Philippines.

[NA, not applicable]

Theme	Name or Title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Bureau of Mines and Geosciences (2004b)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data (MRDS)	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Region 6 Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites and technical reports	NA	See tables D3 and D4.

**Table D6.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7305, Masbate-Negros Arc—Philippines.

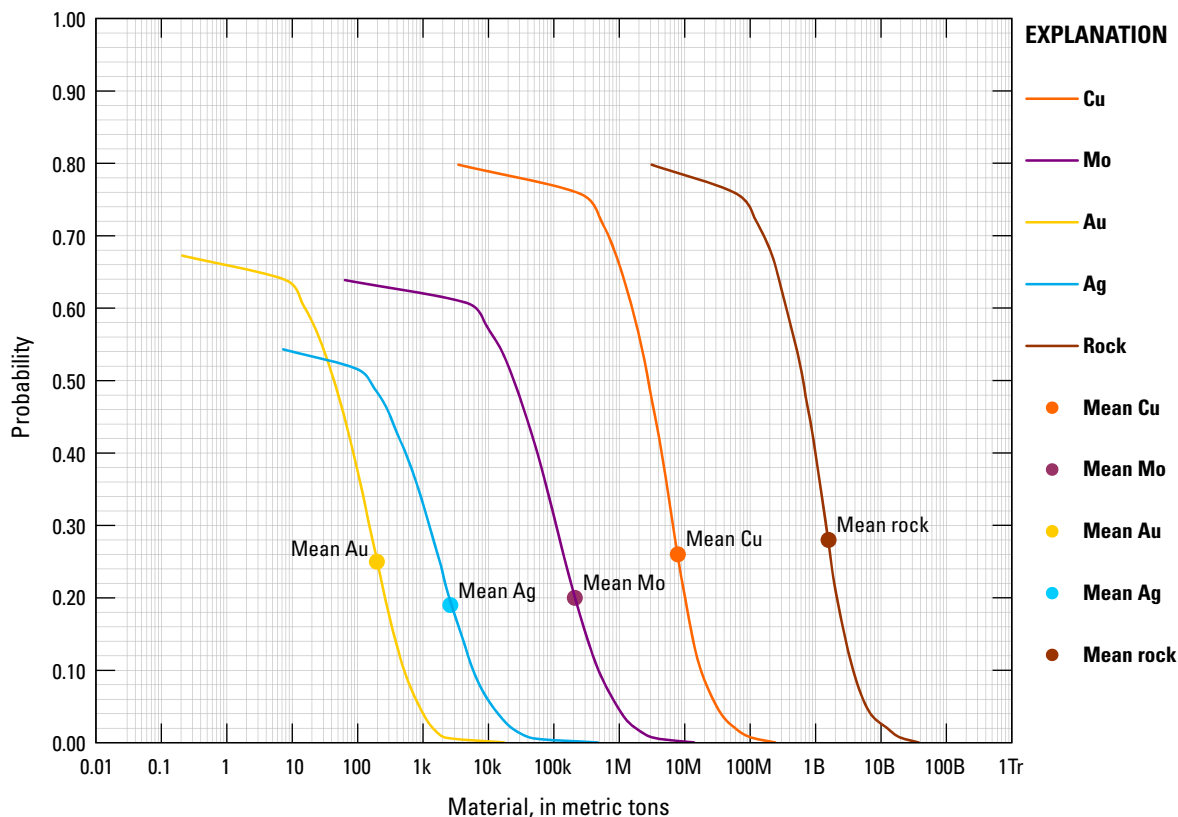
[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model; 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

Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $\text{km}^2$ )	Deposit density ( $N_{total}/100,000 \text{ km}^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
0	2	4	4	4	2	1.5	73	5	7	12,230	57

**Table D7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7305, Masbate-Negros Arc—Philippines.

[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	2,800,000	18,000,000	31,000,000	7,800,000	0.26	0.20
Mo	0	0	25,000	480,000	950,000	210,000	0.20	0.36
Au	0	0	44	520	850	200	0.25	0.33
Ag	0	0	150	5,900	12,000	2,600	0.19	0.46
Rock	0	0	640	3,700	6,100	1,600	0.28	0.20



**Figure D3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7305, Masbate-Negros Arc—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix E. Porphyry Copper Assessment for Tract 142pCu7309, Philippine Arc—Philippines

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### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table E1 summarizes selected assessment results.

**Table E1.** Summary of selected resource assessment results for tract 142pCu7309, Philippine Arc—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified copper rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	23,700	6,300,000	24,000,000	15,000,000

### Location

Eastern Philippines, extending from the Bicol Peninsula of southeastern Luzon Island southwards through Leyte and along eastern Mindanao (fig. E1).

### Geologic Feature Assessed

Oligocene to Holocene Philippine Arc.

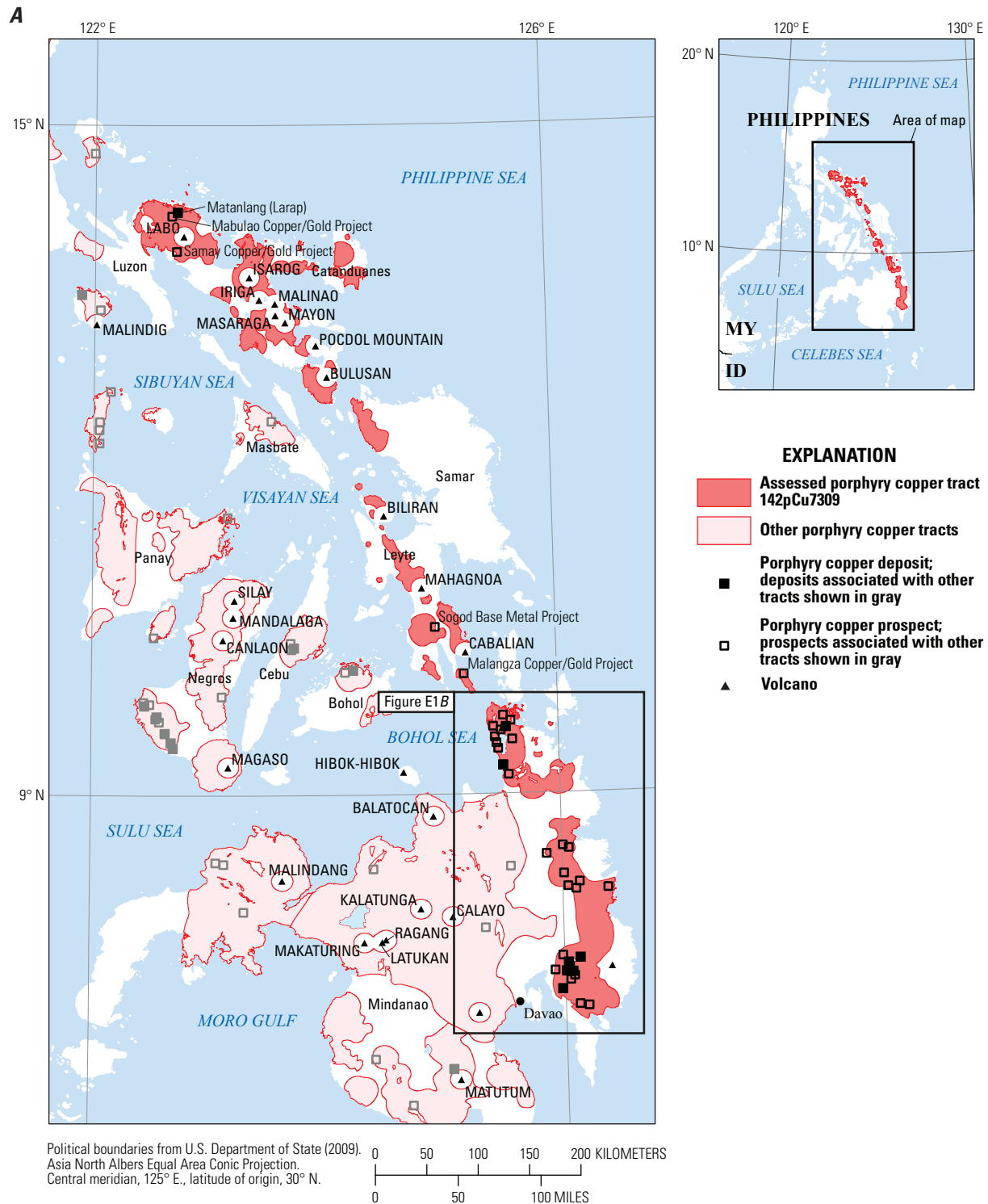
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<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure E1.** Maps showing tract location and significant porphyry copper prospects for tract 142pCu7309, Philippine Arc—Philippines. *A*, Map of entire tract; *B*, map of eastern Mindanao. MY, Malaysia; ID, Indonesia.



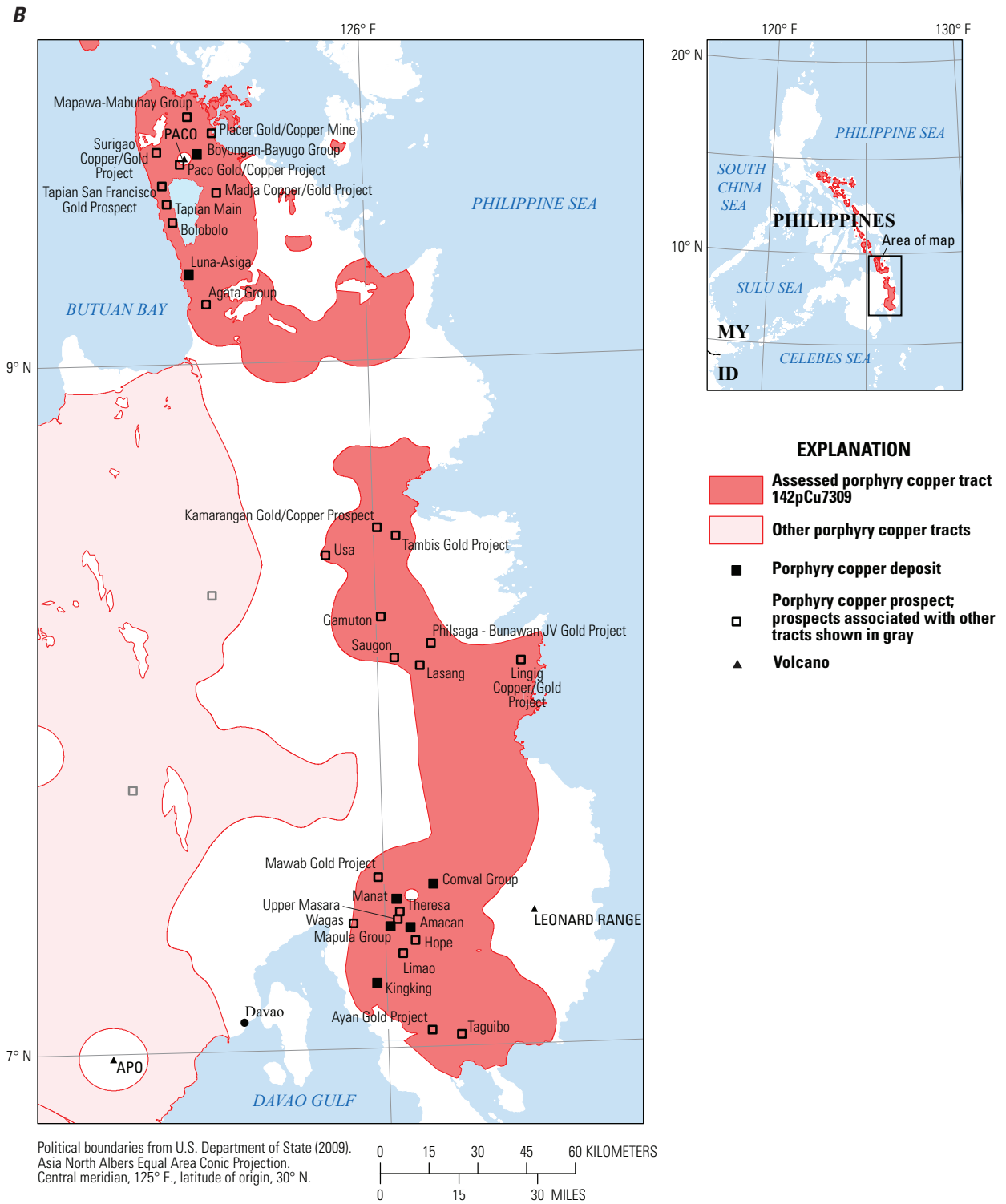


Figure E1.—Continued

## Delineation of the Permissive Tract

### Tectonic Setting

The 1,000-km-long Oligocene to Holocene Philippine Arc extends from Bicol to eastern Mindanao, parallel to the Philippine Fault (fig. 5B<sup>6</sup>). Arc magmatism is related to west-directed subduction of the Philippine Sea Plate at the Philippine Trench (fig. 5B). Arc segments (fig. E2), from north to south, are (Yumul and others, 2008):

- *Bicol (northern) segment*—medium- to high-K calc-alkalic rocks, high-Al basalts and andesites
- *Leyte segment*—a 250-km-long, southeast-trending belt of Plio-Pleistocene volcanoes characterized as medium- to high-K calc-alkalic rocks, Miocene andesitic rocks
- *Northeastern Mindanao segment*—Lower Oligocene–Lower Miocene rocks and Pliocene–Quaternary andesites

The level of erosion generally increases from north to south on the basis of the relative amounts of mapped volcanic and intrusive rocks (fig. E2). The Bicol arc segment includes several Quaternary volcanoes. The Leyte segment is mostly defined by permissive volcanic rocks, and the northeastern Mindanao segment is mainly defined by scattered intrusions.

### Geologic Criteria

The tract outlines the mapped extent of Paleogene and Neogene intrusions, including diorite complexes, and Oligocene–Miocene andesitic volcanic rocks (fig. E2, table E2). The tract includes Late Pliocene intrusions associated with porphyry deposits in northeastern Mindanao. Parts of the tract are overlain by Pliocene–Quaternary volcanic cover (map units QVP and QV, not shown on fig. E2). The Philippine Fault Zone forms the western boundary of the tract, which extends to the coast of eastern Mindanao.

The tract was constructed by selecting permissive Eocene to Holocene igneous rocks that lie within the Philippine Arc as defined by Garwin and others (2005) from the digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines and Geosciences, 2004a). A preliminary tract was constructed by using GIS tools to make 10- and 2-km buffers around intrusive and volcanic rocks, respectively. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand and tract boundaries were checked to include known prospects and permissive igneous rocks shown on maps included in topical studies (Malaihollo and others, 2002). Circular cutouts in the tract represent areas around the Quaternary stratovolcanoes, where the thickness of

volcanic cover is likely to be greater than 1 km thick above the tops of undiscovered porphyry systems. Final tract boundaries were edited by hand to honor fault boundaries and include prospects and dated igneous-rock localities (Malaihollo and others, 2002). As a last step, the tracts were clipped to coastlines (U.S. Department of State, 2009).

Deposits and prospects (figs. E1, E2) do not always overlie permissive mapped igneous rocks. This is an effect of map scale (1:1,000,000). Many of the intrusions associated with porphyry copper deposits, if exposed at all, crop out over an area of greater than 1 km<sup>2</sup>. The 1:50,000-scale geologic maps series for the Philippines shows more detail. Spot checks of available 1:50,000-scale maps show that small intrusions of permissive rocks lie within the tract boundaries based on the smaller scale maps.

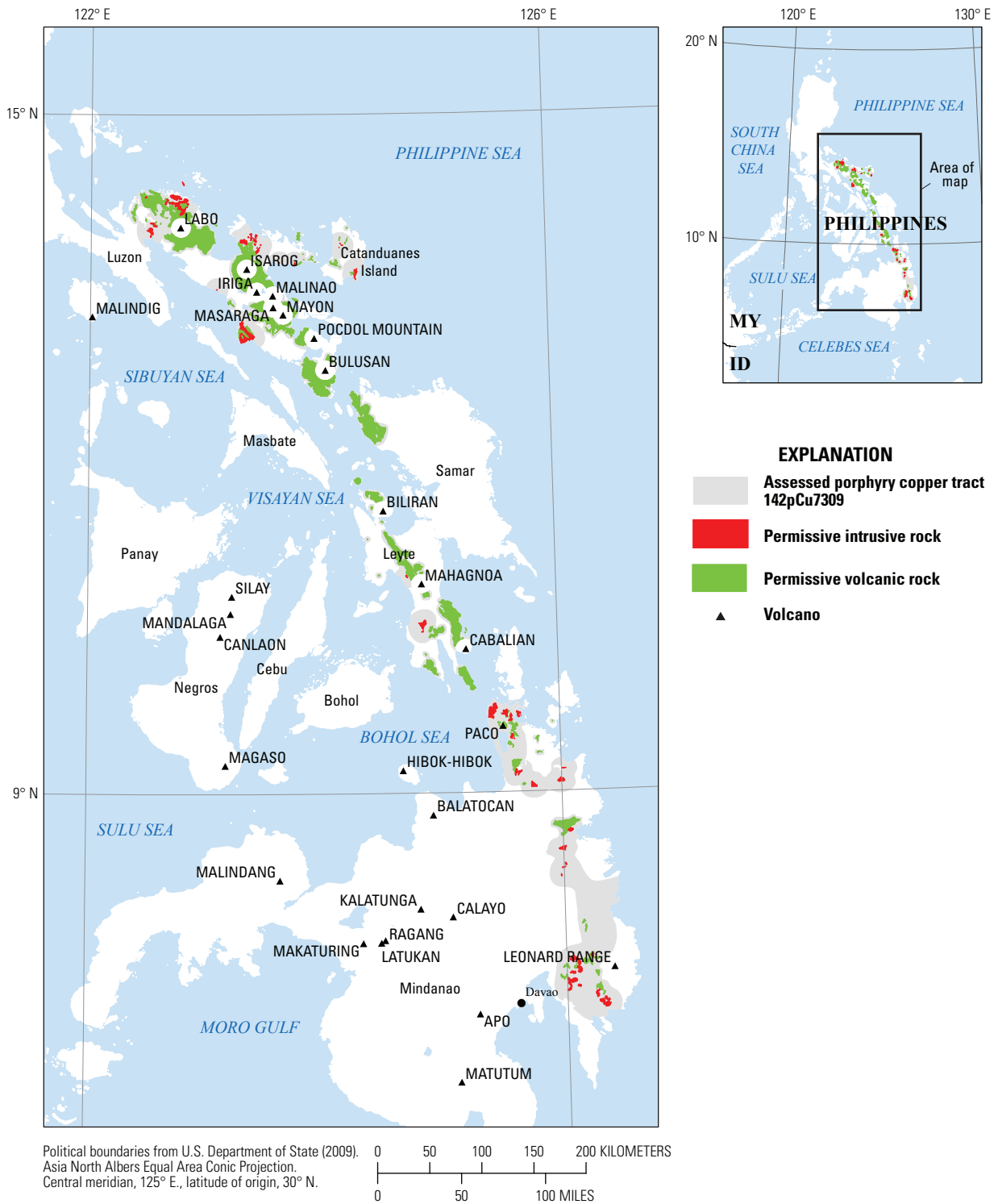
### Known Deposits

The tract includes 8 porphyry copper deposits that range in age from 4 Ma at Boyongan to 21 Ma at Matanlang (table E3). Characteristics of the larger deposits in the tract are described below. Data reported for Mapula represent 1963–1980 era drilling; historical data are listed for Kalamatan and Taagpura–Maangob as reported by Singer and others (2008). Taagpura–Maangob was mined by open-pit methods from 1978–1981. However, these two deposits remain open and are currently under exploration as part of the Comval Group (fig. E1, table E4). Inferred resources reported in 2013 for the Comval copper-gold project (32.675 Mt at 0.42 percent copper and 0.13 g/t gold for greater than 0.3 percent copper) include the Maangob, Kalamantan, Tagpura West, and Tagpura East target areas within a 4,310 hectare (ha) exploration area (Cadan Resources, 2013). The additional resources suggest that the total contained copper for the group may be on the order of 560,000 t.

### Boyongan–Bayugo Group

The Boyongan deposit has the highest average copper grade (0.82 percent copper) of all the deposits within the Philippine Arc. The high grade reflects the ultra-deep oxidation zone (600 m thick), which is the deepest oxidation reported for a porphyry system anywhere in the world (Braxton and others, 2009). This oxidation profile is especially unusual for a humid tropical setting where most oxidation profiles are less than 100 m thick. The deposit was preserved under 50–350 m of postmineral cover. The local physiographic conditions allowed a thick supergene zone to form at Boyongan, in contrast to the adjacent Bayugo deposit, where the zone is about 70 m thick. The deposits are associated with the multiple diorite intrusive complexes and were discovered by exploration in the late 1990s along a belt of intrusion-centered gold-rich porphyry deposits in northeastern Mindanao.

<sup>6</sup>Refer to figures and tables in main report.



**Figure E2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7309, Philippine Arc—Philippines. MY, Malaysia; ID, Indonesia. The Philippine arc is divided into three segments—the Bicol segment extends northwestward from Samar Island, the Leyte segment covers the central part of the arc, and the Mindanao segment extends southeastward from northern Mindanao Island.

**Table E2. Map units that define tract 142pCu7309, Philippine Arc—Philippines.**

[Map unit, age range, and principal lithologies are based on a digital compilation of the 1963 1:1,000,000 scale geologic map of the Philippines (Philippine Bureau of Mines, 1963)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene rock sequences.	Neogene
Paleogene intrusive rocks	Pg <sub>1</sub>	Mostly quartz diorite.	Paleogene
Volcanic rocks			
Neogene volcanic rocks	IN <sub>2</sub>	Principally dacite and (or) andesite flows, generally with pyroclastics. Sporadic in north Luzon. Locally thick and associated with reef limestone lenses in southern Zamboanga.	Late Miocene-Pliocene
Neogene volcanic rocks	IN <sub>1</sub>	Mostly submarine andesite and (or) basalt flows. Intercalated with pyroclastics and clastic sedimentary rocks and/or reef limestone lenses. Largely confined within the axial zone of Luzon, Visayas, and Mindanao.	Oligocene-Miocene
Paleogene volcanic rocks	IPg <sub>2</sub>	Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin. Undifferentiated from early Miocene sedimentary rocks in some areas.	Oligocene
Paleogene volcanic rocks	IPg <sub>1</sub>	Limited dacite and andesite flows and dikes, generally intercalated with and/or intrude Eocene clastics. Included with Eocene sedimentary rocks in this map.	Paleocene(?)–Eocene

### Kingking

The Kingking deposit, which is exposed at the surface, is located between two splays of the Philippine Fault. Copper and gold are associated with a 1,800 by 400 m, northwest-striking, elongated Miocene diorite complex that has intruded pyroclastic rocks, andesite flows, and intercalated sedimentary rocks (Hester and others, 2010). In the main intrusion, a biotite diorite porphyry, the principal ore mineral is bornite. The hydrothermal alteration at Kingking differs from many other Philippine porphyry copper deposits in several aspects (Hester and others, 2010)—(1) biotite and potassic alteration zones are well-developed; (2) a phyllic (quartz-sericite-pyrite) zone is absent and replaced by a quartz-sericite-chlorite, so the deposit has a low pyrite content; (3) epidote occurs in all alteration zones, not only in the propylitic zone; and (4) advanced argillic alteration is only developed locally along structures outside the main ore zone.

The deposit was first drilled in the late 1960s and had a tonnage estimate of 93 Mt at that time. The most recent resources announced are total (measured, indicated, and inferred) resources of 1,151 Mt at 0.25 percent copper and 0.32 g/t gold (Hester and others, 2010). About a third of the resource is oxide ore in a 230 m thick supergene zone with an average grade of 0.62 percent copper (Braxton and others, 2009). As of May 2012, the deposit was in the initial phases of permitting for development (St. Augustine Gold and Copper Limited, 2012).

### Amacan

The exposed Amacan deposit was staked in 1963 and operated as an open-pit mine from 1982 until 1992. The mine produced 50 Mt of ore averaging 0.39 percent copper and 0.30 g/t gold. Drill-indicated reserves of 65 Mt at 0.34 percent copper and 0.412 g/t gold remain. The mine closed due to low copper prices, decreasing copper grades, and operational issues.

**Table E3.** Porphyry copper deposits in tract 142pCu7309, Philippine Arc—Philippines.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent. Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as  $(Mt \times 1,000,000) \times (Cu \text{ grade, \%} \div 100)$ . Deposits are listed from north to south. \*, Historical resource estimates reported by Singer and others (2008); these are part of the Comval copper-gold prospect area shown on figure E1B. Age, based on mid-point of age range reported by Singer and others, 2008]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Matanlang (Larap)	14.233	122.733	Cu-Au	20.5	65	0.35	0.005	0.40	n.d.	227,500	Frost (1959), Mitchell and Leach (1991), Sillitoe and Gappe (1984), Singer and others (2008), Uriate (1972)
Boyongan-Bayugo Group	9.605	125.554	Cu-Au	3.5	244	0.82	n.d.	0.83	n.d.	2,000,800	Anonymous (2001a,b), Anonymous (2001c), Anonymous (2002), Braxton and Cooke (2005), Braxton and others (2009), Feebrey (2001), Ferreira (2008, 2009), Josef (2002), Philippine Mines and Geosciences Bureau (2007), Singer and others (2008)
Luna-Asiga	9.258	125.523	NA	3.5	26	0.36	0.01	n.d.	n.d.	93,600	Mitchell and Leach (1991), Sillitoe and Gappe (1984), Singer and others (2008)
Kalamatan*	7.504	126.130	Cu-Au	n.d.	26	0.34	n.d.	0.37	n.d.	88,400	Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008), Sur American Gold Corp. (2007)
Tagpura-Maangob*	7.476	126.131	Cu-Au	n.d.	76	0.44	0.008	0.50	4	332,640	Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008), Society of Economic Geologists (1999), Sur American Gold Corp. (2007)
Mapula Group	7.355	126.014	Cu-Au	10.0	78	0.40	n.d.	0.37	3.6	312,000	Bolaño (2010), Fernandez (1986), Saegart and Lewis (1976), Sillitoe and Gappe (1984), Singer and others (2008)
Amacan	7.350	126.067	Cu-Au	10.0	110	0.37	n.d.	0.40	2.5	407,000	Fernandez (1986), Mercado and others (1987), Philippine Mines and Geosciences Bureau (2007), Mitchell and Leach (1991), Sillitoe and Gappe (1984), Singer and others (2008)
Kingking	7.192	125.975	Cu-Au	10.0	1,151	0.25	n.d.	0.32	5	2,877,500	Almogela (1974), Fernandez (1986), Fortuna (1998), Philippine Mines and Geosciences Bureau (2007), Mitchell and Leach (1991), Philippine Society of Mining Engineers (2007), Sillitoe (1989), Sillitoe and Gappe (1984), Singer and others (2008), St. Augustine Gold and Copper, Ltd. (2012)

## Prospects, Mineral Occurrences, and Related Deposit Types

The tract contains 34 prospect areas (fig. E1, table E4) most of which lie in the southernmost segment of the Philippine Arc in eastern Mindanao. Many of these prospects are relatively recent, early stage exploration targets that have not been confirmed by drilling. Prospects include partially drilled deposits, grass roots exploration targets, epithermal gold deposits or prospects that have some indications of a possible associated porphyry system, and copper occurrences that reportedly represent porphyry-copper types (C. Manipon, written commun., 2004). For example, the Tapian Main and Tapian San Francisco porphyry prospects are in an area mined for gold before World War II, where 1990s-era stream-sediment and soil geochemical anomalies and mapped alteration prompted further interest. Prospects within the tract are listed from north to south in table E4.

## Exploration History

The tract area was explored in the 1960s and has recently (late 1990s to present) been the focus of another round of exploration. Discovery of the buried Boyongan deposit prompted exploration interest in eastern Mindanao for additional targets. Historical epithermal gold districts described by Mitchell and Leach (1991) in the Eastern Mindanao Gold Province (Surigao, Central, and Masara districts on fig. E1) are a focus of recent exploration for porphyry systems at depth below epithermal vein systems or adjacent to such deposits.

## Sources of Information

Principal sources of information for this assessment are listed in table E5.

## Grade and Tonnage Model Selection

The porphyry copper-gold subtype model is appropriate for the assessment, as indicated by the statistical tests (table 4), although the deposits also fit a the general model. Molybdenum grades are available for only three of the deposits, so the general model was rejected. Historical tonnages reported in the older literature are not compliant with modern reporting standards; some of these “deposits” are being reevaluated and are almost certainly “open” in one or more directions.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The tract contains 34 prospects that include known porphyry copper prospects, exploration projects targeting porphyry copper/gold systems, and some gold exploration targets that may overlie or lie adjacent to porphyry systems. Recent exploration projects are targeting buried systems; the Boyongan deposit, for example, is covered by 50 to 300 m of lake sediments and lava flows. Indications that additional



**Table E4.** Significant prospects and occurrences in tract 142pCu7309, Philippine Arc—Philippines.

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares; ppm, parts per million; SCC, sericite-chlorite-clay. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Bicol arc segment						
Mabulao Copper/ Gold Project	14.200	122.683	Neogene	Exploration project in Paracele old mining district, ~7 km SW of 20.5 Ma Matanglan (Larap) porphyry copper-gold deposit. Explored 1960.	Altai Resources, Inc. (2003)	3
Samay Copper/ Gold Project	13.886	122.727	Neogene	Exploration on epithermal veins and potential porphyry copper at depth on property explored by Phelps/Dodge in 2004–2005. Drill targets in argillic alteration zones.	RoyalCo Resources, Ltd. (2006)	2
Leyte arc segment						
Sogod Base Metal Project (Leyte)	10.520	124.960	Neogene	Epithermal gold and porphyry copper-gold early exploration project on southern Leyte in large areas of hydrothermal alteration, geochemical anomalies.	Indophil Resources NL (2002)	1
Malangza Cop- per/Gold Project	10.095	125.204	Neogene	Exploration project for epithermal gold-porphyry system based on hydrothermally-altered area; drilling was targeted for 2008; outcome unknown.	RoyalCo Resources, Ltd. (2010)	1
Northeast Mindanao arc segment						
Mapawa- Mabuhay Group	9.712	125.530	Neogene	Mapawa exploration target: diorite-hosted copper-gold porphyry system with intact cap in altered andesite; drill intercepts 53 m of 0.2% Cu, 0.8 g/t Au, and 2.4 g/t Ag. Mabuhay: Old gold mine (underground 1957 to 1953; open pit 1995–2000); exploration target for a deep porphyry copper-gold system associated with high-sulfidation epithermal gold deposit; drill intercept (1 hole) 243 m of 0.227% Cu, 0.24 g/t Au, and 0.0088% Mo. Drilling to 770 and 1,000 m in other holes encountered only weakly altered diorite, possible diatreme breccia.	Red 5 Limited (2010), Rugby Mining, Ltd. (2011a, b; 2012)	3
Placer Gold/ Copper Mine	9.664	125.595	Miocene (?)	Small, low-grade porphyry copper mineralization in SCC-altered basaltic to andesitic flows with chalcocopyrite± molybdenite, pyrite, magnetite, and hematite in veinlets. May be mid- to late Miocene.	Manila Mining Corporation (2010), Mitchell and Leach (1991)	1
Surigao Copper/ Gold Project (MAT-I)	9.612	125.445	Neogene	Exploration project area on Eastern Mindanao Ridge. Cu-Au soil anomalies. Historical artisanal gold mining area.	Oz Minerals Ltd. (2010), Bailey (2003)	2

**Table E4.** Significant prospects and occurrences in tract 142pCu7309, Philippine Arc—Philippines.—Continued

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares; ppm, parts per million; SCC, sericite-chlorite-clay. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Kalaya-an Copper/Gold Project	9.611	125.545	Neogene	Exploration area adjacent to (north of) Boyongan project area. Diorite porphyry dikes; breccias.	Manila Mining Corporation (2010)	1
Paco Gold/Copper Project	9.576	125.507	Neogene	Adjacent to the porphyry copper-gold deposits at Boyongan and Bayugo. Geophysical data suggest similar structural settings at Paco with potential for porphyry-epithermal systems. Reconnaissance drilling has so far failed to penetrate the overlying Quaternary cover to test targets.	Oceana Gold Corporation (2010)	2
Tapian San Francisco Gold Prospect	9.515	125.457	Neogene	Porphyry Cu-Au prospect along NE-trending lineaments towards Boyongan and Bayugo. Partly overlaps 6 km intrusive complex (Masgad porphyry and Mayag porphyry). Induced polarization anomalies, drilled intercepts of >20 m of 1.01% Cu, 0.56 g/t Au, 19.02 g/t Ag. Cu, Au, Zn soil anomalies. Altered andesite (propylitic, argillic, phyllic, potassic).	Mindoro Resources, Ltd. (2010), Rohrlach (2005)	4
Madja Copper/Gold Prospect	9.493	125.604	Neogene	Exploration project adjacent to Tapian project area, porphyry Cu-Au target.	Panoro Minerals, Ltd. (2010)	1
Tapian Main	9.462	125.469	Neogene	Exploration project several km S of Tapian San Francisco property; pre-WWII underground gold mining. Soil and stream-sediment Au and Cu anomalies.	Mindoro Resources, Ltd. (2010), Rohrlach (2005), Bailey (2003)	1
Bolobolo	9.409	125.484	Neogene	Structural exploration target S of Tapian Main prospect based on intersections of northeast- to southwest-trending faults with northwest splays of the Philippine Fault. Altered and mineralized float boulders with chalcopyrite and bornite. May be in propylitic halo.	Mindoro Resources, Ltd. (2012)	1
Agata Group	9.172	125.568	Neogene	Cluster of porphyry copper-gold prospects. Artisanal mining of high-grade copper ore from six shafts and tunnels. Multiphase syenite, quartz monzonite. Monzodiorite, diorite intrusions as dikes, sills, and small stocks intruding ultramafic rocks. Potassic, phyllic alteration. Intersections of Philippine Fault splays and cross-cutting faults. Epithermal gold mined at American Tunnels; younger epithermal gold cuts older porphyry-related alteration. Late phyllic and skarn overprint early potassic alteration. Note that there is an Agata nickel laterite deposit nearby.	Mindoro Resources, Ltd. (2010), Rohrlach (2005)	2

**Table E4.** Significant prospects and occurrences in tract 142pCu7309, Philippine Arc—Philippines.—Continued

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares; ppm, parts per million; SCC, sericite-chlorite-clay. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Kamarangan Gold/Copper Prospect	8.515	126.010	Neogene	Ten holes drilled below a large area of variably mineralized magnetite skarn; Cu-Au in diorite and andesite; highest concentrations in skarn. Mo (244 ppm max; average 37, 41 ppm in two holes. Deep magnetic anomaly; possible pencil porphyry at depth.	Medusa Mining, Ltd. (2010, 2013)	3
Tambis Gold Project	8.490	126.060	Neogene	Intermediate sulfidation epithermal gold system (+Ag, ±Zn, ±Cu, ±Pb) in and adjacent to Tambis intrusive breccia complex. Subvolcanic calc-alkaline intrusions cut by diatremes and hydrothermal breccia. Gold mineralized veins to 500 m. Porphyry potential at depth?	Medusa Mining, Ltd. (2010, 2013)	1
Usa	8.439	125.870	Neogene	Cu-Au diorite porphyry target (500 m by 500 m) along the Baroba fault corridor; rock chips to 0.59% Cu and 0.42 g/t Au. Cu and Au anomalies overlie three magnetic highs, interpreted as magnetite alteration in the diorite. Pyrite with bornite, some chalcopyrite.	Medusa Mining, Ltd. (2012)	1
Gamuton	8.257	126.013	Neogene	Drilling to test gold-bearing quartz veins to the west of the Co-O underground epithermal gold mine (located 6 km north of Banawan) intersected intense propylitic alteration with epidote, zones of silicification and hydrothermal breccias associated with strongly anomalous gold contents of approximately 0.5 g/t and anomalous silver values accompanied by irregular chalcopyrite veinlets. Interpreted as indicative of nearby porphyry copper.	Medusa Mining, Ltd. (2012)	2
Philsaga-Bunawan JV Gold Project	8.175	126.145	Neogene	Exploration project - stream sediment sampling	Magnum Mining and Exploration Limited (2006)	1
Saugon	8.137	126.046	Neogene	High grade gold-silver vein target in andesite. Grass roots project for porphyry potential.	Medusa Mining, Ltd. (2010)	1
Lingig Copper/Gold Project (das-Agan)	8.119	126.384	Neogene	Discovered in 1970s, mapping and geochemical surveys, partly drilled (5 hole). Modern exploration defined two targets within a thrust zone: (1) Basalt prospect, thrust-related copper in basalt and (2) Breccia prospect, porphyry style copper mineralization in diorite below the thrust. Breccia prospect drill intercept example: ~155 m of 0.19% Cu and 0.03 g/t Au.	Medusa Mining, Ltd. (2007, 2012)	2
Lasang	8.112	126.114	Neogene	Conceptual porphyry copper target based on aeromagnetic data interpretation	Medusa Mining, Ltd. (2010)	1

**Table E4.** Significant prospects and occurrences in tract 142pCu7309, Philippine Arc—Philippines.—Continued

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares; ppm, parts per million; SCC, sericite-chlorite-clay. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Mawab Gold Project	7.500	125.985	Neogene	Exploration target area; soil geochemistry	Sierra Mining Ltd. (2012)	1
Comval Copper/ Gold Project	7.476	126.131	Neogene	Diorite with quartz stockworks, skarn, and epithermal gold quartz veins cut porphyry and skarn. Copper and gold along the margins of quartz diorite intrusions and associated porphyries. Comval project consists of two tenements (4,310 ha). Inferred resources (2013) of 32.675 Mt at 0.42% Cu and 0.13 g/t Au (for >0.3 % Cu) for the Maangob, Kalamantan, Tagpura West, and Tagpura East target areas. Note that this prospect area includes the historical mines reported in table E3 and additional target areas.	Cadan Resources Corporation (2010a, 2013), Mining Group Limited (2012)	4
Wagas Mapula	7.467	126.083	Neogene	Wagas Mapula Copper Project; surface operation by Apex Exploration and Mining Company, Inc., in the 1970s.	U.S. Geological Survey (2012)	1
Upper Masara	7.467	126.083	Neogene	Copper prospect associated with andesite. Chalcopyrite, bornite.	Philippine Mines and Geosciences Bureau (2004, written commun.)	1
Manat	7.433	126.033	Neogene	Hornblende andesite, hornblende diorite intrusive, basaltic-andesite plagiophyric andesite, and limestone. Exploration by Indophil discovered a new porphyry copper-gold system (drilled 227 m at 0.19% Cu and 0.30 g/t Au) S of the Magas polymetallic vein system.	Indophil Resources (2011)	2
Theresa Group	7.398	126.040	Neogene	Group of 4 prospects within 2 km of each other in the Masara District. Location given is for Theresa. (1) Theresa: Cu prospect associated with quartz diorite. Chalcopyrite, bornite. (2) Kanarubi Cu prospect. (3) Maco Au mine: Exploration project west of Philippine Fault; Miocene diorite and quartz diorite and late Miocene to Pliocene diorite and andesitic plugs and dikes. Quartz sulfide porphyry copper stockworks in mid-Miocene diorite. (4) Panurao: Porphyry Cu-Au deposit mined in 1962–1971. Landslide in 1972 led to mine closure. INCO reported that it mined 200,000 t of ore at 0.8% Cu and 7 g/t Au. May be open at depth.	Crew Gold (2010), Philippine Mines and Geosciences Bureau (2004, written commun.), Philippine Mining Development Corporation (2010)	3
Hope	7.312	126.079	Neogene	Copper prospect associated with quartz diorite. Chalcopyrite, bornite.	Philippine Mines and Geosciences Bureau (2004, written commun.)	1

**Table E4.** Significant prospects and occurrences in tract 142pCu7309, Philippine Arc—Philippines.—Continued

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares; ppm, parts per million; SCC, sericite-chlorite-clay. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Limao	7.275	126.046	Neogene	Copper prospect associated with aphanitic volcanic rock.	Philippine Mines and Geosciences Bureau (2004, written commun.)	1
Ayan Gold Project	7.050	126.117	Neogene	Exploration target area along a NW-SE structural trend between the Kingking deposit and the Taguibo project area (artisanal gold and high grade copper mining).	Sierra Mining, Ltd. (2012)	1
Taguibo	7.034	126.194	Neogene	Potential buried porphyry copper exploration target associated with a brecciated, hydrothermally-altered (propylitic, potassic, argillic) diorite and andesite (Taguibo volcano-plutonic complex). Initial drilling reports low-grade Cu zone in two holes (125.6 m at 0.15% Cu and 111.6 m at 0.15% Cu. )	Sierra Mining, Ltd. (2012)	2

**Table E5.** Principal sources of information used for tract 142pCu7309, Philippine Arc—Philippines.

[NA, not applicable]

Theme	Name or Title	Scale	Citation
Geology	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Mining places in the Philippines (kml file)	NA	GoogleEarth® (2013)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
Exploration	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Commercial databases	NA	<a href="http://www.infomine.com/">http://www.infomine.com/</a>
	Company Web sites and technical reports	NA	Numerous—see references in table E4

deposits may be present within the tract include the discovery of Boyongan-Bayugo, increased reliance on aeromagnetic data for target selection, the presence of splays of the Philippine Fault that could provide conduits for hydrothermal fluids and localize emplacement of intrusions, and a spatial association with a belt of epithermal gold deposits.

On the basis of these data, the assessment team estimated a 90-percent chance for 3 or more undiscovered deposits, a 50-percent chance for 7 or more, and a 10-percent chance of 14 or more deposits (table E6). The team considered that historically, the tract area may be underexplored relative to some other areas of the Philippines, such as the Luzon Central Cordillera. Note that the assessment was done in 2010. Attempts were made to update prospect information to further validate prospects that were known but less well-delineated in 2010.

### Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team’s estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Span-ski, 2012). Selected simulation results are reported in table E7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. E3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean estimated amount of undiscovered copper is about four times the amount of identified resources in the tract. See table 6 for comparisons with other tracts.

**Table E6.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7309, Philippine Arc—Philippines.

[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model;  $N_{total}$ , total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers ( $km^2$ ); 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)]

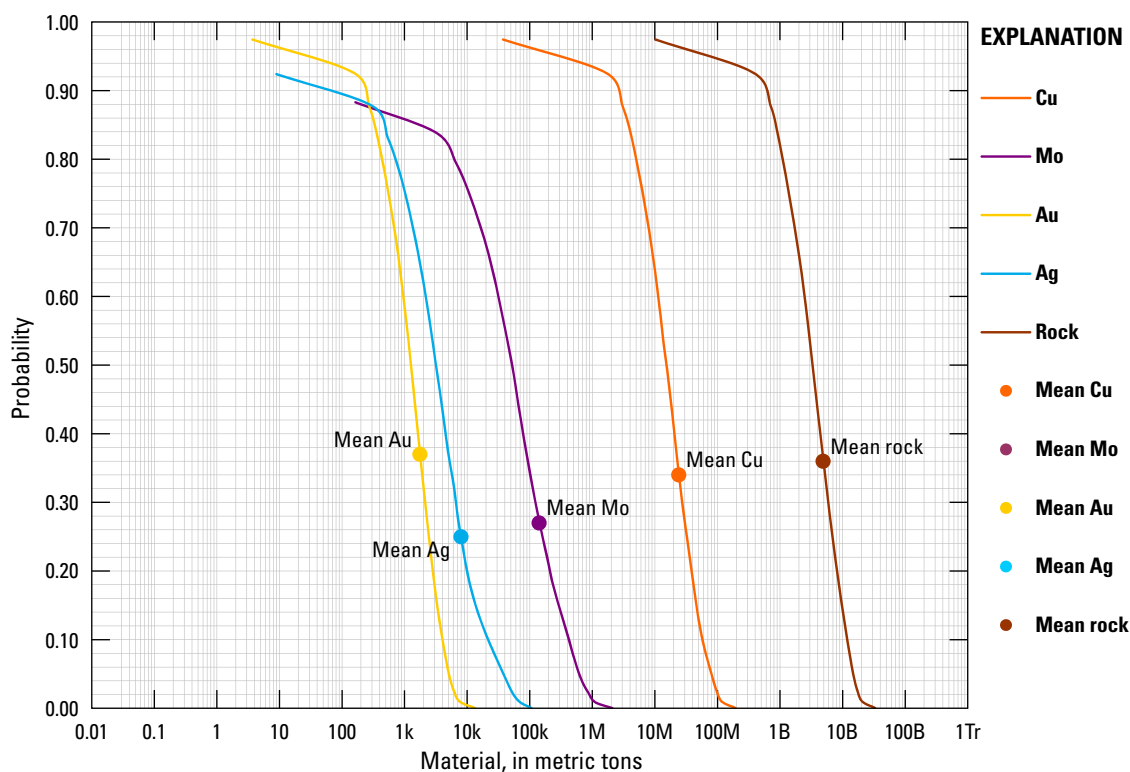
Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $km^2$ )	Deposit density ( $N_{total}/100,000 km^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
3	7	14	14	14	7.7	4.1	53	8	15.7	23,700	66

**Table E7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7309, Philippine Arc—Philippines.

[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	960,000	2,400,000	15,000,000	58,000,000	80,000,000	24,000,000	0.34	0.03
Mo	0	0	52,000	420,000	620,000	140,000	0.27	0.12
Au	82	210	1,300	4,000	5,000	1,800	0.37	0.03
Ag	0	190	3,200	22,000	38,000	8,000	0.25	0.08
Rock	210	570	3,300	12,000	15,000	4,900	0.36	0.03





**Figure E3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7309, Philippine Arc—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix F. Porphyry Copper Assessment for Tract 142pCu7302, Cordon Alkalic Complex—Philippines

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### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table F1 summarizes selected assessment results.

**Table F1.** Summary of selected resource assessment results for tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified copper rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	4,860	1,400,000	4,900,000	1,200,000

### Location

Caraballo Range, southern end of the Cagayan Basin in North Luzon (fig. F1).

### Geologic Feature Assessed

Late Oligocene to early Miocene K-alkalic magmatic province at the south end of the Cagayan rift basin.

<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

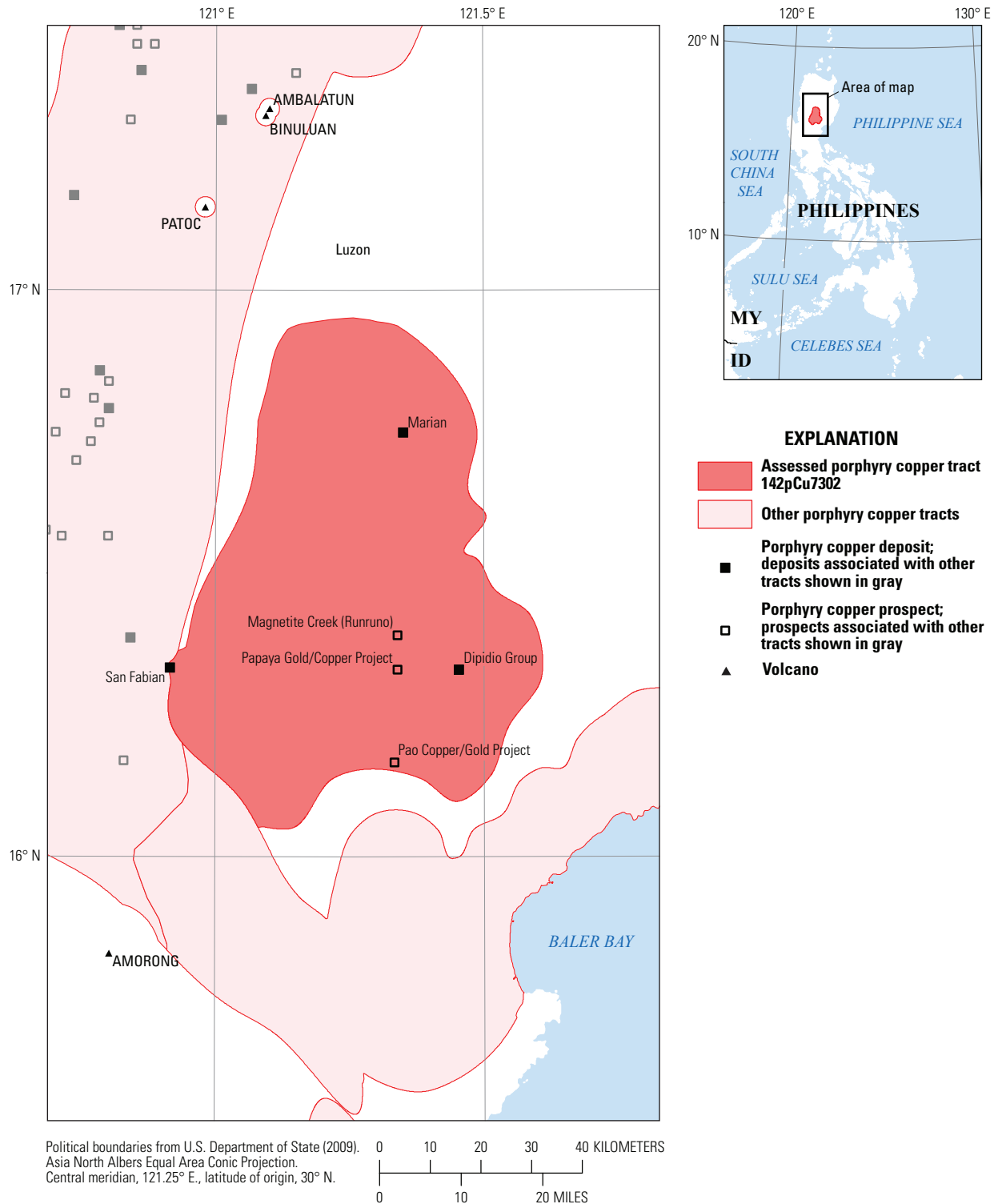
<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.





**Figure F1.** Map showing tract location and significant porphyry copper prospects for tract 142pCu7302, Cordon Alkalic Complex—Philippines. MY, Malaysia; ID, Indonesia.



## Delineation of the Permissive Tract

### Tectonic Setting

The Cordon Alkalic Complex may be related to intra-arc rifting that occurred after westward subduction along the East Luzon Trench ceased in the late Oligocene and before mid-Miocene, east-directed subduction began along the Manila Trench (fig. 5B<sup>6</sup>). Intraplate magmatism, partial melting of a subducted slab, intra-arc extension, and back-arc rift have all been proposed to explain these rocks (Garwin and others, 2005), and Mitchell and Leach (1991) noted that it was unclear if these rocks are arc-related. More recently, Hollings and others (2011) concluded that the potassic igneous rocks of the Cagayan Valley formed in a back-arc setting coeval with the main arc formed by eastward subduction of the Luzon Arc to the west since the late Eocene. Basement rocks are oceanic, including ophiolite complexes.

### Geologic Criteria

The tract is defined by the occurrence of alkalic rocks (fig. F2, table F2) that constitute the Cordon Alkalic Complex and associated copper prospects. The tract was constructed by selecting Oligocene to Miocene igneous rocks from the digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a) that lie within the area referred to as the Cordon secondary magmatic arc by Garwin and others (2005). A preliminary tract was constructed using GIS tools to make 10- and 2-km buffers around intrusive and volcanic rocks, respectively. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand, and tract boundaries were checked to include known prospects and permissive igneous rocks shown on maps included in topical studies (Imai, 2005; Wolfe and others, 2010). Point locations for dated alkalic rocks in the database of Malaihollo and others (2002) were plotted to ensure inclusion within the tract area.

The tract includes alkali syenites, monzonites, and trachyandesites of the Dipidio Igneous Complex and Palali batholiths, as well as the Cordon Syenite Complex (Knittel and Cundari, 1990; Knittel and Defant, 1988). The alkalic rocks are characterized by uniformly low initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios (0.7035–0.7039) and elevated strontium contents (approximately 1,000–3,000 ppm). The tract also includes the calc-alkalic Oligocene-Miocene Dupax batholith (fig. F2), which is not part of the alkalic suite and might be slightly older. Most of the tract area is covered by late Oligocene to middle Miocene sedimentary and volcanic rocks; few intrusive rocks

are mapped at a scale of 1:1,000,000 (fig. F2). See figure 3 of Hollings and others (2011) for a detailed map of the distribution of alkalic igneous rocks in the Dipidio area.

### Known Deposits

The tract contains three well-characterized Oligocene porphyry copper-gold deposits: Dipidio(Dinkidi), Marian, and San Fabian (table F3). Deposits are plotted as filled squares in figure F1.

#### Dipidio Group

The Dipidio (Dinkidi) deposit, notable as one of the few recognized alkaline porphyry deposits outside of British Columbia, Canada, is hosted by the Dipidio Igneous Complex (Wolfe and others, 2010; Wolfe and Cooke, 2011). New U-Pb ages on zircon for the Dipidio area reported by Hollings and others (2011) include ages of 24.81±0.28 and 24.79±0.22 Ma for syenite and monzonite associated with the copper-gold mineralization. The deposit contains measured, indicated, and inferred resources of 101 Mt of 0.36 percent copper, 0.79 g/t gold (OceanaGold Corporation, 2011), updated from previous resource estimates (Joyce and Thomson, 2002; Climax Mining Limited, 2010). Mining began in 2012 as an open pit with plans to start underground mining in year 8; estimated mine life is 16 or 17 years (OceanaGold Corporation, 2011, 2013).

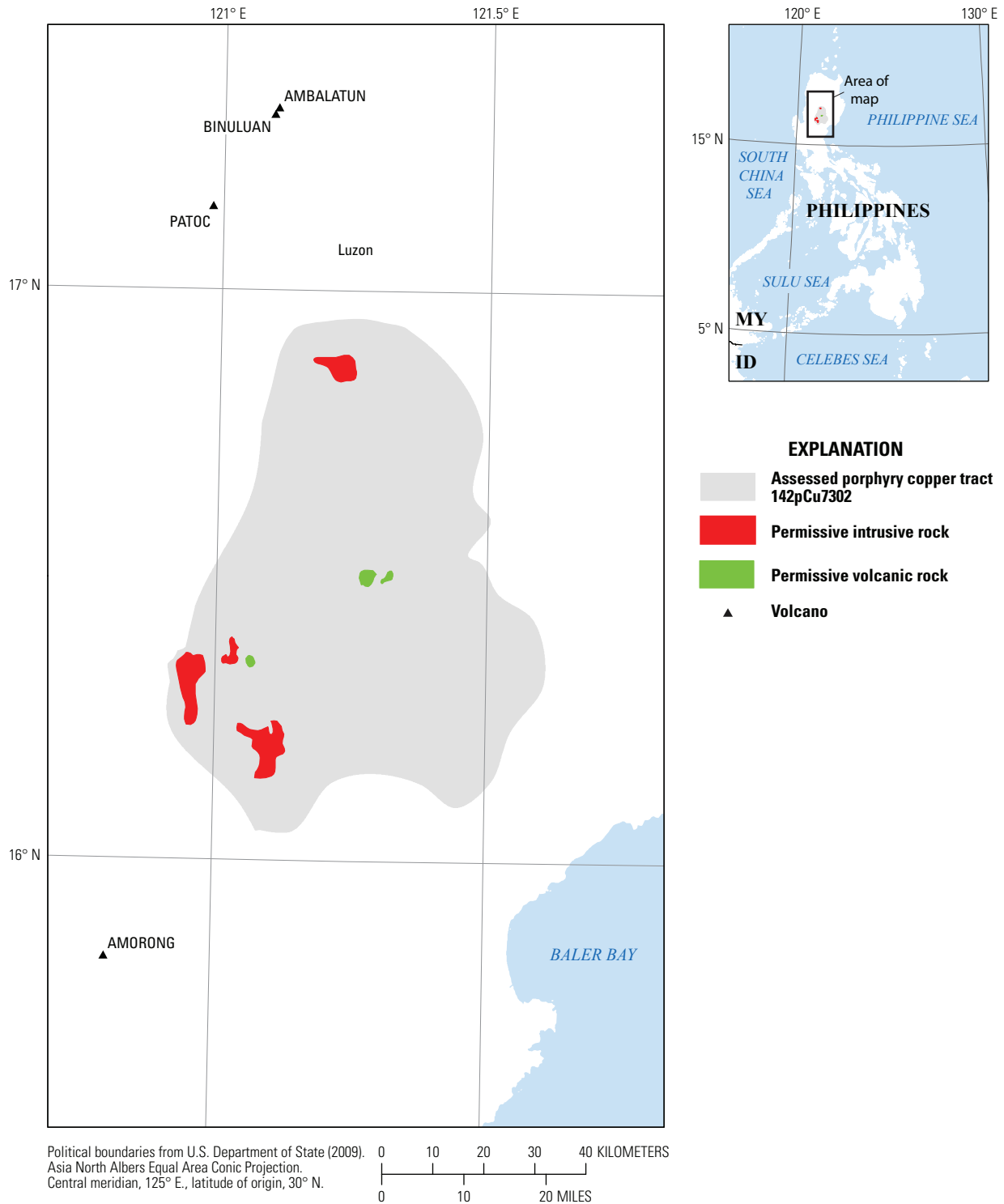
The deposit is hosted in the pipe-like, composite Dinkidi stock (monzonite, syenite, porphyry, syenite dike) within the Dipidio igneous complex (gabbro, clinopyroxenite, diorite, monzodiorite, monzonite). The geochemical signature (low TiO<sub>2</sub>, low HFSE<sup>7</sup>, high Al<sub>2</sub>O<sub>3</sub>) of the alkaline to potassic host rocks is interpreted as representing the final LILE<sup>8</sup>-enriched product of island arc magmatism related to partial melting of a mantle wedge above the eastward-subducting, dehydrating Eurasian Plate (Wolfe and others, 2010). The stock has a potassically altered core, surrounded by a zone of sericite-carbonate-clay alteration. Ore minerals, principally chalcopyrite and electrum, occur in narrow quartz-feldspar-carbonate-sulfide veins in the center of the stock, as peripheral stockworks, and as disseminations with magnetite and pyrite. Bornite is present as rims and along fractures in chalcopyrite. Oxidation (silicification, clay and carbonate mineral, malachite, chrysocolla) extends from the surface to 15–60 m, with an average thickness of 30 m (Redden and Moore, 2011).

Wolfe and Cooke (2011) published a detailed map showing the distribution of different phases of late Oligocene alkalic rocks at Dinkidi, documented alteration stages as well as sulfur isotope compositions (δ<sup>34</sup>S values of –4.2 to –0.2 per mil) and fluid inclusion characteristics of the deposit. Their study showed that the deposit formed in a multiphase alkali stock that intruded a composite diorite-monzonite pluton at depths of 2.9–4.5 km. Copper-gold ore is associated with both

<sup>6</sup>Refer to figures and tables in main report.

<sup>7</sup>HFSE, high field strength elements (Y, Hf, Zr, Ti, Nb, Ta).

<sup>8</sup>LILE, large-ion lithophile elements (Cs, Rb, K, Ba, Sr, Eu).



**Figure F2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7302, Cordon Alkalic Complex—Philippines. MY, Malaysia; ID, Indonesia.

**Table F2.** Map units that define tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963, and references in table F5)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Include granodiorite and diorite porphyry facies and late Miocene dacite. Also include Dupax batholith (Aritao quadrangle) and alkalic rocks mapped around Dipidio.	Neogene
Volcanic rocks			
Neogene volcanic rocks	QV	Nonactive cones (generally pyroxene andesite); also dacitic and (or) andesitic plugs.	Pliocene-Quaternary

**Table F3.** Porphyry copper deposits in tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data. Contained Cu in metric tons is computed as  $(Mt \times 1,000,000) \times (Cu \text{ grade, in } \% \div 100)$ ]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Dipidio (Dinkidi) Group	16.331	121.453	Cu-Au	23.2	121	0.39	n.d.	0.97	n.d.	471,900	Climax Mining, Ltd. (2010), Feebrey (2001), Garrett (1996), Haggman (1997), Hollings and others (2011), Kamenetsky and others (1999), Leach (1999), Wolfe and others (1999, 2010), OceanaGold Corporation (2009, 2011), Singer and others (2008), van der Heyden and others (2008)
Marian	16.750	121.350	Cu-Au	Late Oligocene (~25)	55	0.43	n.d.	0.24	n.d.	236,500	Baquiran (1975), Knittel (1987), Mitchell and Leach (1991), Sillitoe and Gappe (1984), Singer and others (2008)
San Fabian	16.335	120.916	Cu-Au	Early Miocene (~20.6)	314	0.27	n.d.	0.21	n.d.	847,800	MMAJ-JICA (1977), Sillitoe and Gappe (1984), Singer and others (2008)

silica-undersaturated (quartz free) and silica-saturated stages of development of the deposit, which experienced two phases of tectonic brecciation, the latter of which was accompanied by development of a calcic zeolite alteration assemblage.

Exploration around the deposit area includes some 35 prospects, including a gold-rich copper porphyry associated with a collapse breccia at the D-Fox project and a low-grade alkali porphyry at the True Blue project (these are described in table F4). These exploration projects of OceanaGold Corporation (2011), located 3.2 and 0.6 km from the Dipidio project, are considered to be extensions of the Dipidio deposit.

### Marian

The Marian gold mine in the Cordon Syenite Complex produced gold and silver (1978–1984) from an underground mine exploiting epithermal gold-rich quartz veins. The veins, which extended to depths of 100 m, are hosted in syenite and tinguaitite. The associated gold-rich Marian porphyry copper deposit is hosted in monzonite (Mitchell and Leach, 1991; Medusa Mining, Ltd., 2004).

### San Fabian

The abandoned San Fabian porphyry system (1,500 by 400 m in area) was drilled by the Philex Mining Co. between 1960 and 1975, followed by additional mapping and sampling in the 1980s and 1990s. At San Fabian, andesitic dikes cut quartz diorite porphyry, tonalite, syenite and monzonite. Ore minerals include chalcocopyrite, bornite, and minor chalcocite associated with pyrite in stringers and disseminations in chloritic, propylitic, sericitic, and argillic alteration zones.

### Prospects, Mineral Occurrences, and Related Deposit Types

In addition to the prospects immediately around Dipidio, two prospect areas located more than 10 km away from the deposit may represent discrete porphyry centers (fig. F1, table F4). The Papaya prospect on the south wall of the Miocene Runruno caldera, 12 km west of Dipidio, includes a 7-km circular area of hydrothermal alteration associated with quartz monzonite intrusions and anomalous concentration of

**Table F4.** Significant prospects and occurrences in tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[%, percent; g/t, grams per metric ton; km, kilometers; m, meters. Ages all assumed to be Oligocene-Miocene based on associated map units or dated igneous rocks. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend. \*, considered an extension of identified resources]

Name	Latitude	Longitude	Comments	Reference	Rank
True Blue Gold/ Copper Project	16.330	121.463	Exploration in the Dipidio area (35 prospects). Area near the Dipidio open pit has been extensively explored. Drilling at True Blue in 2006 identified a small intrusive stock.	OceanaGold Corporation (2011)	*
D'Fox Gold/ Copper Project	16.310	121.484	May be an extension of Dipidio. Exploration of a gold-rich copper porphyry associated with a collapse breccia 1.5 km southeast of Dipidio Gold project. Structural intersection. Previous exploration drilling reported 36 m of 0.4% Cu, 1.1 g/t Au, and 84 m of 0.4% Cu and 1.0 g/t Au.	OceanaGold Corporation (2011)	*
Papaya	16.200	121.480	Circular alteration area (7 km in diameter) in an alkaline Miocene volcano-plutonic complex; approximate location ~12 km W of Dipidio. Anomalous Au (3.7 g/t), Cu (0.1%), Mo (0.1%) from channel samples in highly altered (potassic-magnetite) monzonite.	Climax Mining, Ltd. (2002)	2
Magnetite Creek (Runruno)	16.3921	121.389	Drilling in an area 2 km to the south of the Runruno Au-Mo deposit intercepted a brecciated, potassic alteration zone in a monzonite-monzodiorite intrusion; drilled (500 m max.); drill intercepts of 13.2 m of 0.75 g/t Au and 0.23% Cu; 28 m of 0.16 g/t Au and 0.21% Cu.	Metals Exploration plc (2011)	3
Pao Yabbe	16.167	121.333	Epithermal gold veins associated with alkalic volcanic rocks, with possible porphyry-style mineralization at depth.	RoyalCo Resources, Ltd. (2010)	1

copper, gold and molybdenum in stream sediment and channel samples (OceanaGold Corporation, 2011). Exploration at the Pao Yabbe exploration tenement (fig. F1) is focused on epithermal gold veins associated with alkalic volcanic rocks, with possible porphyry-style mineralization at depth (RoyalCo Resources, Ltd., 2010). Garwin and others (2005) described Runruno as an intermediate-sulfidation gold deposit and Pao as a high-sulfidation enargite-gold occurrence associated with alkalic volcanic rocks based on the work of Kavalieris and Gonzalez (1990). A gold-molybdenum deposit centered on a 3-km-wide argillically altered volcanic center is in development at Runruno by Metals Exploration plc (2012). Drilling in an area 2 km to the south of Runruno (Magnetite Creek area) intercepted a brecciated monzonite-monzodiorite intrusion; assays on three drill holes returned intercepts for copper and gold (table F4). Climax Mining, Ltd., (2002) described a prospect area called Papaya-FHB Intrusive Complex as a 50-km<sup>2</sup> Miocene alkaline volcano-plutonic complex located about 12 km west of Dipidio; anomalous gold, copper, and molybdenum concentrations were obtained from channel samples in highly altered (potassic-magnetite) monzonite.

## Exploration History

Alluvial gold mining led to recognition of the Dipidio area as a gold province in the 1970s (Joyce and Thomson, 2002). Dinkidi was discovered in 1988, based on recognition of the unusual topographic expression of an apparent collapse caldera (Haggman, 1997). The Marian gold mine was discovered during regional exploration in the 1970s. The Dipidio copper-gold project area includes the Dipidio (Dinkidi) open pit mine and 30 prospects within the FTAA (Financial or Technical Assistance Agreement) area (OceanaGold Corporation, 2011). The Dipidio area (215 km<sup>2</sup>) was explored under an FTAA granted to Climax Mining Limited in 1998 (Joyce and Thomson, 2002); the expected mine development (15 year-minimum mine life producing 15,000 t of copper concentrate and 12,000 ounces of gold per year in the first 10 years of operation) did not occur at that time. The mine development was placed on care and maintenance in 2008, with a review of feasibility to renew development in 2009 (OceanaGold Corporation, 2009). Global economic conditions, as well as local social and environmental opposition to mining, are factors that affected mine development until very recently (2012).

Exploration for epithermal gold and alkali-associated porphyry deposits using stream sediment, soil, rock chip sampling and limited drilling led to the identification of additional targets (True Blue, d'Fox are partially drilled). Exploration for deep porphyry copper-gold targets associated with high-level epithermal gold systems is underway in several areas, including proximal to the Runruno gold-molybdenum deposit, which is currently in development with announced resources of 26 Mt at 1.69 g/t gold and 470 ppm molybdenum (Metals Exploration plc, 2012).

## Sources of Information

Principal sources of information used for the assessment are listed in table F5.

## Grade and Tonnage Model Selection

The known deposits are copper-gold porphyry deposits. The porphyry Cu-Au subtype model was selected. In addition to the known gold grades, porphyry copper deposits associated with alkaline source rocks typically are gold-rich.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

Based on the wide spatial distribution of the three known deposits in the tract, the presence of alkalic rocks, and active, but incompletely explored prospect areas, the assessment team estimated a 50-percent chance for one or more deposits like those in the model, a 10-percent chance for four or more, and a 5-percent chance of five or more undiscovered deposits (table F6). The expected number of undiscovered deposit associated with this distribution is two. The small tract area (4,860 km<sup>2</sup>) is a limiting factor on the number of deposits. In addition, the thicknesses of some of the stratigraphic units in the Caraballo Mountains are on the order of 3,000–4,000 m (Philippine Bureau of Mines and Geosciences, 1981), so the depth of cover may exceed the 1-km protocol adopted for this study.

## Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the team's estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper-gold model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table F7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. F3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The simulation estimates that the median amount of copper in undiscovered deposits in the tract (1.2 Mt) is slightly less than the identified resources (1.4 Mt); the mean estimated resources (4.9 Mt) exceed the identified resources (table F1). See table 6 for comparisons with identified copper and gold resources, and with other tracts.

**Table F5.** Principal sources of information used for tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981) [Philippine] Mines and Geosciences Bureau (2010)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Mining places in the Philippines (kml file)	NA	GoogleEarth® (2013)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
Exploration	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Commercial databases	NA	<a href="http://www.infomine.com/">http://www.infomine.com/</a>
	Company Web sites and technical reports	NA	Numerous—see references in table E4

**Table F6.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model;  $N_{total}$ , total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers ( $km^2$ ); 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)]

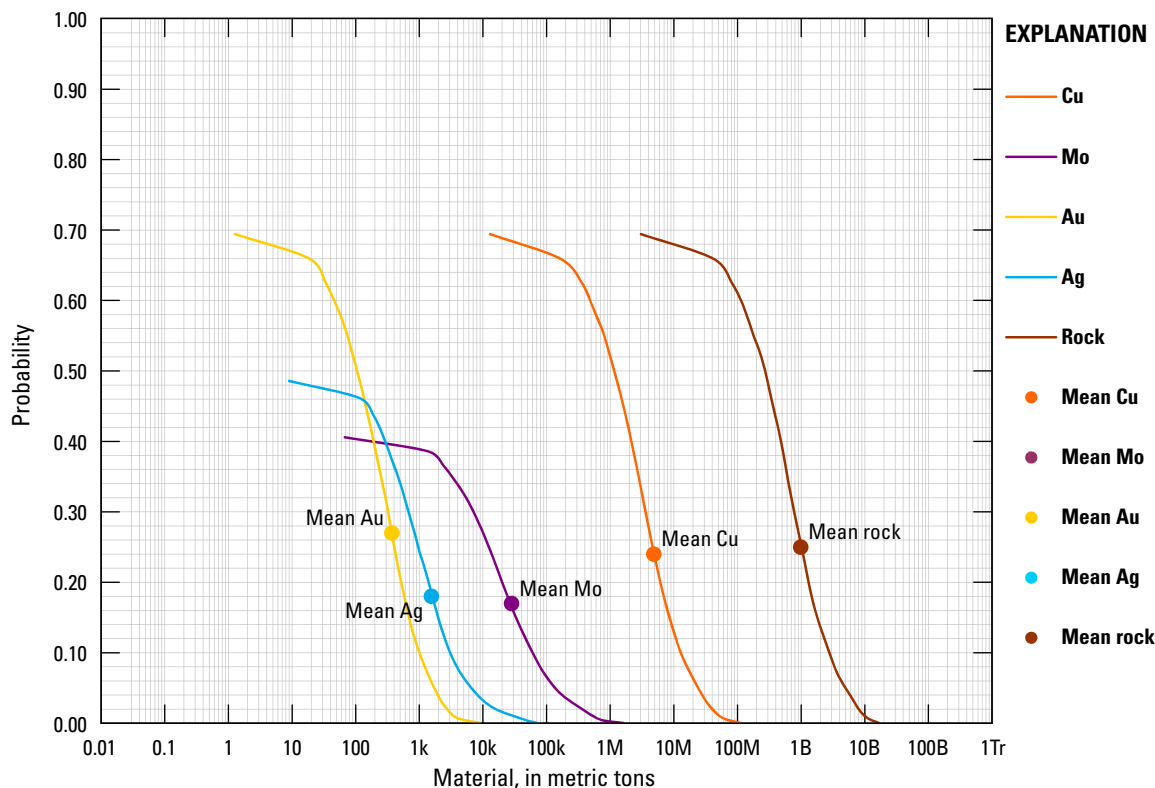
Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $km^2$ )	Deposit density ( $N_{total}/100,000 km^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
0	1	4	5	5	1.7	1.7	100	3	4.7	4,860	97

**Table F7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7302, Cordon Alkalic Complex—Philippines.

[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					Mean	Probability of	
	0.95	0.9	0.5	0.1	0.05		Mean or greater	None
Cu	960,000	2,400,000	15,000,000	58,000,000	80,000,000	24,000,000	0.34	0.03
Mo	0	0	52,000	420,000	620,000	140,000	0.27	0.12
Au	82	210	1,300	4,000	5,000	1,800	0.37	0.03
Ag	0	190	3,200	22,000	38,000	8,000	0.25	0.08
Rock	210	570	3,300	12,000	15,000	4,900	0.36	0.03





**Figure F3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7302, Cordon Alkalic Complex—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix G. Porphyry Copper Assessment for Tract 142pCu7304, Sierra Madre Arc—Philippines

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### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, general model (Singer and others, 2008)

Table G1 summarizes selected assessment results.

**Table G1.** Summary of selected resource assessment results for tract 142pCu7304, Sierra Madre Arc—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified copper rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	14,000	310,000	1,400,000	0

### Location

Northern and Southern Sierra Madre of eastern Luzon and Polillo Island (fig. G1).

### Geologic Feature Assessed

Sierra Madre Arc.

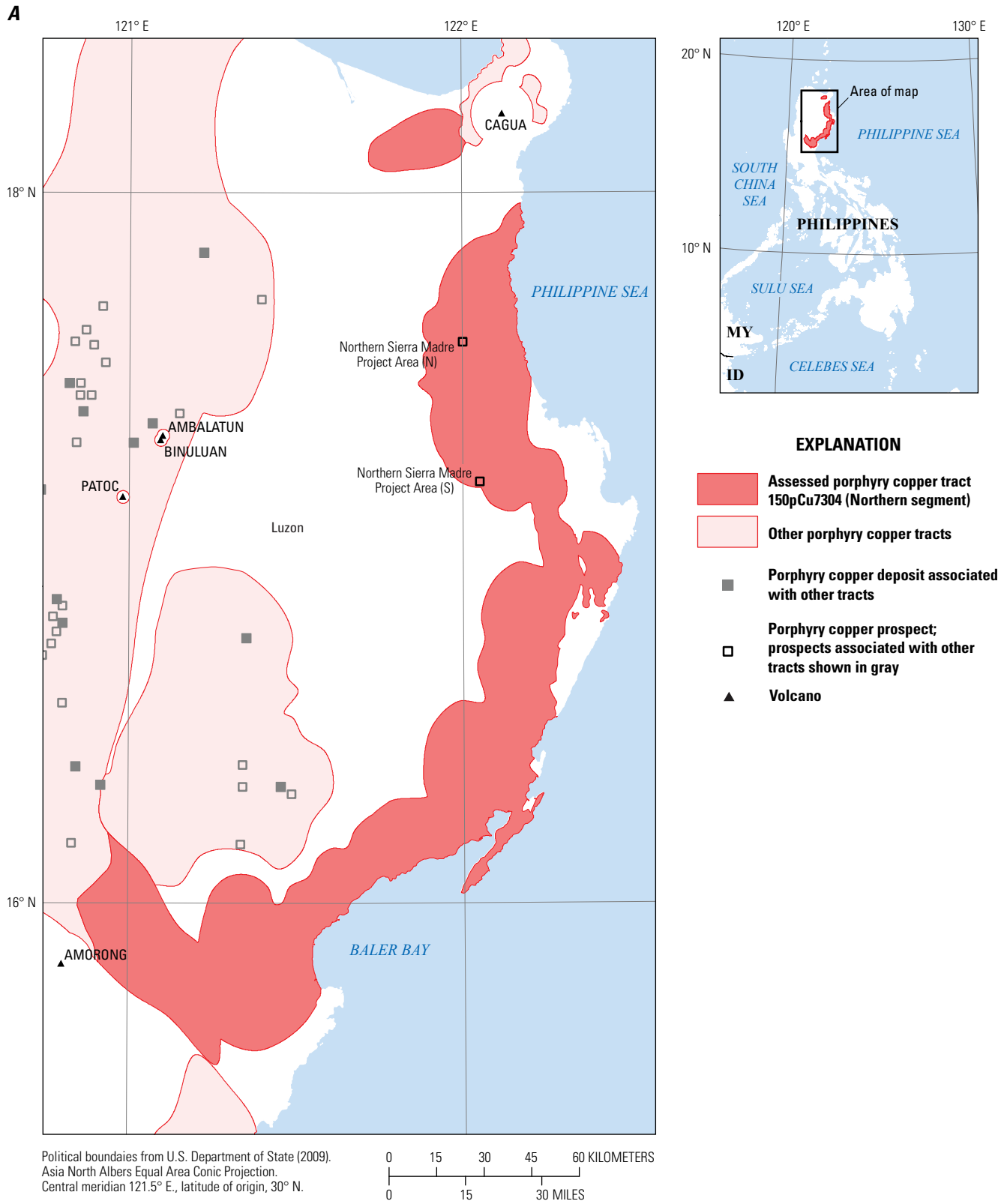
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

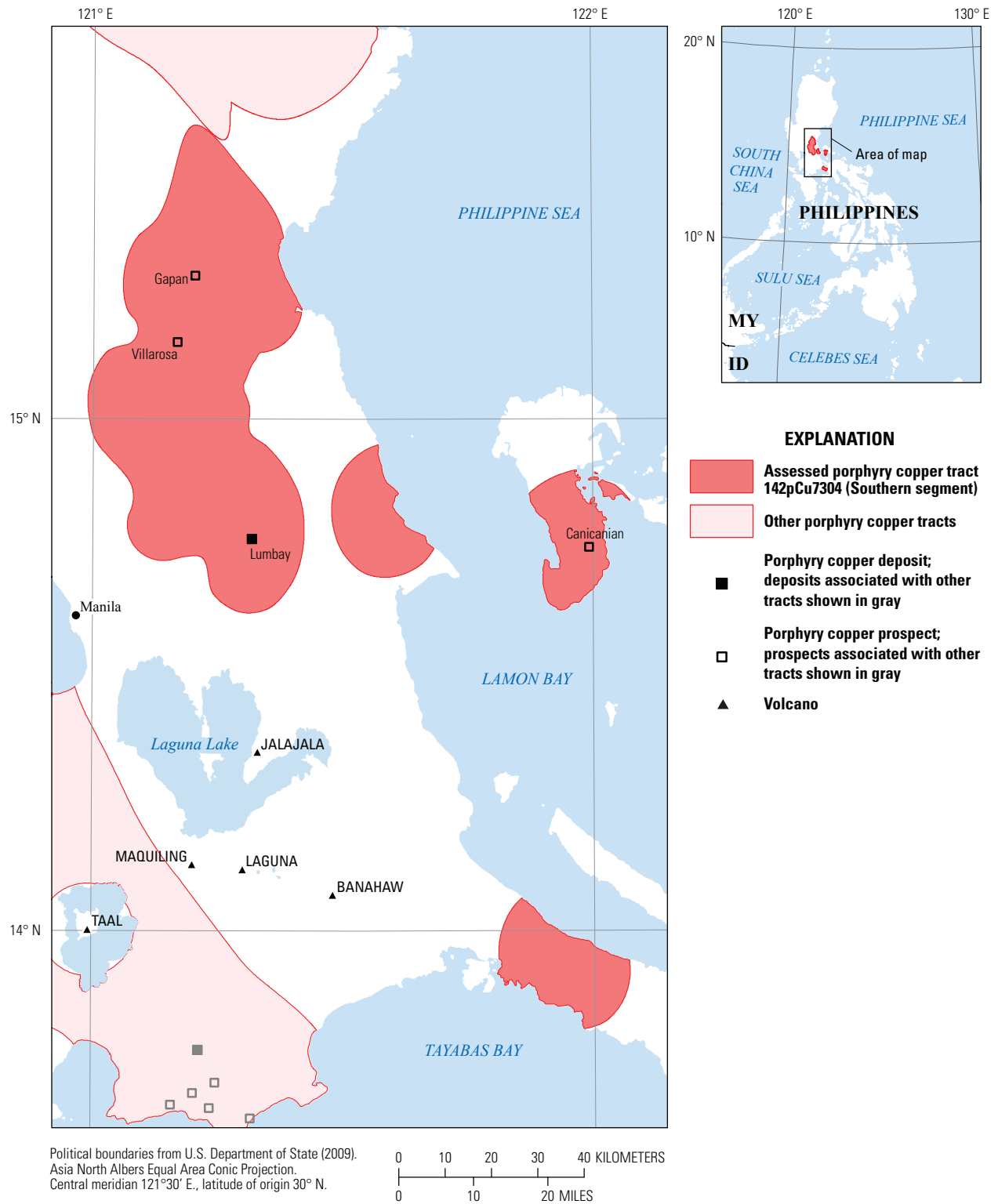
<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure G1.** Maps showing tract location, deposits, and significant porphyry copper prospects for tract 142pCu7304, Sierra Madre Arc—Philippines. *A*, Northern Sierra Madre. *B*, Southern Sierra Madre. MY, Malaysia; ID, Indonesia.



**B**



**Figure G1.—Continued**

## Delineation of the Permissive Tract

### Tectonic Setting

The Sierra Madre Arc borders the eastern coast of Luzon (fig. G1). The Eocene-Oligocene Sierra Madre Arc includes two segments both formed on oceanic basement. The northern segment is defined by the Northern Sierra Madre (fig. 4B). The southern segment extends from the Caraballo Mountains (fig. 4B) through the Southern Sierra Madre (fig. 4C), south and west of the Philippine Fault. Although the arc lies to the west of the East Luzon Trough, the polarity of the subduction (eastward or westward) and the extent of the arc are uncertain (Hall, 2002; Wolfe, 1988). The arc may continue to the Masbate-Negros Arc to the south (fig. 2<sup>6</sup>). Yumul and others (2003) indicate that the Southern Sierra Madre Arc has a northwest-southeast orientation and includes Oligocene plutons on Polillo, Paleogene and Neogene intrusions and Oligocene-Miocene volcanic rocks in the province of Camarines Norte, and volcanic rocks on Catuandanes Island (fig. 4A). Polillo Island (fig. G1B), located about 30 km east of Luzon, may have been rifted from Luzon by strike-slip movement along the Philippine Fault or may be the northern end of an island arc accreted to the Mobile Belt (Knittel and Burton, 1985). Polillo Island is included here with the Southern Sierra Madre (although it does lie within present-day extent of the Philippine Arc shown in fig. 2A); the permissive rocks in Camarines Norte and on Catuandanes Island are included in the northern (Bicol) segment of the Oligocene to Holocene Philippine Arc (tract 142pCu7301).

### Geologic Criteria

The permissive tract is delineated on the mapped extent of Paleogene and Neogene intrusive rocks and Paleogene and Oligocene andesitic volcanic rocks that lie to the west and south of the Philippine Fault within the Sierra Madre and Northeast Luzon Arcs as shown by Garwin and others (2005). The Philippine Fault is a younger structure (2–4 Ma) that crosscuts the older arc.

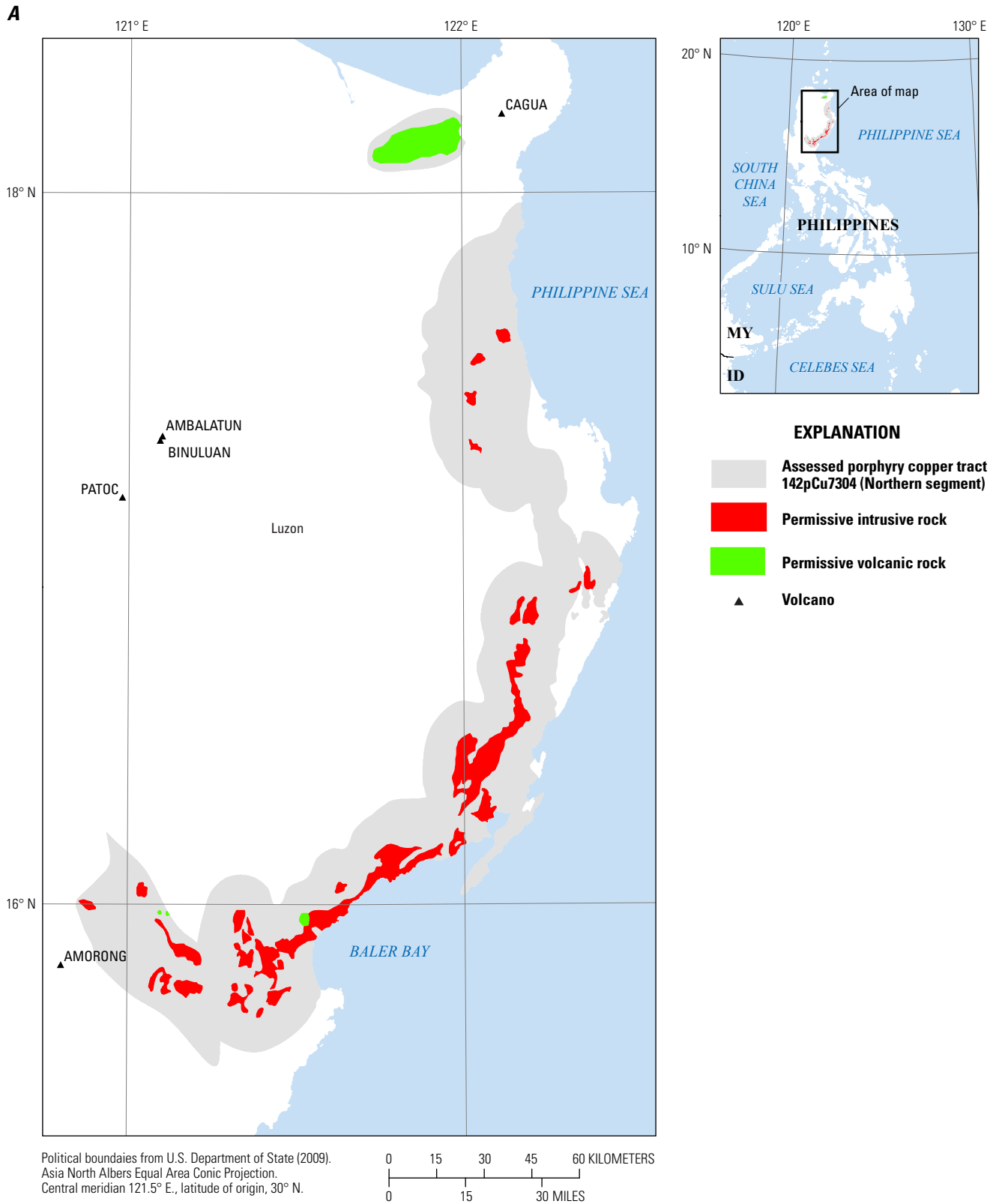
The tract was constructed by selecting map units coded as Paleogene intrusions and volcanic rocks, Oligocene volcanic

rocks, and Oligocene-Miocene volcanic rocks (table G2) from the digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Mines and Geosciences Bureau, 2004a). Permissive rocks used to delineate the tract are shown in figure G2. The preliminary tract was developed using ArcGIS tools to create a 10-km buffer around intrusive rocks and a 2-km buffer around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. Furthermore, Sillitoe and Gappe (1984) noted that 75 percent of the known (as of 1984) porphyry deposits in the Philippines were located less than 4 km from the margins of a pluton with phaneritic texture. The buffered map unit polygons were aggregated, smoothed, and edited by hand to include known but unmapped permissive igneous rocks and prospects. The final tract segments were clipped to coastlines (U.S. Department of State, 2009).

The mountains of the Northern Sierra Madre record two episodes of magmatism—(1) middle to late Eocene volcanic rocks and intermediate composition (mainly tonalite) plutons of the Eocene Coastal Batholith and (2) Oligocene to Miocene volcanic rocks and the Northern Sierra Madre Batholith. K-Ar ages for tonalite, quartz diorite, diorite, and granodiorite in the Northern Sierra Madre batholith range from late Oligocene ( $31.1 \pm 1.5$  Ma) to early Miocene ( $22.3 \pm 1.1$  Ma) (as reported in Hollings and others, 2011, for data from Billedo, 1994, and Metal Mining Agency of Japan, 1987). A calc-alkalic composite tonalite-granodiorite-quartz monzonite pluton dated at 34.4 Ma crops out on southern Polillo Island (Knittel and Burton, 1985). The Coastal Batholith and the intrusions on Polillo Island have initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of 0.7035–0.7043; the compositions of the Polillo rocks are more evolved (higher silica contents,  $\text{K}_2\text{O} > \text{Na}_2\text{O}$ ) than the rocks of the Coastal Batholith (Knittel and Defant, 1988; Knittel and Burton, 1985).

Permissive rocks in the Southern Sierra Madre include quartz diorites dated at 27 to 32 Ma in the Caraballo Mountains, the 36.9-Ma Antipolo diorite, and the correlative Mayopa diorite, which are mapped as Paleogene and Neogene intrusions (table G2) and described in detail in the volume on geology and mineral resources of the Philippines (Philippine Bureau of Mines and Geosciences, 1981).

<sup>6</sup>Refer to figures and tables in main report.



**Figure G2.** Maps showing the distribution of permissive igneous rocks for tract 142pCu7304, Sierra Madre Arc—Philippines. *A*, Northern Sierra Madre. *B*, Southern Sierra Madre. See table G2 for a description of included rocks. MY, Malaysia; ID, Indonesia.

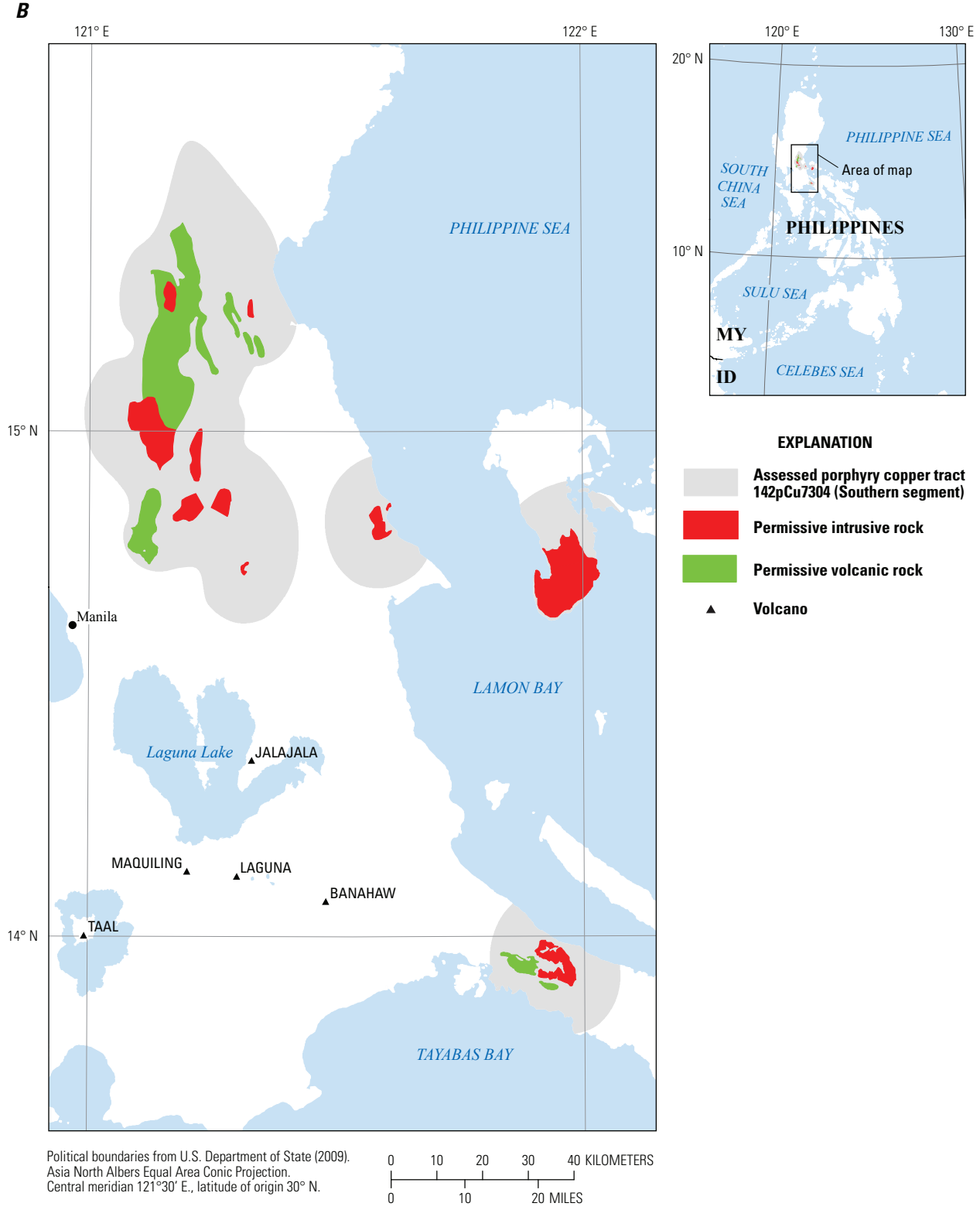


Figure G2.—Continued

**Table G2.** Map units that define tract 142pCu7304, Sierra Madre Arc—Philippines.

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic rock sequences, less widespread in early Miocene rock sequences.	Neogene
Paleogene intrusive rocks	Pg <sub>1</sub>	Mostly quartz diorite.	Paleogene
Volcanic rocks			
Neogene volcanic rocks	IN <sub>1</sub>	Mostly submarine andesite and/or basalt flows. Intercalated with pyroclastics and clastic sedimentary rocks or reef limestone lenses. Largely confined within the axial zone of Luzon, Visayas, and Mindanao.	Oligocene-Miocene
Paleogene volcanic rocks	IPg <sub>2</sub>	Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin. Undifferentiated from early Miocene sedimentary rocks in some areas.	Oligocene
Paleogene volcanic rocks	IPg <sub>1</sub>	Limited dacite and andesite flows and dikes, generally intercalated with or intrude Eocene clastics. Included with Eocene sedimentary rocks in this map.	Paleocene(?)–Eocene

## Known Deposits

The tract includes one deposit having identified resources (Lumbay, fig. G1, table G3).

### Lumbay (Kalawang)

The Lumbay deposit in the Southern Sierra Madre, discovered in 1973, was an exploration project of Colossal Mining and Exploration (Alapan, 1980). It was listed as an abandoned prospect and described by Sillitoe and Gappe (1984) as having the ore geometry of a steep cylinder. Reserves reported in their report and included in Singer and others (2008) reflect 1973–77 drilling. Supergene enrichment at Lumbay is minor, with less than a 30-m depth of partial leaching. No information on recent activity in the area was available.

## Prospects, Mineral Occurrences, and Related Deposit Types

### Sierra Madre (North)

Indophil Resources (2002) described a grass roots exploration project in the Northern Sierra Madre covering an exploration area of 588 km<sup>2</sup> for porphyry copper gold targets. The area on the western side of the Sierra Madre in Cagayan and Isabela Provinces includes seven copper occurrences, hydrothermal alteration associated with granodiorite, diorite, dacite and andesite, and copper and arsenic stream sediment anomalies (70–520 ppm copper). Two prospect areas identified in the Indophil Resources (2002) report are noted in table G4 and figure G1.

**Table G3.** Porphyry copper deposits in tract 142pCu7304, Sierra Madre Arc—Philippines.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; n.d., no data. Contained Cu in metric tons is computed as (Mt × 1,000,000) × (Cu, in % ÷ 100)]

Name	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Lumbay	Cu-Au	n.d.	78	0.40	0.0008	0.03	n.d.	312,000	Alapan (1980), Malicdem (1975), Sillitoe and Gappe (1984), Singer and others (2008)

Kuroko-type copper deposits are known in volcanic rocks and Cyprus-type massive sulfide deposits are associated with ophiolites in northeastern Luzon (Philippine Bureau of Mines and Geosciences, 1986). These deposit types typically are not associated with permissive areas for porphyry copper deposits but may contribute to copper anomalies detected in stream-sediment analyses.

### Sierra Madre (South)

The southern part of the tract includes two copper occurrences that may be porphyry-related and a porphyry molybdenum prospect (table G4). The Canicanian prospect and nearby areas in southern Polillo Island are described as porphyry molybdenum-rich, gold-poor copper prospects associated with hypabyssal quartz monzonite intrusions into tonalite and granodiorite (Philippine Bureau of Mines and Geosciences, 1986; Knittel and Burton, 1985). An anomaly defined by colocated soil molybdenum concentrations (greater than 40 ppm), phyllic alteration, and high induced polarization (IP) was drilled with 26 holes. Drill-based (noncompliant) resource estimates of 16.5 Mt at 0.085 percent MoS<sub>2</sub> reported

by Knittel and Burton (1985) do not include any information on copper concentrations.

### Exploration History

The tract may be underexplored for porphyry copper deposits. The major gold-copper districts in the eastern Philippines (Bicol, east Mindanao) and a lack of exploration in the Sierra Madre led Yumul and others (2003) to note that the Sierra Madre of northern Luzon is an attractive exploration target area for gold and copper deposits. Northeastern Luzon was mapped (unpublished) and a stream-sediment survey was conducted in the 1970s (Republic of the Philippines-Government of Japan Project, 1977). Polillo Island was explored for molybdenum by Inco Mining Corporation and S and L Mining Corporation following the Canicanian discovery in the early 1970s (Philippine Bureau of Mines and Geosciences, 1986; Knittel and Burton, 1985).

### Sources of Information

Table G5 lists principal sources of information used in the assessment.

**Table G4.** Significant prospects and occurrences in tract 142pCu7304, Sierra Madre Arc—Philippines.

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters. Rank 2=drilled or trenched with <20 m of 0.2% Cu or <0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Northern Sierra Madre						
Northern Sierra Madre Project Area (S)	17.191	122.049	n.d.	Area of hydrothermal alteration, four copper occurrences, north and south of Aubuan River. Location approximate, in Indophil concession area EPA-55.	Indophil Resources (2002)	1
Northern Sierra Madre Project Area (N)	17.583	122.000	n.d.	Area of hydrothermal alteration, two copper occurrences, and elevated copper in stream sediments. Location approximate, in central part of Indophil concession areas EPA-52,53,54.	Indophil Resources (2002)	1
Southern Sierra Madre						
Canicanian prospect	14.75	121.992	34.4	Porphyry Mo-Cu prospect, estimated resources 16.5 Mt at 0.085% MoS <sub>2</sub> .	Knittel and Burton (1985)	2
Gapan	15.281	121.201	n.d.	Porphyry copper prospect; diorite porphyry, chalcopyrite, bornite.	Philippine Mines and Geosciences Bureau (2004b)	1
Villarosa	15.151	121.167	n.d.	Copper, gold occurrence associated with diorite.	Philippine Mines and Geosciences Bureau (2004b)	1



**Table G5.** Principal sources of information used for tract 142pCu7304, Sierra Madre Arc—Philippines.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), [Philippine] Mines and Geosciences Bureau (2010)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geologic map of the Unisan quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world: database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Mineral distribution map of the Philippines	1:2,500,000	Philippine Geological Survey Division (1964)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data (MRDS)	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites and technical reports	NA	Indophil Resources (2002)

## Grade and Tonnage Model Selection

The only identified resources within the tract are those associated with the Lumbay deposit in the Southern Sierra Madre. On the basis of reported gold and molybdenum grades (table G3), Lumbay is classified as a copper-gold porphyry deposit. The late Eocene arc rocks on Polillo Island, however, are associated with molybdenum-rich porphyry style mineralization. Due to uncertainties about the types of deposit likely to be present within the tract, the general porphyry copper-gold-molybdenum model was used by default.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The tract is permissive on the basis of (1) the presence of igneous rocks of appropriate composition and (2) a few

prospect areas that have not been fully explored. Exposed batholiths indicate that parts of the area may be too deeply eroded to preserve deposits. Areas with coeval volcanic and intrusive rocks are most likely to be prospective. The tract area does not include any of the major epithermal gold districts of the Philippines; the assessment team regarded this observation as an unfavorable factor for undiscovered porphyry copper deposits. Two potential porphyry prospect areas were active in 2002, but the team is unaware of follow-up work. On the basis of the information on the prospect areas, the lack of modern exploration, and the area of permissive igneous rock, the team estimated a 10-percent chance for one undiscovered deposit (table G6). A 1-percent chance for three or more deposits is based on three clusters of copper occurrences associated with hydrothermal alteration in andesite and granodiorite within the approximately 20 by 80 km prospect area in the Northern Sierra Madre and the likelihood that other such areas may exist within the tract. This distribution produces a mean estimate of less than one undiscovered deposit with a very high associated uncertainty ( $C_v=210$  percent).

**Probabilistic Assessment Simulation Results**

Undiscovered resources for the tract were estimated by combining the team’s estimate for numbers of undiscovered porphyry copper deposits with the porphyry copper 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 G7. Results

of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. G3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean expected amount of copper, 1.4 Mt, is about 4.5 times the amount of identified copper resources associated with the Lumbay deposit. The data for Lumbay, however, are historical and the existing data may not accurately reflect the total resource.

**Table G6.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7304, Sierra Madre Arc—Philippines.

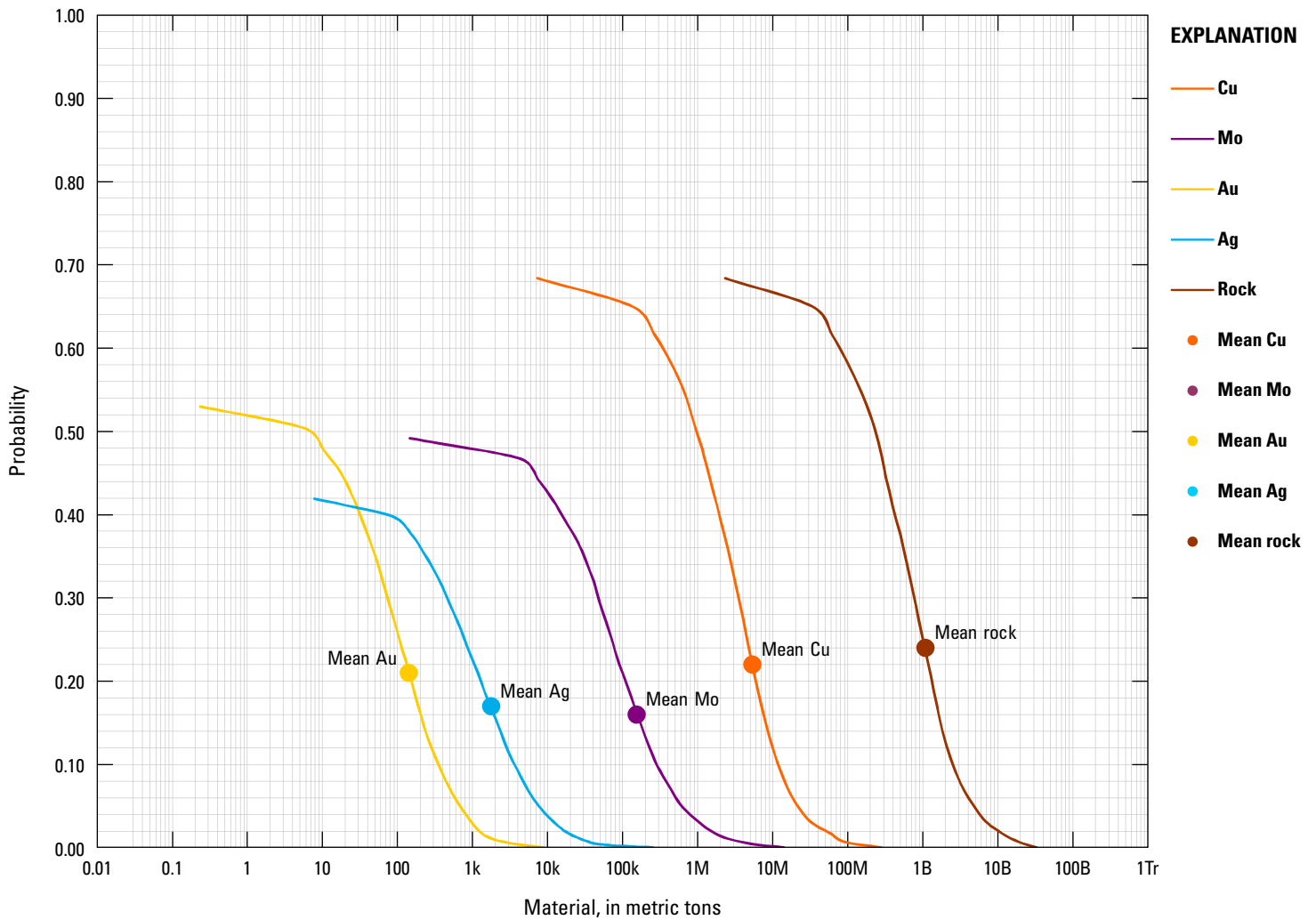
[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model; 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

Consensus undiscovered deposit estimates					Summary statistics					Tract Area (km <sup>2</sup> )	Deposit density ( $N_{total}/100,000$ km <sup>2</sup> )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
0	0	1	1	3	0.36	0.75	210	1	1.36	14,000	10

**Table G7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7304, Sierra Madre Arc—Philippines.

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

Material	Probability of at least the indicated amount					Probability of			
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None	
Cu	0	0	0	2,900,000	6,800,000	1,400,000	0.15	0.69	
Mo	0	0	0	40,000	130,000	35,000	0.11	0.82	
Au	0	0	0	65	170	36	0.13	0.80	
Ag	0	0	0	350	1,500	420	0.10	0.86	
Rock	0	0	0	670	1,400	290	0.16	0.69	



**Figure G3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7304, Sierra Madre Arc—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix H. Porphyry Copper Assessment for Tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines

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### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table H1 summarizes selected assessment results.

**Table H1.** Summary of selected resource assessment results for tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	9,170	0	3,200,000	670,000

### Location

Mindoro, Tablas (Romblon Island Group), and northeastern Palawan Islands and western Panay (Visayas<sup>6</sup>) (fig. H1).

### Geologic Feature Assessed

Neogene Mindoro-Tablas-Western Panay Arc.

<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

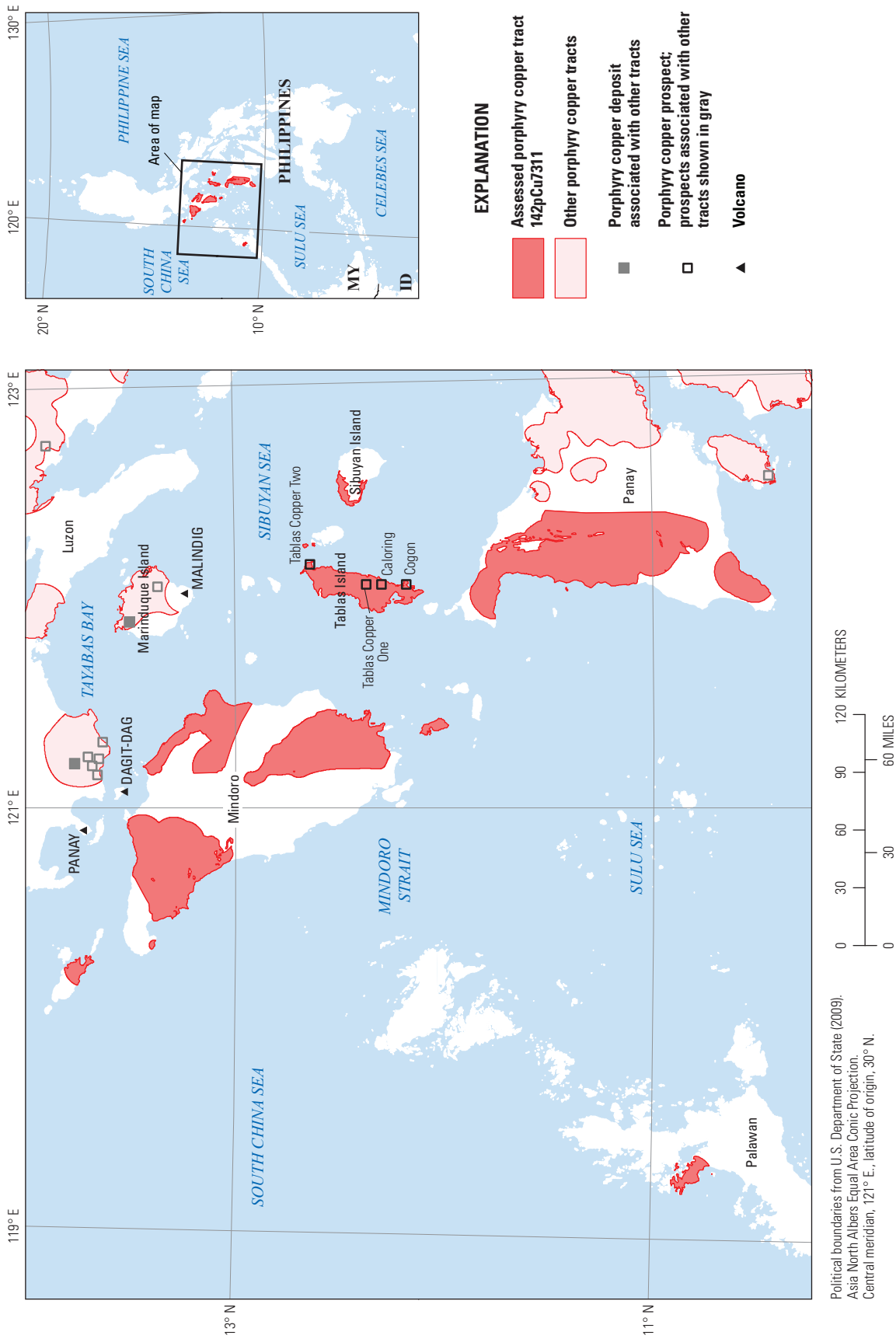
<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.

<sup>6</sup>The Visayas Islands include Panay, Negros, Cebu, Bohol, Leyte, and Samar.



**Figure H1.** Map showing tract location and porphyry copper prospects for tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines. MY, Malaysia; ID, Indonesia.

## Delineation of the Permissive Tract

### Tectonic Setting

This tract outlines Neogene igneous rocks in the collisional area between the Palawan microcontinent and the Philippine Mobile Belt (fig. 5B<sup>7</sup>). The Palawan block formed along an Andean-type subduction zone along the Asian continental margin during the Cretaceous. The Palawan block rifted from the Asian continent, moved southward as the South China Sea opened in the late Eocene to early Miocene, and collided with the northwest-directed Philippine Mobile Belt at about 20–16 Ma (Yumul and others, 2009; Marchadier and Rangin, 1990).

Mitchell and Leach (1991) used the term “Tablas-western Panay-Cagayan Ridge arc” for the area and interpreted the arc as the middle Miocene continuation of the western segment of the Luzon Arc. Dimalanta and Yumul (2004) associated this arc with the subduction of the South China Sea Plate along the Manila-Negros Trench (fig. 5B). The area has been studied extensively to document the timing and nature of the collision of Palawan with the Philippine Mobile Belt.

The westernmost islands of the central Philippines are a complex collage of accretionary prism complexes, metamorphic rocks (schists and marbles), ophiolites, mélanges zones, and igneous rocks. Yumul and others (2009) documented at least five collision/accretion events and concluded that the collision boundary runs through western to central Mindoro Island. In northwestern Panay, the collision zone separates the Buruanga Peninsula (Palawan microcontinent) from the Antique Range (fig. 4C) of the Philippine Mobile Belt (Zamoras and others, 2008).

Multiple lines of geologic and geophysical evidence indicate that the original orientation of these islands was northwest-southeast, like the orientation of Masbate, Leyte, and Samar (fig. 2A). The present northeast-southwest orientation of these islands reflects clockwise rotation of Panay, Negros, Cebu, and Bohol (fig. 4A) and counterclockwise rotation of Mindoro (Yumul and others, 2009; Rangin and others, 1985).

### Geologic Criteria

The tract delineates syncollisional to postcollisional Neogene igneous rocks in an area that spans the collision zone. The tract was constructed by selecting map units coded

as Neogene intrusions and volcanic rocks from the digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines and Geosciences, 2004a) that fall within the Mindoro-Tablas-Western Panay Arc as outlined by Garwin and others (2005). Permissive rocks used to delineate the tract are shown in figure H2 and listed in table H2. The preliminary tract was developed using ArcGIS tools to create a 10-km buffer around intrusive rocks and a 2-km buffer around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand to include known, but unmapped permissive igneous rocks and prospects. The tract boundaries based on the 1:1,000,000-scale digital geology were compared with permissive rock distributions on recently released larger-scale maps for the islands in the tract area to ensure that the permissive rocks shown in the more detailed maps fall within the tract (table H4). The final tract segments were clipped to coastlines (U.S. Department of State, 2009).

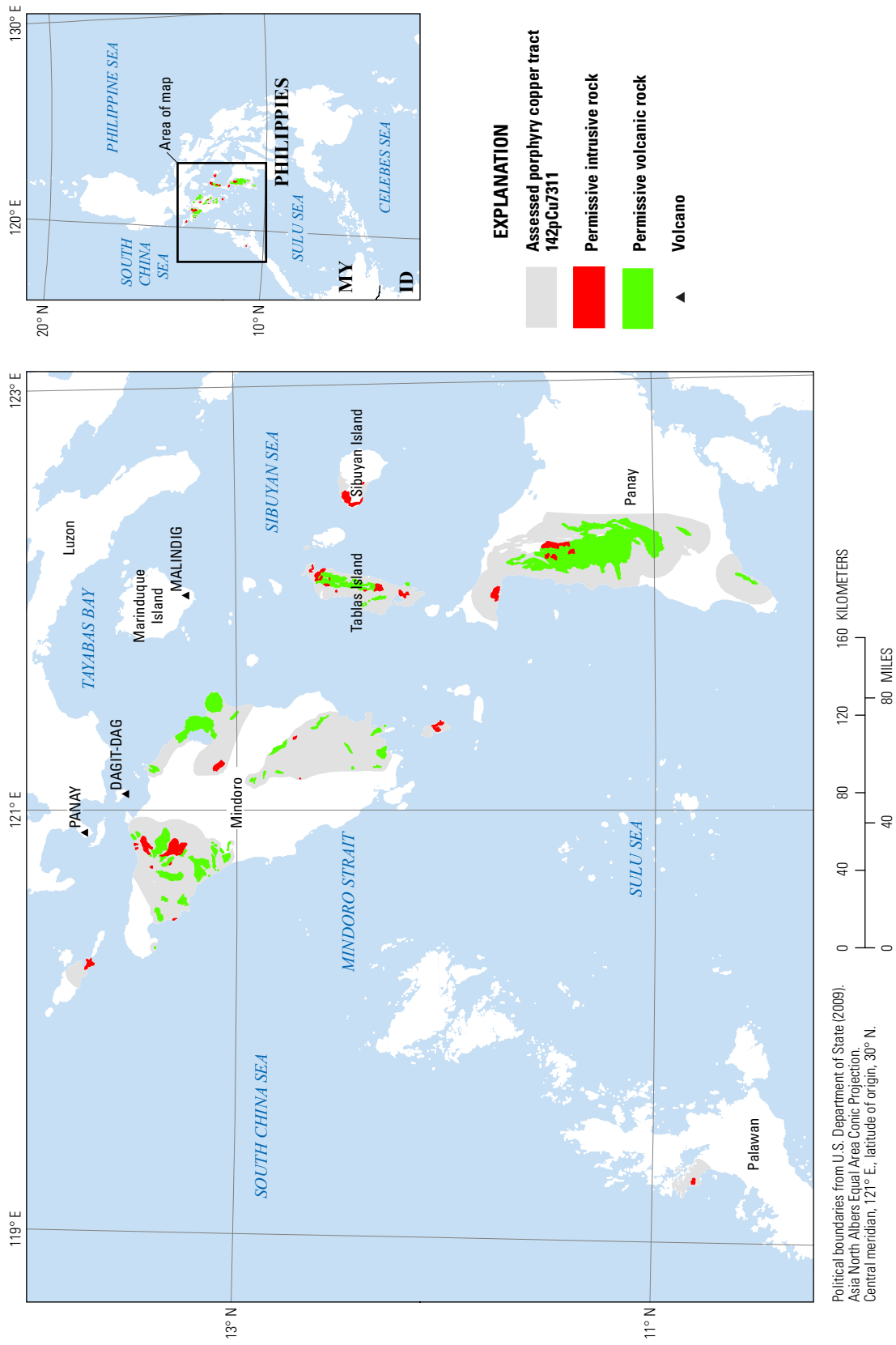
The tract includes Neogene intrusions and volcanic rocks on Mindoro Island, the Romblon Islands, Western Visayas (Panay), and a small area of exposed late Eocene to early Oligocene quartz monzonite in northern Palawan (fig. H2). Northeastern Mindoro Island has the island-arc characteristics of the Philippine Mobile Belt, whereas southwestern Mindoro is linked to the Palawan microcontinent. Romblon Province includes the islands of Tablas, Romblon, and Sibuyan as well as smaller islands. The Romblon islands primarily are composed of strongly deformed pre-Tertiary schists, marbles, and metavolcanic and ultramafic rocks intruded by quartz diorite and porphyritic andesite (Philippine Bureau of Mines and Geosciences, 2010b). Miocene (19.9 Ma, 18.5 Ma) and Pliocene (3.8 Ma, 4.4 Ma) medium-K calc-alkalic andesite and dacite on Tablas Island and Miocene quartz diorite (19.5 Ma) in northwestern Panay record syncollisional magmatism (Bellon and Rangin, 1991). Effects of the collision event (strike-slip faulting, fragmented ophiolite complexes, mélanges) are best displayed on the island of Panay (Rangin and others, 1991). The tract is composed of a number of separate parts because of the geography of the islands, all of which lie west of the Philippine Fault. No permissive rocks for porphyry copper deposits are mapped on Romblon Island, which is entirely metamorphic. Ophiolites are excluded from the tract area; many of the ophiolites have associated nickel prospects.

<sup>7</sup>Refer to figures and tables in main report.

**Table H2.** Map units that define tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines.

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963, and larger-scale maps listed in table H4)]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic rock sequences, less widespread in early Miocene rock sequences.	Neogene
Paleogene intrusive rocks	Pg <sub>1</sub>	Mostly quartz diorite. Quartz monzonite in Palawan, granodiorite to diorite on Mindoro, quartz diorite on Tablas.	Paleogene
Volcanic rocks			
Pliocene-Quaternary volcanic rocks	QV	Nonactive cones (generally pyroxene andesite); also dacitic and (or) andesitic plugs.	Pliocene-Quaternary
Neogene volcanic rocks	IN <sub>2</sub>	Principally dacite and (or) andesite flows, generally with pyroclastics.	Late Miocene-Pliocene
Neogene volcanic rocks	IN <sub>1</sub>	Mostly submarine andesite and (or) basalt flows. Intercalated with pyroclastics and clastic sedimentary rocks and (or) reef limestone lenses.	Oligocene-Miocene
Paleogene volcanic rocks	IPg <sub>2</sub>	Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin. Undifferentiated from early Miocene sedimentary rocks in some areas.	Oligocene
Paleogene volcanic rocks	IPg <sub>1</sub>	Limited dacite and andesite flows and dikes, generally intercalated with and (or) intrude Eocene clastics. Included with Eocene sedimentary rocks in this map.	Paleocene(?)–Eocene



**Figure H2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines. MY, Malaysia; ID, Indonesia.

**Table H3.** Significant prospects and occurrences in tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines.

[n.d., no data. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Northern Sierra Madre						
Caloring	12.300	122.050	n.d.	Porphyry-associated chalcopyrite-bornite on Tablas Island.	Philippine Mines and Geosciences Bureau (2004, written commun.)	1
Cogon	12.183	122.050	n.d.	Porphyry-associated chalcopyrite-bornite on Tablas Island.	Philippine Mines and Geosciences Bureau (2004, written commun.)	1
Tablas Copper One	12.373	122.051	n.d.	Copper prospect on Tablas Island	Philippine Mines and Geosciences Bureau (2010d)	1
Tablas Copper Two	12.641	122.148	n.d.	Copper prospect on northeastern Tablas Island	Philippine Mines and Geosciences Bureau (2010d)	1

## Known Deposits

None.

## Prospects, Mineral Occurrences, and Related Deposit Types

Four prospects and occurrences are known on Tablas Island (fig. H1, table H3). Possible porphyry-related occurrences are present on Mindoro.

### Romblon Islands

The Cogon and Caloring copper prospects on Tablas Island are reportedly porphyry-style occurrences having disseminated bornite and chalcopyrite associated with silicified diorite and andesite porphyry and metavolcanic rocks (fig. H1). Copper-staining is reported in quartz diorite and altered volcanic rocks in roadcuts and along shorelines in northeastern Tablas. Chalcopyrite and bornite also are reported in quartz veins in silicified serpentinite and quartz diorite on northwestern Sibuyan; it is not clear if these occurrences are porphyry related.

### Mindoro Island

A number of copper-rich polymetallic vein deposits are present in northern Mindoro, as well as in the Mindoro gold district. The Mindoro gold-quartz veins are associated with greenschist-facies metasedimentary rocks (Mitchell and Leach, 1991) and do not appear to be porphyry related. Pre-Pliocene porphyry and skarn prospects in eastern Mindoro were noted by Mitchell and Leach (1991), but we have no locations for these prospects. The Lubang volcanogenic massive sulfide copper deposit is located in the far northwestern part of the tract (Philippine Mines and Geosciences Bureau, 2004b).

## Exploration History

Prospect-scale exploration has taken place on Tablas and Mindoro Islands proximal to the porphyry-style and polymetallic vein occurrences. Ivanhoe Philippines, Inc., sought permits for mineral exploration for copper and gold on Tablas Island in 2010; applications were withdrawn following strong local opposition to mineral exploration (Mindanao Examiner, 2011). A geochemical soil survey for copper in northeastern Mindoro that followed up on vein and fissure-type copper associated with Paleogene dioritic intrusions in northeastern Mindoro concluded that the extent of mineralization was limited (Philippine Mines and Geosciences Bureau, 2010a). Some exploration and prospecting for mercury and manganese took place in Palawan; it is possible that indications of hydrothermal processes associated with porphyry copper were missed, but no copper occurrences are noted. Other than academic studies on the tectonics and stratigraphy within the North Palawan area, no exploration of any significance is known to have taken place.

According to the January 2012 mining tenement control maps for the area (Mindoro, Romblon, Tablas), no copper projects were active. Local opposition to metal mining and exploration is strong in the region, where several municipalities have sought a 25-year moratorium on metals extraction and changes in the mining law. The islands included in the tract lie within Region 4b of the Philippine Mines and Geosciences Bureau; the most recent information on exploration and development in the area can be accessed on their Web site at [http://region4b.mgb.gov.ph/?q=geology\\_and\\_mineralresource\\_list](http://region4b.mgb.gov.ph/?q=geology_and_mineralresource_list).



## Sources of Information

The tract was based on permissive igneous rocks as shown on the 1:1,000,000-scale geologic map of the Philippines and larger scale maps of Tablas, Mindoro, Panay, and Palawan. Local and regional mineral occurrence databases and occurrences shown on geological and mineral occurrence maps also were used (Philippine Mines and Geosciences Bureau, 2004a, b). See table H4 for sources of information.

## Grade and Tonnage Model Selection

On the basis of the gold-rich character of most porphyry deposits in the Philippines, recommendations of a regional analysis (Drew and Singer, 2005), and the possibility that the

tract area may be a continuation of the western segment of the Luzon Arc that hosts numerous porphyry copper-gold deposits (Dizon, Taysan, Marcopper), the copper-gold subtype model was used for the assessment of the tract.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The tract does not encompass a well-defined, mineralized magmatic arc. The relation between the collision events and magmatism is not fully understood; reported ages indicate that multiple pulses of magmatism occurred. The level

**Table H4.** Principal sources of information used for tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010e)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Geology and mineral resources of Mindoro Island	1:400,000	Philippine Mines and Geosciences Bureau (2010a)
	Geology and mineral resources of map of Tablas Island, Romblon Province	1:500,000	Philippine Mines and Geosciences Bureau (2010d)
	Geology and mineral resources of map of Romblon Island	1:50,000	Philippine Mines and Geosciences Bureau (2010b)
	Geology and mineral resources of map of Sibuyan Island, Romblon Province	1:50,000	Philippine Mines and Geosciences Bureau (2010c)
	Digital geologic map of East and Southeast Asia	1:2,000,000	Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia (CCOP) and Geological Survey of Japan (1997)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Bureau of Mines and Geosciences (2004b)
	Mineral resource map of Asia: Metal Mining Agency of Japan	NA	Kamitani and Naito (1998)
Exploration	Philippine Mines and Geosciences Bureau Region 4B Web site, tenement maps and reports	NA	<a href="http://region4b.mgb.gov.ph/">http://region4b.mgb.gov.ph/</a>

of exposure is permissive for porphyry deposits because the tract area includes both intrusions and coeval volcanic rocks. The tract lacks the association with epithermal gold deposits that is characteristic of the major porphyry districts in the Philippines. Plans for copper and gold exploration on Tablas Island were halted due to social opposition, so no modern exploration data are available. Consideration of the remoteness, the fact that much of the tract has not been thoroughly explored, and that parts of the tract are covered led the assessment team to estimate a 50-percent chance of one or more deposits, a 10-percent chance for two or more deposits, and a 5-percent chance of three or more deposits. The mean result is one undiscovered deposit with a relatively high degree of uncertainty ( $C_v=91$  percent).

### Probabilistic Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining the consensus estimate for numbers of undiscovered porphyry copper deposits with the global copper-gold subtype 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 H6. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. H3). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock.

**Table H5.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines.

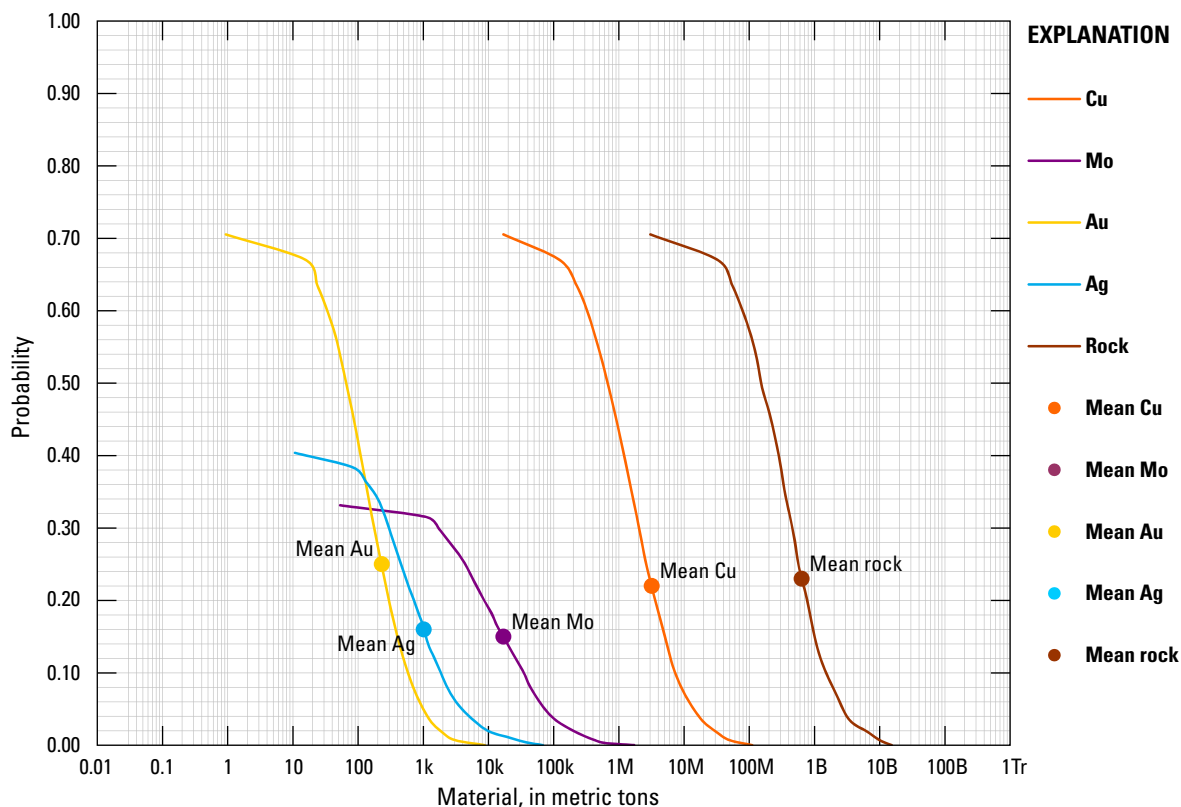
[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model;  $N_{total}$ , total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers ( $km^2$ ); 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	1	2	3	3	1.1	0.98	91	0	1.1	9,170	12

**Table H6.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7311, Mindoro-Tablas-West Panay—Philippines.

[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	670,000	7,300,000	14,000,000	3,200,000	0.22	0.29
Mo	0	0	0	35,000	73,000	17,000	0.15	0.67
Au	0	0	66	590	990	230	0.25	0.29
Ag	0	0	0	1,900	4,200	1,000	0.16	0.60
Rock	0	0	150	1,500	2,800	630	0.23	0.29



**Figure H3.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7311, Mindoro-Tablas-West Panay Area—Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix I. Porphyry Copper Assessment for Tract 142pCu7306, Bohol-Cebu Area—Philippines

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### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, general model (Singer and others, 2008)

Table I1 summarizes selected assessment results.

**Table I1.** Summary of selected resource assessment results for tract 142pCu7306 Bohol-Cebu Area—Philippines.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified resources rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	9,170	0	3,200,000	670,000

### Location

Bohol Island and Cebu Island (fig. I1).

### Geologic Feature Assessed

Cretaceous, Paleogene, and Miocene magmatic belt on Bohol and Cebu Islands.

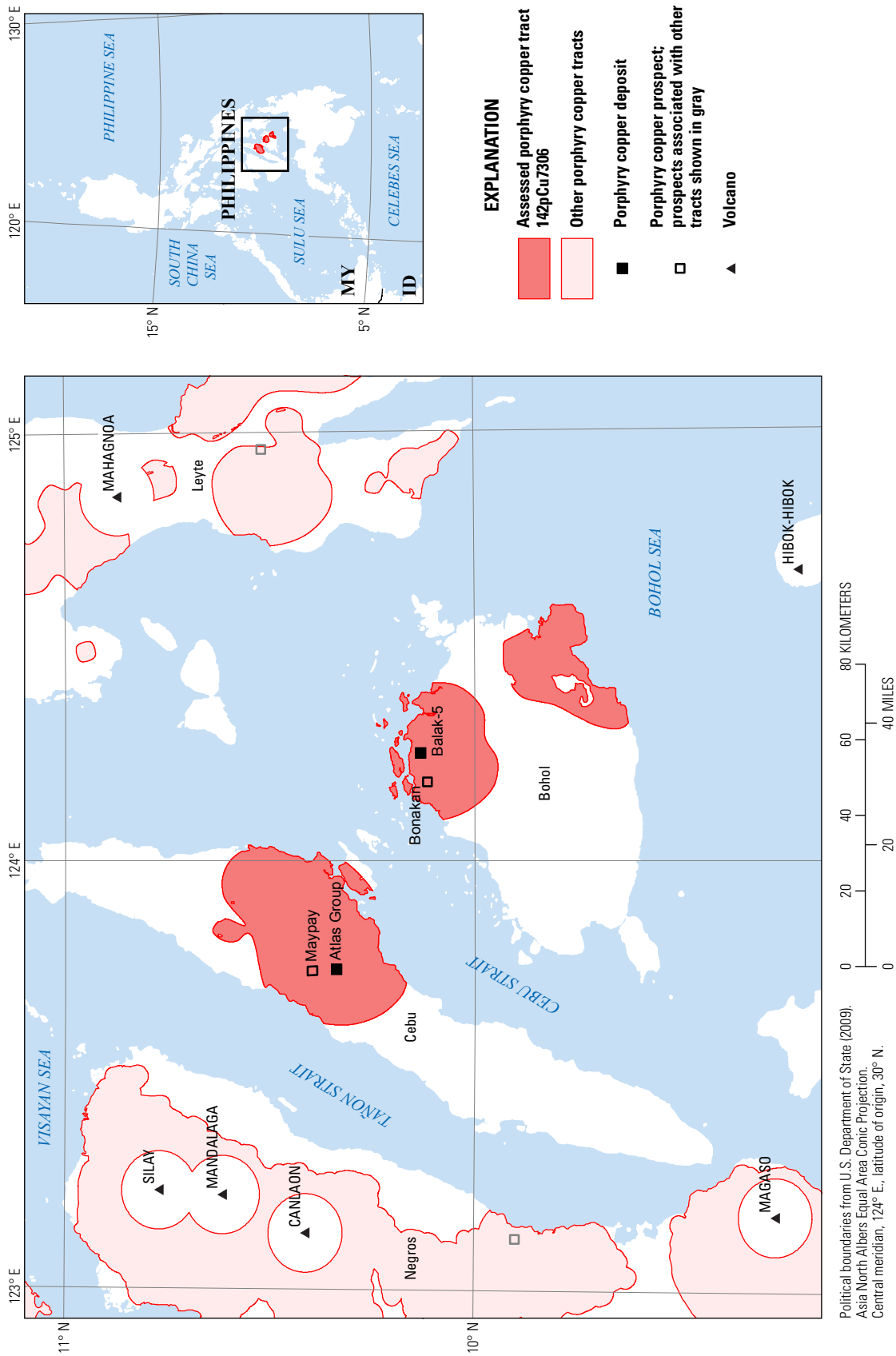
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure 11.** Map showing tract location and significant porphyry copper prospects for tract 142pCu7306, Bohol-Cebu Area, Philippines. MY, Malaysia; ID, Indonesia.

## Delineation of the Permissive Tract

### Tectonic Setting

The relation of igneous rocks on Bohol and Cebu Islands to magmatic arcs and subduction zones is uncertain. Miocene diorite plutons and andesitic and dacitic volcanic rocks, possibly related to an early Miocene trench that lay to the east of Bohol, are described as the Northwestern Bohol Arc by Mitchell and Leach (1991). They suggested that middle Miocene andesites on Cebu might be part of a single arc system that extended to western Mindanao to the south; alternatively, an east-facing Miocene arc may have been continuous with the Sulu-Zamboanga arc system (fig. 2<sup>6</sup>). Miocene andesitic volcanic rocks also are present in southeastern Bohol.

Cretaceous and Paleogene igneous rocks (quartz diorite, andesite) are present on both islands. Isolated areas of Cretaceous arc rocks were documented farther north in the Philippines on Catuandanes Island and in southeastern Luzon on Rapu Rapu Island (fig. 4A) (Dimalanta and Yumul, 2004), where a northwest-striking (present-day orientation) Late Cretaceous arc may be related to subduction of the Philippine Sea Plate along a proto-East Luzon Trough (Yumul and others, 2003). The nature and extent of Cretaceous arc magmatism on Cebu and the relation to younger arc rocks requires further studies. As noted by Mitchell and Leach (1991), pre-Tertiary unmetamorphosed arc volcanic rocks have been recognized only on Cebu Island, and on some maps, Cretaceous-Paleogene ages were incorrectly assigned to Tertiary rocks because of hydrothermal alteration and lack of fossils. For the purposes of this assessment, the occurrence of the disparate age groups on the two islands is considered informally as the Bohol-Cebu magmatic belt.

### Geologic Criteria

Tract 142pCu7306 delineates pre-Pliocene quartz diorite intrusions and andesitic rocks that occur in a northwest-trending belt extending from southeastern Bohol to the central highlands of Cebu (fig. I2). The permissive tract was constructed by selecting igneous rocks from a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines and Geosciences, 2004a). The map units were classified by age groups, and subdivided into intrusive and volcanic subgroups. Larger scale maps for central Cebu and southeastern Bohol (listed in table I5) were rectified and compared with the smaller-scale digital maps (table I2). Map unit lithologies were examined, and rock types that were not considered permissive for porphyry copper deposits, such as ultramafic rocks and ophiolite complexes, were excluded.

Using GIS tools, a 10-km buffer was created around intrusive rocks and a 2-km buffer was created around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand to include known but unmapped permissive igneous rocks and prospects. Site locations for dated and classified igneous rocks were also used to constrain tract boundaries (Malaihollo and others, 2002). The final tract segments were clipped to coastlines (U.S. Department of State, 2009).

### Bohol Island

The Paleocene-late Eocene Ubay Volcanics in northeastern Bohol include dacite, pyroxene andesite, and basalt. They have been intruded by diorite. Hydrothermally altered rocks are described in a limited area in the northwestern part of the island. Small diorite bodies (Talibon diorite) are present along a northeasterly trend in northern Bohol. The diorite (late Eocene-early Oligocene) intrudes coeval porphyritic hornblende andesite. A Miocene andesite (Janga andesite) crops out on southeastern Bohol Island (Philippine Bureau of Mines and Geosciences, 1981).

### Cebu Island

The northeast-trending composite Lutopan Diorite (diorite, quartz diorite, andesite, dacite, gabbro) intruded Cretaceous sedimentary and volcanic rocks on central Cebu Island. The age of the complex is problematic and may record a long magmatic history. Reported radiometric ages include the following: 101-Ma K-Ar and 107-Ma Rb-Sr ages from the Biga and Frank ore bodies at the Atlas Mine (Walther and others, 1981) and a 59.7±1.2-Ma whole-rock K-Ar age for diorite from the Lutopan pit at the Atlas Mine (Wolfe, 1973; Malaihollo and others, 2002). Middle Miocene diorite and quartz monzonite stocks dated at 12.5±0.6 Ma and mid- to late Miocene andesite flows and pyroclastic rocks are exposed in the central highland areas of Cebu Island. Geochemical data for seven samples of hornblende quartz diorite, quartz diorite porphyry, and postmineral andesite at the Atlas Mine were reported by Divis (1983); these samples ranged from 61 to 68 percent in SiO<sub>2</sub> content and contained elevated metal concentrations (12–523 ppm copper, 380–10,800 ppm tin).

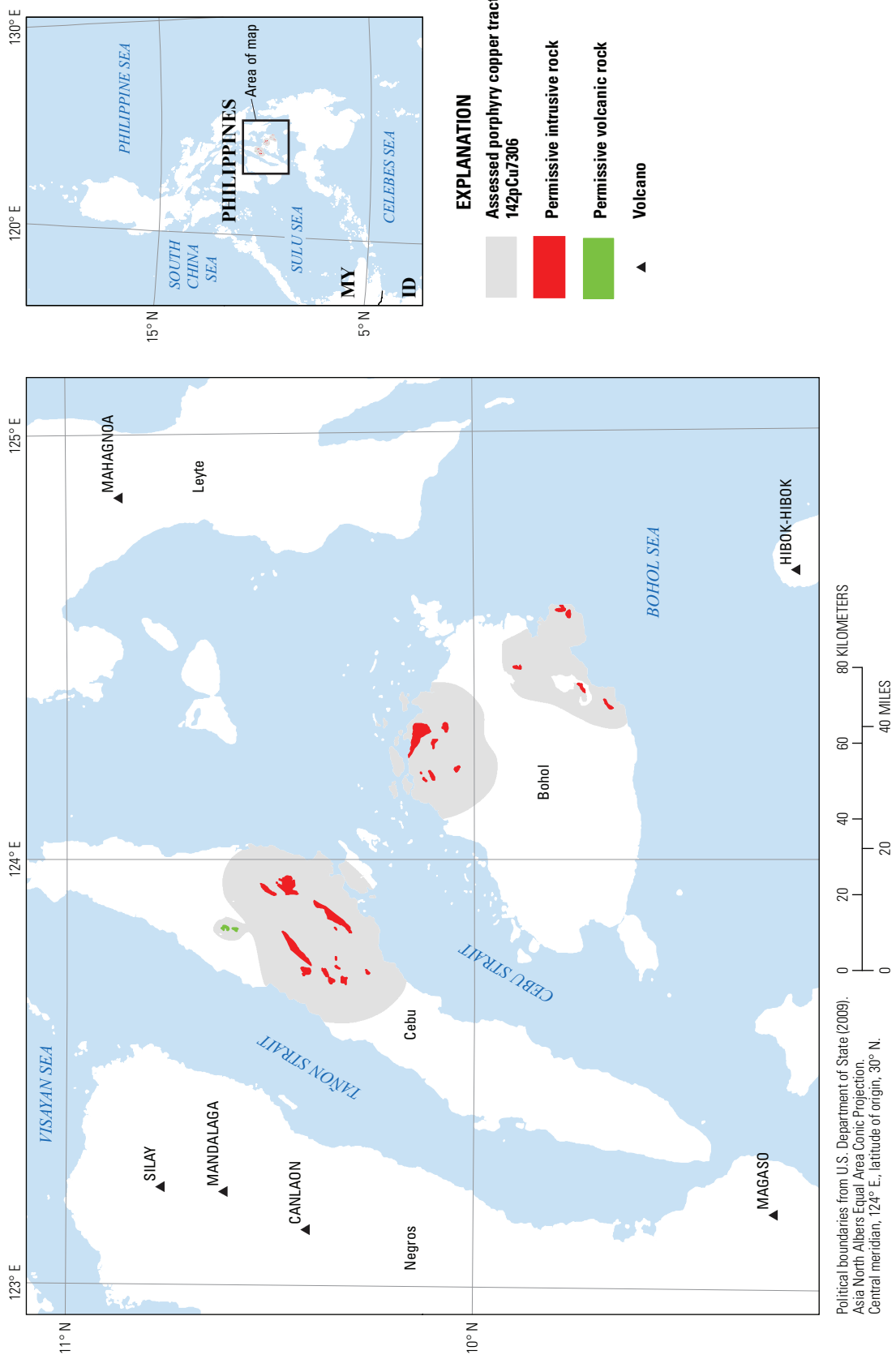
Figure I3 illustrates the geology in the Atlas Mine area, as shown by Divis (1983) and the Philippine Bureau of Mines and Geosciences (1986). The Pardo 1:50,000-scale geological map, which covers the mine area, shows that the mapped Cretaceous Lutopan Diorite (dated at the Lutopan pit as Paleocene or Eocene) intrudes the Cretaceous Managa Group, which includes the Pandan Formation and Cansi Volcanics shown in figure I3.

<sup>6</sup>Refer to figures and tables in main report.

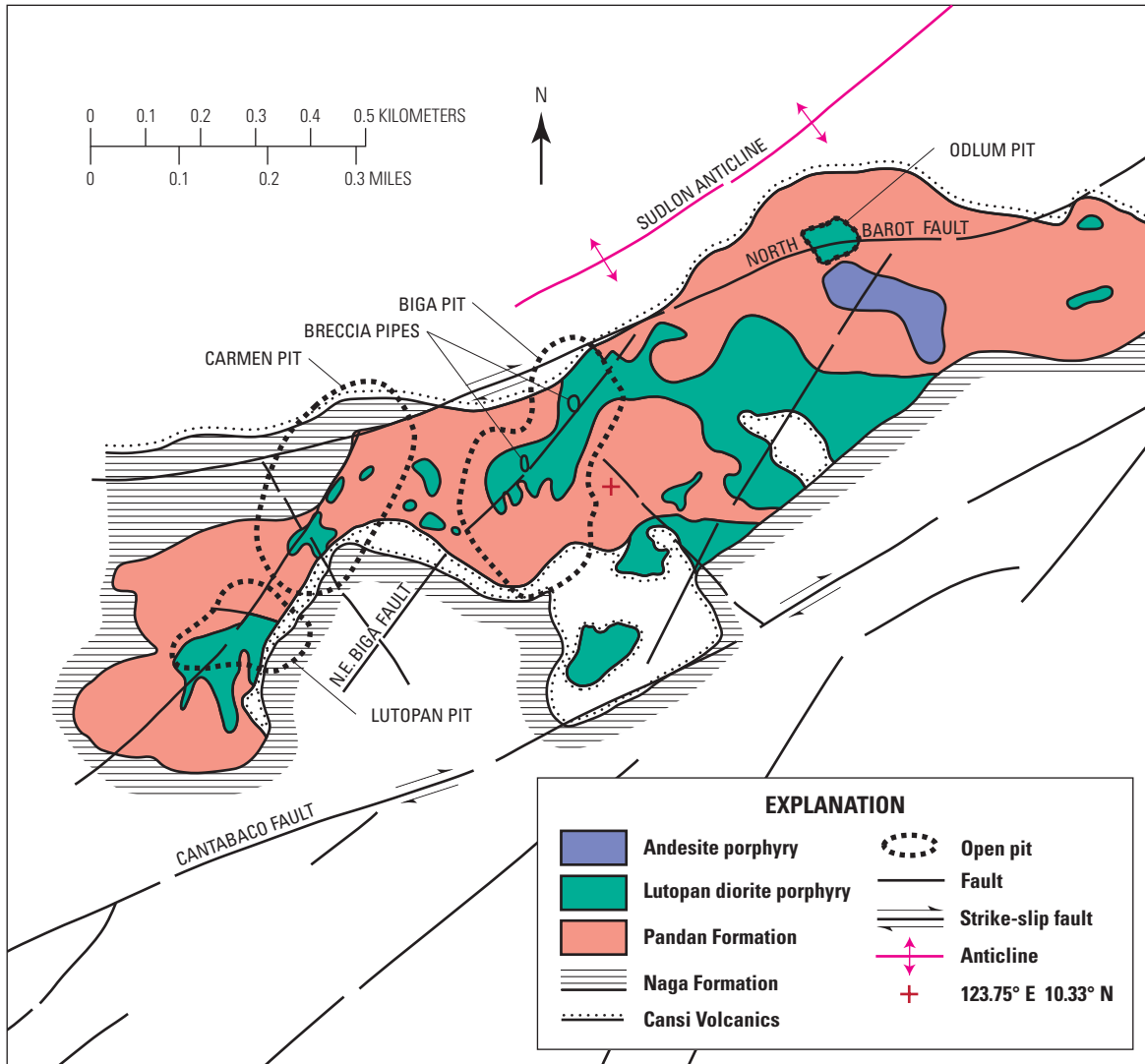
**Table 12.** Map units that define tract 142pCu7306, Bohol-Cebu Area—Philippines.

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963). Named units are from the 1:50,000-scale maps for Buanoy, Danao, Balamban, Liloan, and Pardo quadrangles on Cebu Island and the Anda, Jagna, and Sierra Bullones quadrangles in southeastern part of Bohol Island]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
Neogene intrusive rocks	NI	Largely Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Include granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene rock sequences.	Neogene
Paleogene intrusive rocks	Pg <sub>1</sub>	Mostly quartz diorite.	Paleogene
Lutopon Diorite	LD	Cebu: Medium-to coarse equigranular hornblende biotite diorite	Cretaceous
Talamban Diorite	Td	Cebu: Medium to fine-grained hornblende diorite with magnetite-bearing skarn along contact zones.	Middle Miocene
Talibon Diorite	Td	Bohol: Quartz diorite in scattered bodies in northern Bohol, associated porphyry; gold and copper mineralized halos along contacts with volcanic rocks.	Paleocene
Volcanic rocks			
Paleogene volcanic rocks	IPg <sub>2</sub>	Essentially keratophyre and andesite flows. Often with pyroclastics and chert of volcanic origin. Undifferentiated from early Miocene sedimentary rocks in some areas.	Oligocene
Bulucao Andesite	BA	Cebu: Porphyritic andesite; partly intrusive breccia.	Middle Miocene
Jagna Andesite	JA, Njo	Bohol: Porphyritic andesite, porphyritic andesite plug.	Early to middle Miocene
Ubay Volcanics	Puv	Bohol: Agglomerates, volcanic flows of andesitic and basaltic composition, and intrusives of gabbro and diabase.	Early to middle Miocene



**Figure 12.** Map showing the distribution of permissive igneous rocks for tract 142pCu7306, Bohol-Cebu Area, Phipippines. MY, Malaysia; ID, Indonesia.



**Figure 13.** Sketch map of the historical Atlas Mine on Cebu Island, modified from Divis (1983) and Philippine Bureau of Mines and Geosciences (1986).

### Known Deposits

The tract contains two deposits with reported grades and tonnages, the Balak deposit on Bohol Island and the Atlas Group of deposits on Cebu Island (fig. I1, table I3.)

#### Bohol Island

The Balak deposit has supergene reserves of 5 Mt of 0.80 percent copper. Drilling in the 1970s reported intercepts greater than 90 m with grades for copper (less than or equal to 0.43 percent), molybdenum (0.035 percent) and gold (0.6 g/t). Minerals reported at Balak include alunite, chalcopryrite, hematite, pyrite, malachite, cuprite, copper, neotocite, limonite, sericite, and tourmaline.

#### Cebu Island

The oldest porphyry copper deposit recognized to date in the Philippines is the Atlas Group (fig. I1), which is associated with Cretaceous (?) and Paleogene quartz diorite, hornblende diorite porphyry intrusions, dacite porphyry, breccia, and volcanoclastic rocks on Cebu. The deposit lies within a 2-km wide horst (Divis, 1983). The major ore bodies in the deposit, Lutopan, Biga, and Carmen (fig. I3) are bounded by parallel east-northeast-striking faults that define the horst (Philippine Bureau of Mines and Geosciences, 1986). A dacite porphyry sill was mapped in the upper part of a mushroom-shaped diorite porphyry in the Lutopan pit at the Atlas Mine.

Garwin and others (2005) classified the Atlas deposit as a porphyry copper-gold-molybdenum system. Ore minerals include both hypogene (chalcopryrite, bornite) and supergene (chalcocite, covellite, azurite/malachite, chrysocolla) copper minerals.



**Table I3.** Porphyry copper deposits in tract 142pCu7306, Bohol-Cebu Area—Philippines.

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × (Cu grade, in % ÷ 100); NA, not applicable; n.d., no data]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Bohol Island											
Balak-5	10.133	124.250	NA	n.d.	5	0.80	n.d.	n.d.	n.d.	40,000	Hope (1971), Kinkel and others (1956), Sillitoe and Gappe (1984)
Cebu Island											
Atlas Group	10.339	123.746	NA	108	1,420	0.448	0.018	0.24	1.8	6,400,000	Arcilla and others (1990), Atlas Consolidated Mining and Development Corporation (2010, 2012), Clark and Arancibia (1996), Divis (1983), Hutchinson (1996), Kinkel and others (1956), Madamba (1972), Motegi (1977), Philippine Bureau of Mines and Geosciences (1986), Reyes and others (1985), Sillitoe and Gappe (1984), Singer and others (2008), Walther and others (1981)

Production from the Atlas Mine on Cebu Island began in 1955. Mining was suspended in 1995; the Carmen Copper Corporation (a subsidiary of Atlas Consolidated Mining and Development Corporation) reopened the mine in 2007 with reported reserves of 873.8 Mt at 0.41 percent copper (Atlas Consolidated Mining and Development Co., 2010, 2012). In 2008, the Biga pit (fig. I3) was converted to a tailings pond. Most of the ore produced in 2011 came from the Lutopan pit. In 2012, both the Lutopan and Carmen pits were mined (Atlas Consolidated Mining and Development Corporation, 2013). Singer and others (2008) reported total resources and reserves for the Atlas (also known as the Biga or Toledo deposit) ore bodies, including the Biga, Carmen 1, Carmen 2, and Lutopan pit areas, as 1,420 Mt having average grades of 0.45 percent copper, 0.018 percent molybdenum, 0.24 g/t gold, and 1.8 g/t silver with 8 ppb platinum and 56 ppb palladium in Biga ore concentrate.

## Prospects, Mineral Occurrences, and Related Deposit Types

Porphyry copper-related prospects are plotted as open squares on fig. I1 and described in table I4.

### Bohol Island

Five porphyry prospects were identified within a 25-km<sup>2</sup> area during exploration in the 1950s to 1970s, which led to delineation of the resource at Balak-5. Porphyry copper

prospects are related to the Talibon diorite and the Ubay volcanics. The Bonakan copper-gold prospect (fig. I1) has reported grades of 1.02 percent copper and 4.18 g/t gold in narrow gold-bearing veins in andesite.

Alluvial gold was worked in areas south and west of the porphyry area; advanced argillic alteration is associated with some porphyry prospects and in areas unrelated to known epithermal or porphyry prospects.

### Cebu Island

The Toledo Copper Complex exploration area (Atlas Consolidated Mining and Development Corporation, 2012) includes several prospects within and outside of the structural corridor that hosts the Lutopan, Biga, and Carmen pits, along parallel faults. Most of these are within approximately 2 km of the areas of identified resources. These are active exploration areas (mapping, grid soil sampling) for the identification of drill targets. Bornite is present in a 4.5 km long by 1.5 km wide zone of hydrothermal alteration (biotite-quartz-sericite-clay) along a diorite contact at the Maypay porphyry copper-gold prospect, located 6 km north of the Carmen ore body (fig. I1). Structurally controlled, east-northeast-striking en echelon quartz veins in altered volcanic rocks may be the source of the artisanal gold mined in the Maypay area (Atlas Consolidated Mining and Development Corporation, 2012).

Other porphyry prospects on Cebu are based on wild-cat drilling in the 1960s, mapping, and grid sampling in the West Lutopan area, but we do not have information on exact locations or the age of the mineralized intrusions. According

to the Atlas Consolidated Mining and Development Corporation Web site (2012), separate, concealed porphyry copper targets are present 1 km south of the Biga ore body, 2 km south along the Biga Northeast Fault, 0.5 km and 1 km south of the Lutopan ore body, and 5 km west-northwest of the Lutopan ore body (see fig. 13 for the 1977-era locations of the historical pits and mapped faults). Based on spatial rules, these targets would all probably be considered as extensions of the identified resources. An approximate location for the Maypay prospect, which could represent a separate deposit, is plotted in figure I1.

## Exploration History

Exploration activities on Cebu include two ongoing projects of the Atlas Consolidated Mining and Development Corporation (2012). One project is an assessment of mine waste dumps (1.2 billion metric tons) from 1955 to 1993 for copper recovery. Historical cutoff grades (0.5 and 0.3 percent copper) suggest that recoverable copper may be present in the piles. The second project is exploration of six partially explored prospects for extensions and satellites of the Lutopan, Carmen, and Biga resources.

## Sources of Information

Principal sources of information used by the assessment team are listed in table I5. Descriptions of the rocks on Bohol and Cebu, as described in the revised edition of the geology of the Philippines (Philippines Mines and Geosciences Bureau, 2010), also are available on the Region 7 Web site at <http://dvasia.ph/viewgeology.php?region=Region%20VII>.

## Grade and Tonnage Model Selection

The Atlas and Balak deposits are copper-gold-molybdenum deposits. Statistical tests indicate that both global general and copper-gold subtypes are acceptable models for the simulation. No reliable average grades for molybdenum, gold, or silver are available for Balak; however, the reported drill intercepts indicate that both molybdenum and gold are present. Therefore, the general porphyry copper model of Singer and others (2008) was used for the simulation of undiscovered resources.

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

The small size of the permissive tract area (2,600 km<sup>2</sup>) defined by the extent of onshore exposures of permissive rocks on islands limits the number of individual porphyry systems that could be present. The horst in central Cebu accommodated erosion that exposed the Atlas deposit; Cretaceous sedimentary rocks elsewhere in central Cebu can be as much as 2 km thick and may conceal buried deposits at depths greater than the 1-km depth adopted for the assessment. Based on assessment protocols, deposits that have overlapping alteration zones within 2 km of each other are grouped as a single deposit. Most of the known prospects on Cebu Island are likely to be extensions of the Atlas system. However, the team, considered the possibility of a discrete ore body on Cebu, as well as the area of permissive rock and prospects on

**Table I4.** Significant prospects and occurrences in tract 142pCu7306 Bohol-Cebu Area—Philippines.

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Bohol Island						
Bonakan	10.117	124.183	n.d.	Bonakan Cu-Au prospect (1.02% Cu, 4.18 g/t Au); narrow gold-bearing veins in andesite.	Philippine Mines and Geosciences Bureau (2004b)	2
Cebu Island						
Maypay	10.026	123.726	n.d.	Porphyry copper-gold prospect located 6 km north of the Carmen pit of the Atlas Mine. Chalcopyrite and bornite associated with biotite-quartz-sericite-pyrite-clay alteration. Preliminary drilling planned (2013).	Atlas Consolidated Mining and Development Corporation (2012), Philippine Mines and Geosciences Bureau (2004b)	2

**Table I5.** Principal sources of information used for tract 142pCu7306 Bohol-Cebu Area—Philippines.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
	Geological map of the Jagna quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1987b)
	Geological map of Sierra Bullones quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1987c)
	Geological map of Anda quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1987a)
	Geological map of Balilihan quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1987d)
	Geological map of Pardo quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983a)
	Geological map of Buanoy quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983b)
	Geological map of Danao quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983c)
	Geological map of Liloan quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983d)
	Geological map of Balamban quadrangle	1:50,000	Philippine Bureau of Mines and Geosciences (1983e)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Bureau of Mines and Geosciences (2004b)
	Mining places in the Philippines (kml file)	NA	GoogleEarth® (2013)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984), Mitchell and Leach (check)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites	NA	Atlas Consolidated Mining and Development Corporation (2010, 2012)

Bohol (table I4) and estimated a 50-percent chance of one or more undiscovered deposit within the Bohol-Cebu tract and a 10-percent chance of three or more deposits (table I6). This estimate results in a mean of 1.3 undiscovered deposits with a relatively high coefficient of variation (90 percent), reflecting a high degree of uncertainty.

**Probabilistic Assessment Simulation Results**

Undiscovered resources for the tract were estimated by combining the consensus estimate for numbers of undiscovered porphyry copper deposits with the global 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 I7. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. I4). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. Both the mean and the median predicted amounts of undiscovered copper within the tract are less than the identified resources at the two known deposits (table I1). See table 6 for comparisons with identified copper and gold resources and with other tracts.

**Table I6.** Undiscovered deposit estimates, deposit numbers, and tract area for tract 142pCu7306 Bohol-Cebu Area—Philippines.

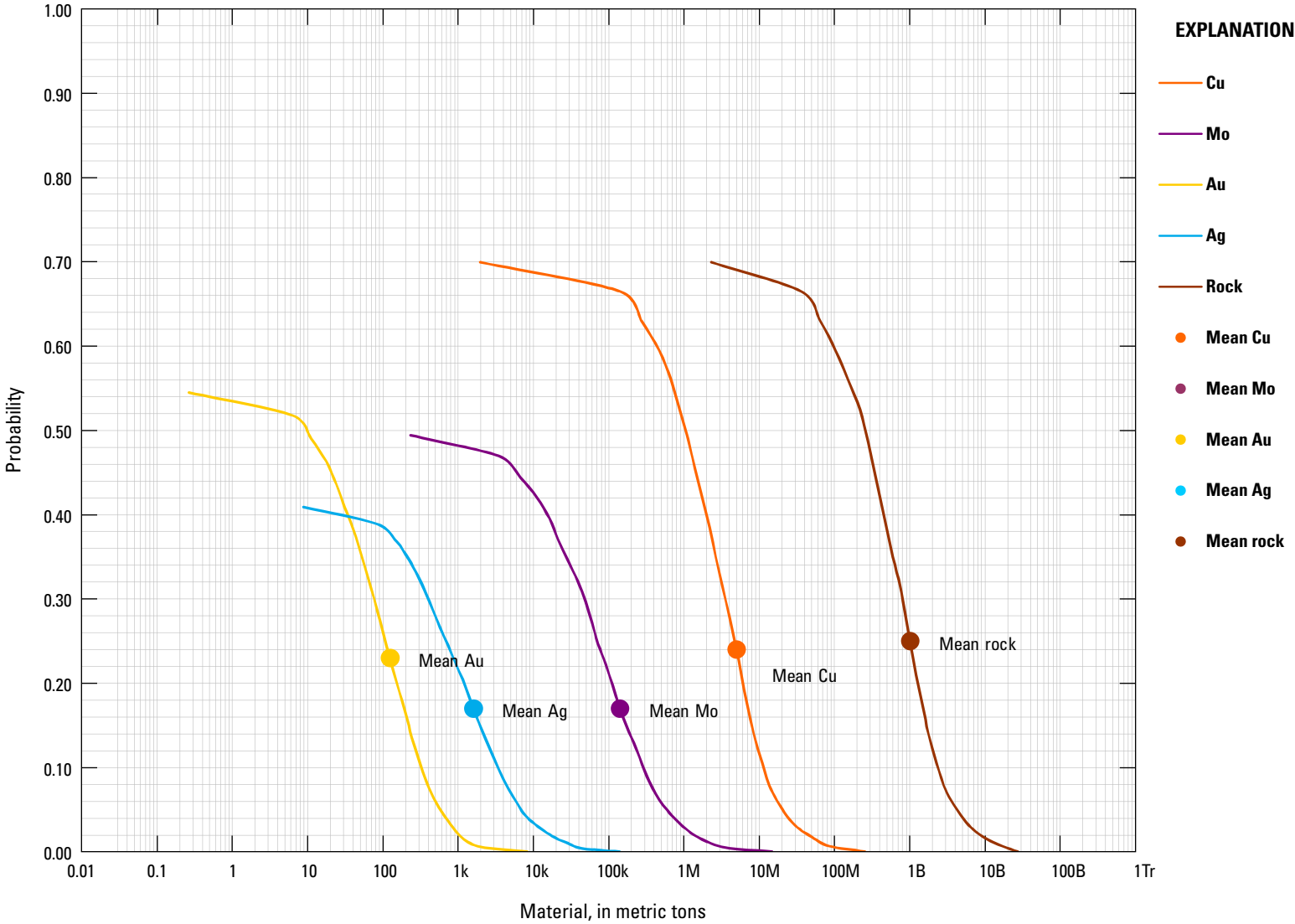
[ $N_{xx}$ , estimated number of deposits associated with the xxth percentile;  $N_{und}$ , expected number of undiscovered deposits;  $s$ , standard deviation;  $C_v\%$ , coefficient of variance;  $N_{known}$ , number of known deposits in the tract that are included in the grade and tonnage model;  $N_{total}$ , total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers ( $km^2$ ); 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	1	3	3	3	1.3	1.2	90	2	3.3	2,600	127

**Table I7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7306 Bohol-Cebu Area—Philippines.

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

Material	Probability of at least the indicated amount					Probability of		
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu	0	0	1,000,000	11,000,000	20,000,000	5,000,000	0.24	0.30
Mo	0	0	0	290,000	590,000	140,000	0.17	0.51
Au	0	0	9	320	580	130	0.23	0.45
Ag	0	0	0	3,400	6,800	1,600	0.17	0.59
Rock	0	0	260	2,400	4,000	1,000	0.25	0.30



**Figure I4.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in 142pCu7306, Bohol-Cebu Area, Philippines. k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix J. Porphyry Copper Assessment for Tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China)

By Jane M. Hammarstrom<sup>1</sup>, Arthur A. Bookstrom<sup>2</sup>, Connie L. Dicken<sup>1</sup>, Steve Ludington<sup>3</sup>, Gilpin R. Robinson, Jr.<sup>1</sup>, and Michael L. Zientek<sup>2</sup> with contributions from Seville (Bill) D. David, Jr.<sup>4</sup>, Claro J. Manipon<sup>4</sup>, Lilian A. Rollan<sup>4</sup>, and Yasushi Watanabe<sup>5</sup>

### Deposit Type Assessed: Porphyry copper, copper-gold subtype

**Descriptive model:** Porphyry copper (Cox, 1986; Berger and others, 2008; John and others, 2010; Sillitoe and Gappe, 1984)

**Grade and tonnage model:** Porphyry copper, copper-gold subtype (Singer and others, 2008)

Table J1 summarizes selected assessment results.

**Table J1.** Summary of selected resource assessment results for tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric tons; identified resources rounded to two significant figures]

Date of assessment	Assessment depth (km)	Tract segment	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2010	1	(a) Northern (Taiwan)	1,058	0	31,000,000	22,000,000
		(b) Luzon Central Cordillera	15,970	12,000,000		
		(c) Western Luzon	6,071	5,100,000		
		(d) Eastern Luzon	599	0		
Total			23,700	17,000,000	31,000,000	22,000,000

### Location

The tract extends for approximately 1,200 km from western Luzon Island in the Philippines to southeastern Taiwan (Republic of China) (fig. J1).

### Geologic Feature Assessed

Oligocene to Holocene Luzon Arc.

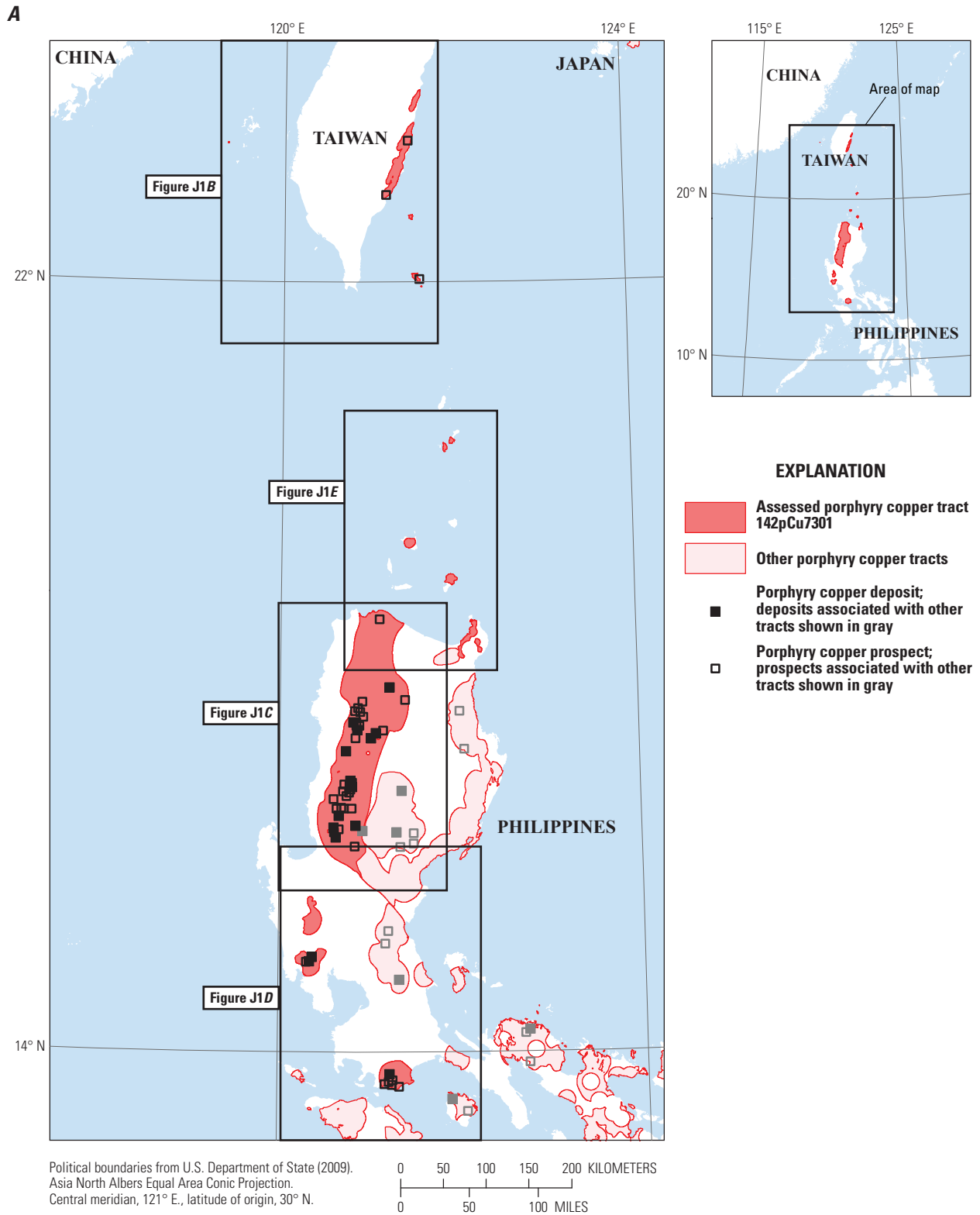
<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Spokane, Washington, United States.

<sup>3</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>4</sup>Philippine Department of Environment and Natural Resources, Mines and Geosciences Bureau, Quezon City, Philippines.

<sup>5</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.



**Figure J1.** Maps showing tract location, deposits, and significant prospects for tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China). *A*, Overview. *B*, Taiwan segment. *C*, Luzon Central Cordillera segment. *D*, Western segment. *E*, Eastern segment. TW, Taiwan (Republic of China).

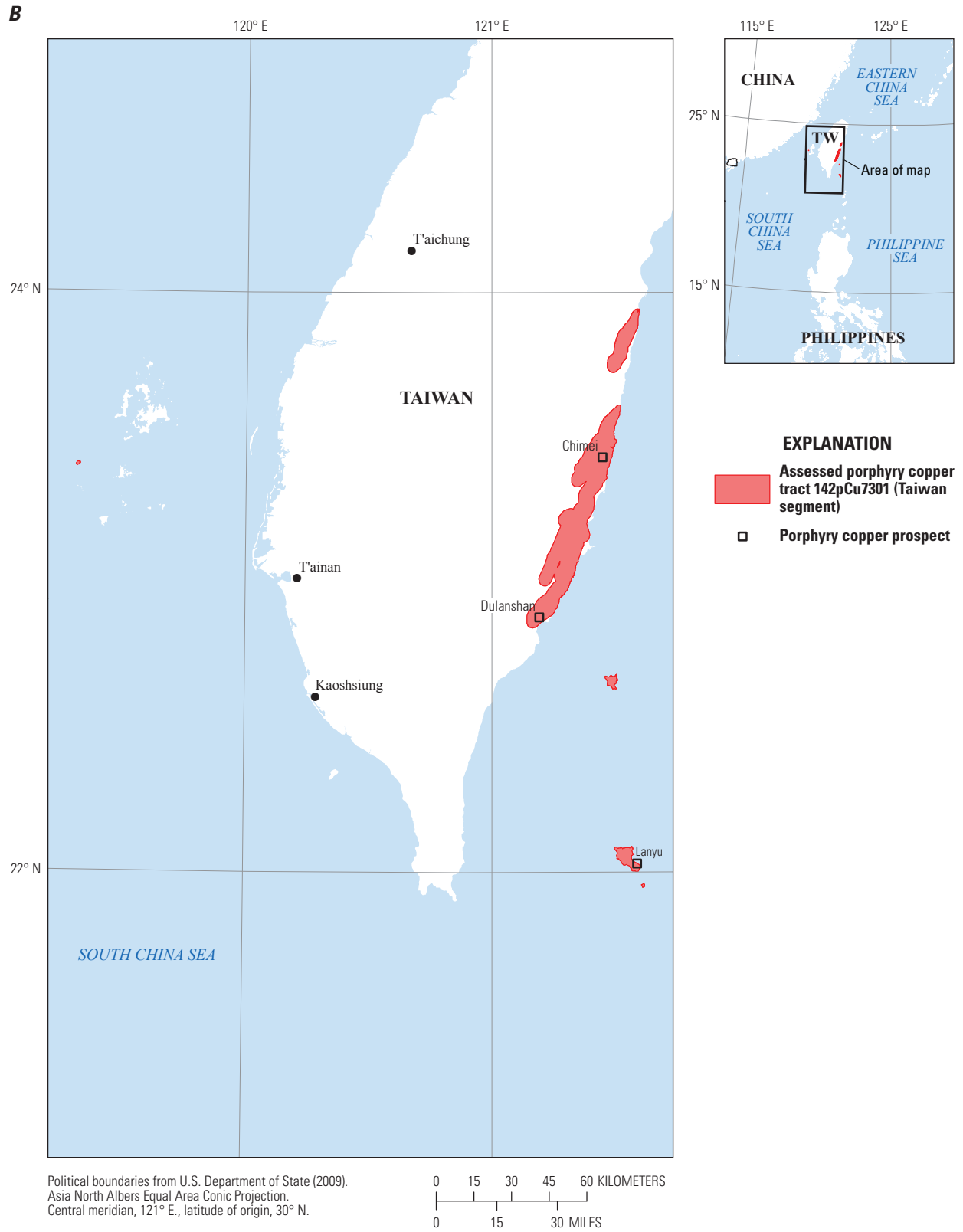


Figure J1.—Continued

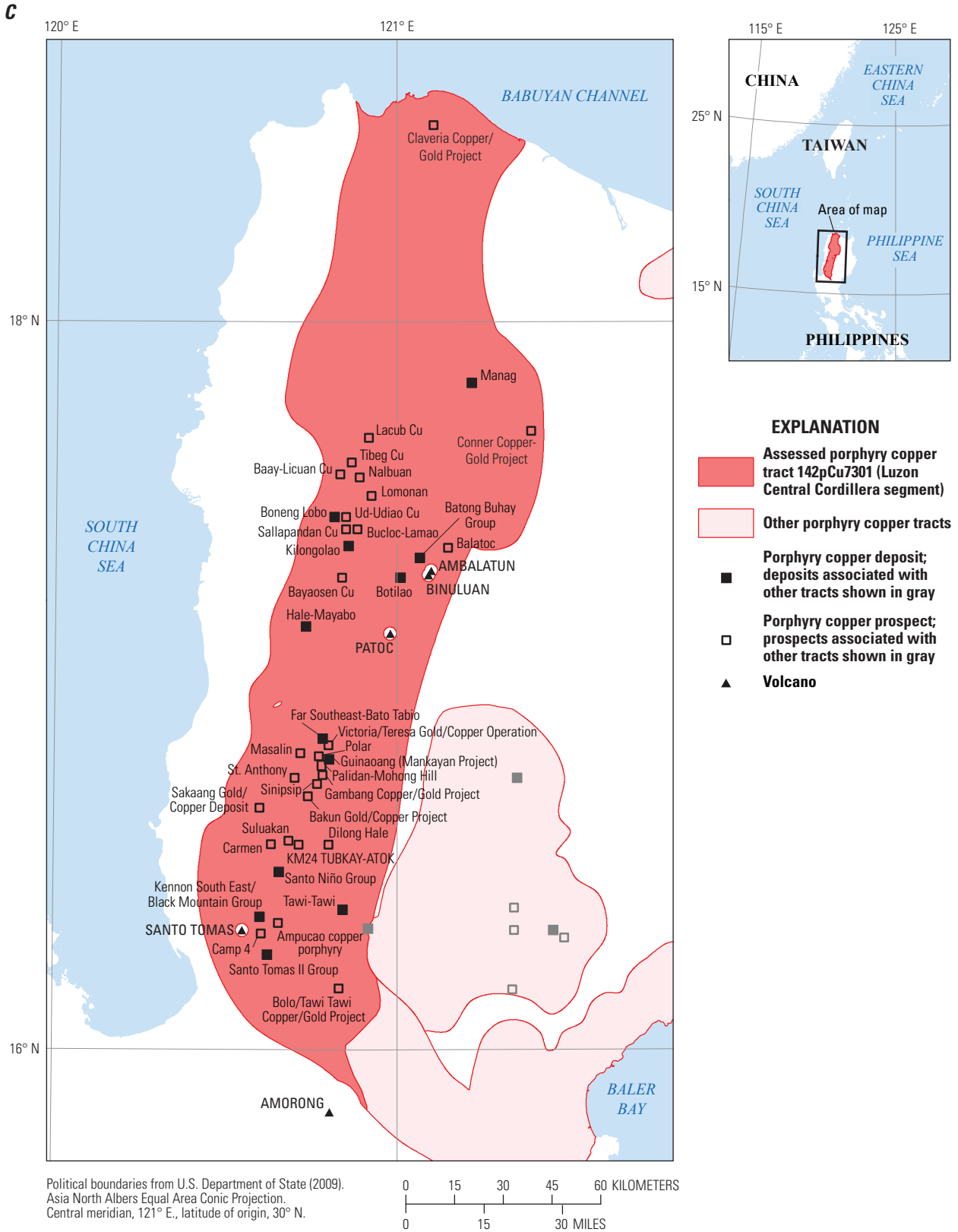


Figure J1.—Continued



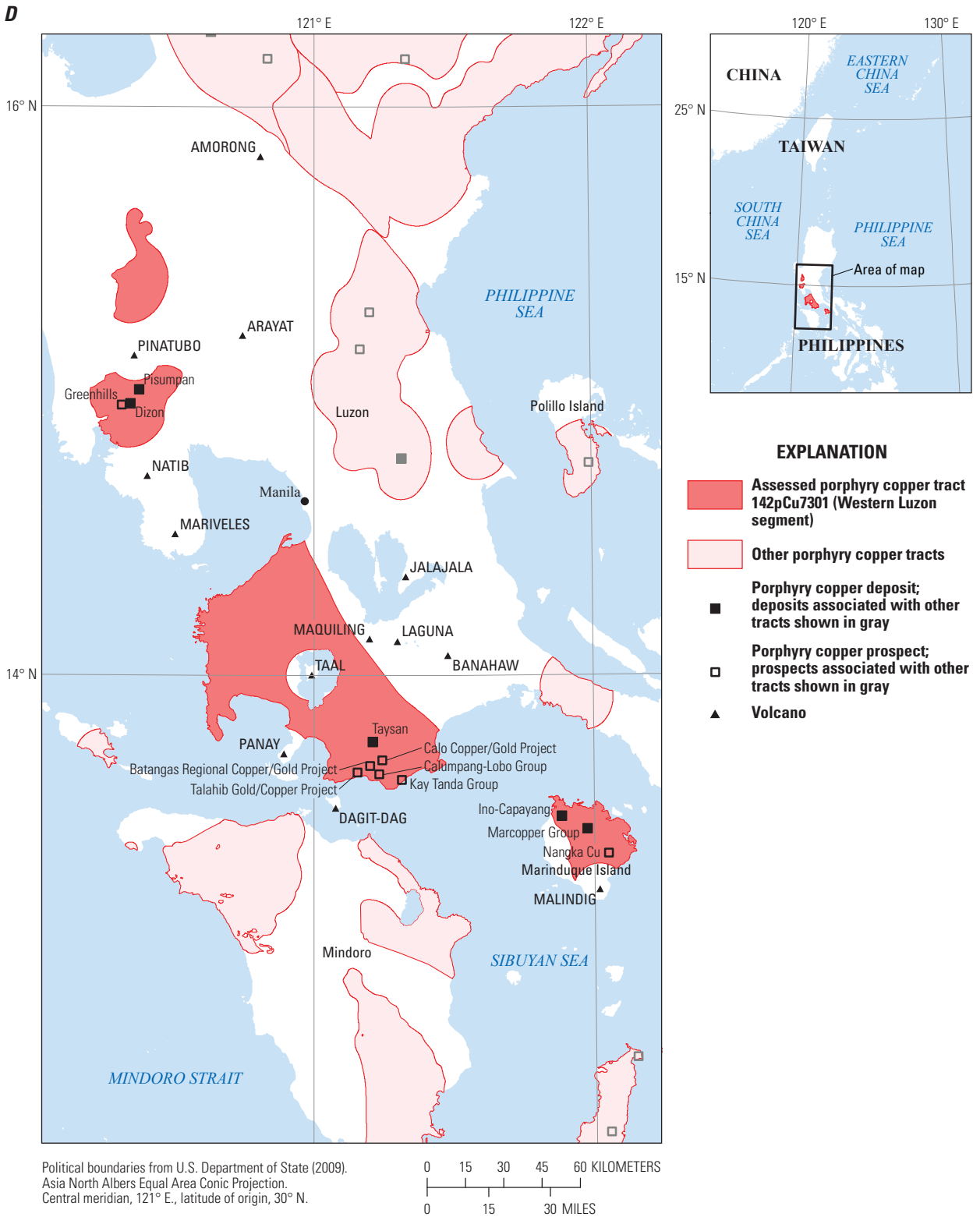


Figure J1.—Continued

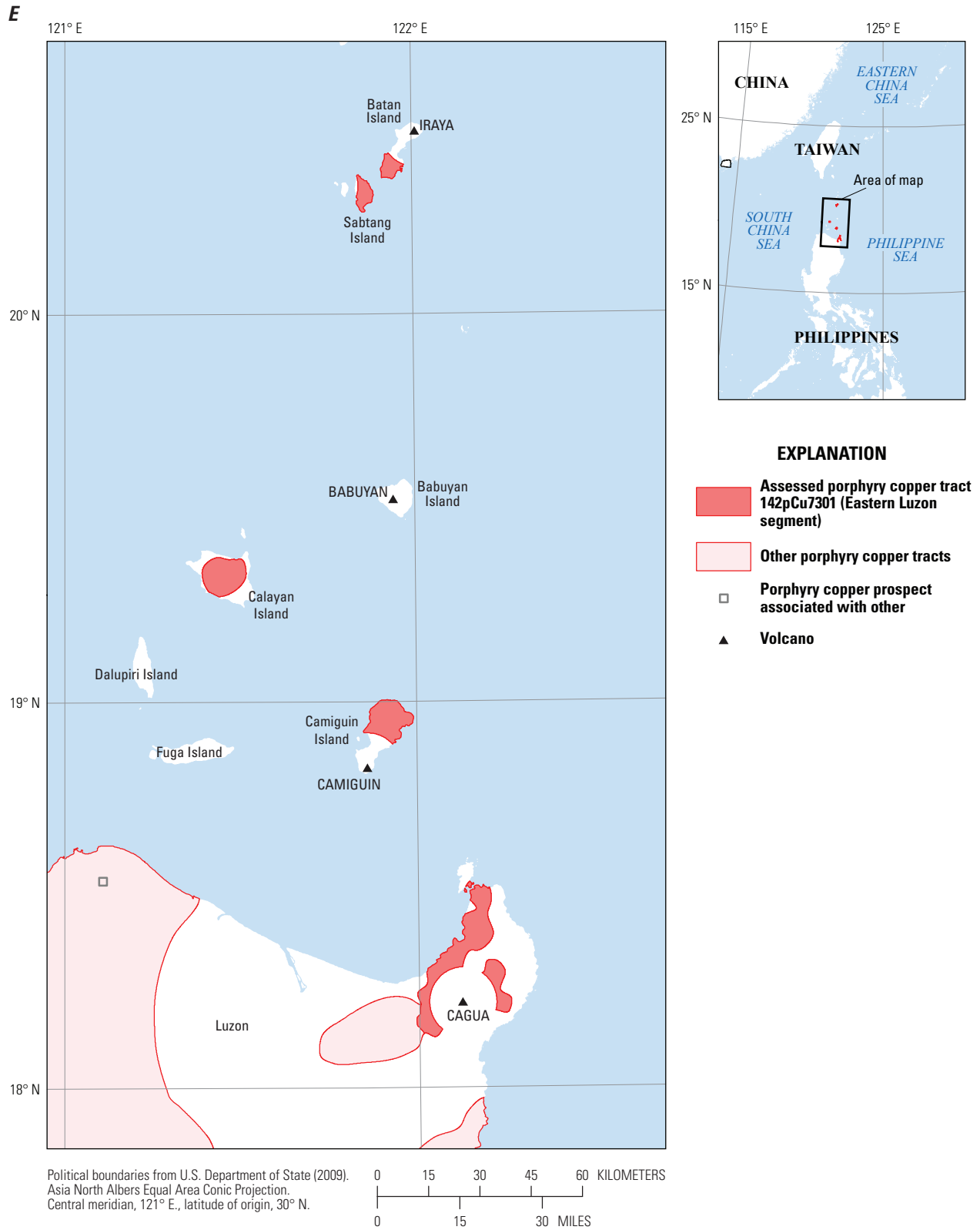


Figure J1.—Continued

## Delineation of the Permissive Tract

### Tectonic Setting

The Neogene Luzon Arc is a composite arc system extending from Marinduque Island through western Luzon Island in the Philippines to the Coastal Range of eastern Taiwan (fig. 4A<sup>6</sup>). The arc became active in the early Miocene and is now underlain by an east-dipping Benioff zone related to the Manila Trench. In northern Luzon, an early to middle Miocene reversal in arc polarity may have shifted the locus of arc activity from east to west as the geodynamics switched from subduction of the proto-Philippine Sea Plate along the proto-East Luzon Trough to subduction of the South China Sea Plate along the Manila Trench (fig. 7) (Yumul and others, 2008a; Bautista and others, 2001). The 900-km-long Manila Trench marks Plio-Pleistocene eastward subduction of the South China Sea ocean basin on the Eurasian Plate beneath the Luzon Arc of the Philippine Mobile Belt. The Manila Trench trends approximately north-south from the Taiwan collision zone to Mindoro in the south, where the Palawan block collides with southwestern Luzon Island (figs. 5B, 7). Subduction of the Scarborough Seamounts (the aseismic mid-ocean ridge of the South China Sea) at 5–4 Ma may have caused a change in subduction angle (buoyancy) that interrupted subduction, caused regional uplift and erosion, and led to a gap in magmatic activity expressed as an approximately 50-km-wide gap between the western and eastern volcanic zones of the double island arc between Luzon and Taiwan to the north.

The Luzon Arc represents a chain of stratovolcanoes and volcanic necks that erupted tholeiitic, calc-alkalic to shoshonitic, and adakitic rocks (Yumul and others, 2008b). The oldest rocks associated with the Luzon Arc are 30–9 Ma igneous rocks on Taiwan and Miocene rocks in the Baguio mineral district (fig. 4B) on northern Luzon.

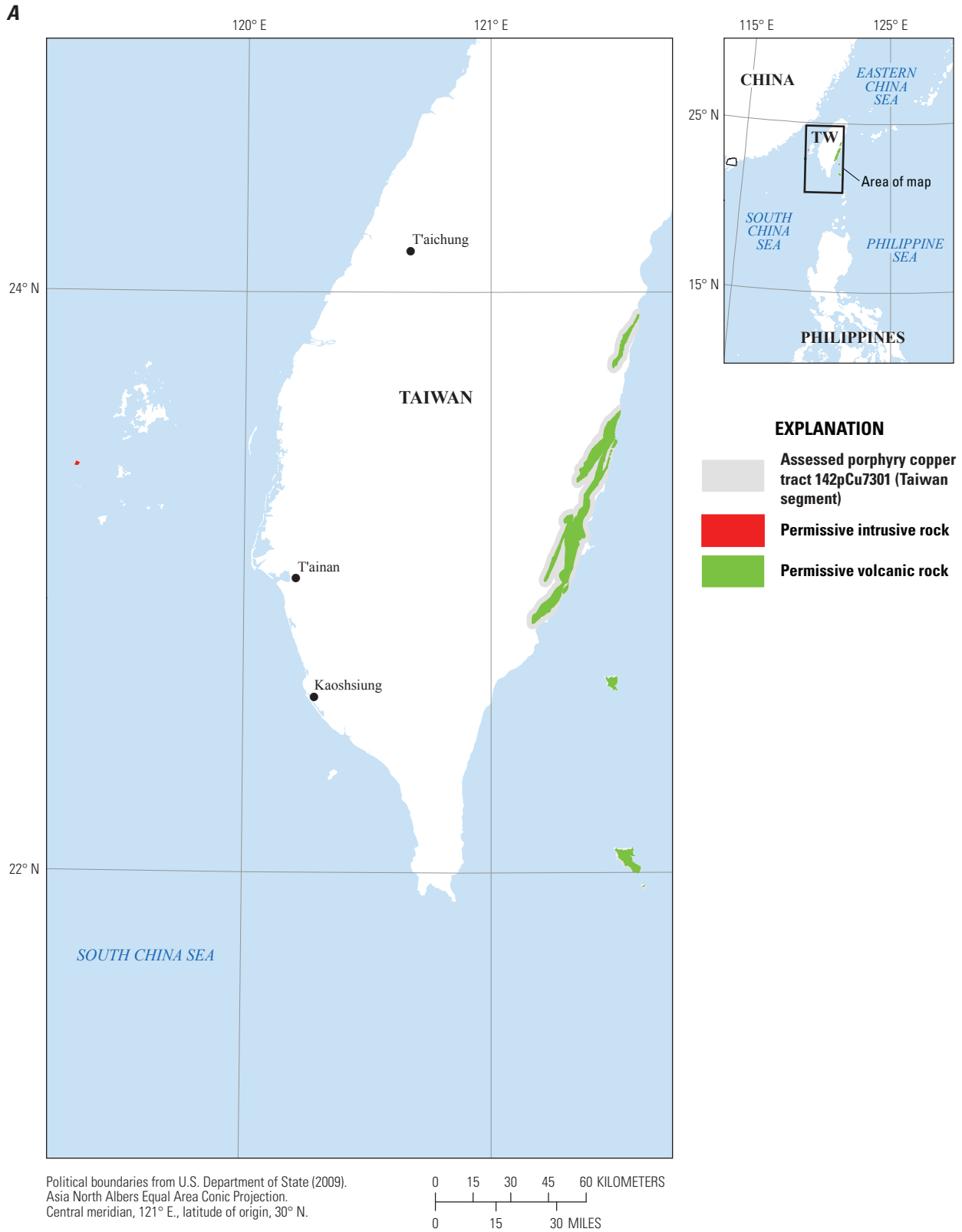
The four Luzon Arc segments are based on arc segments described by Yang and others (1996) and Garwin and others (2005)—Taiwan, Luzon Central Cordillera, Western Luzon, and Eastern Luzon. The Eastern Luzon Arc segment was excluded from the probabilistic assessment of undiscovered porphyry copper resources; this arc segment is considered to be too volcanically active to be permissive for porphyry copper deposits within 1 km of the surface.

### Geologic Criteria

The permissive tracts were constructed by selecting igneous rocks from a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines and Geosciences, 2004a) and the 1:500,000-scale digital geologic map of Taiwan (Ministry of Economic Affairs, 2006). The map units were classified by age groups, and subdivided into intrusive and volcanic rocks. Permissive rocks used to delineate the tract are shown in figure J2 and listed in table J2. A 10-km buffer was created around intrusive rocks, and a 2-km buffer was created around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map unit polygons were aggregated, smoothed, and edited by hand to honor fault boundaries and include known but unmapped permissive igneous rocks and prospects. Site locations for dated and classified igneous rocks were also used to constrain tract boundaries (Malaihollo and others, 2002). The final tract segments were clipped to coastlines (U.S. Department of State, 2009).

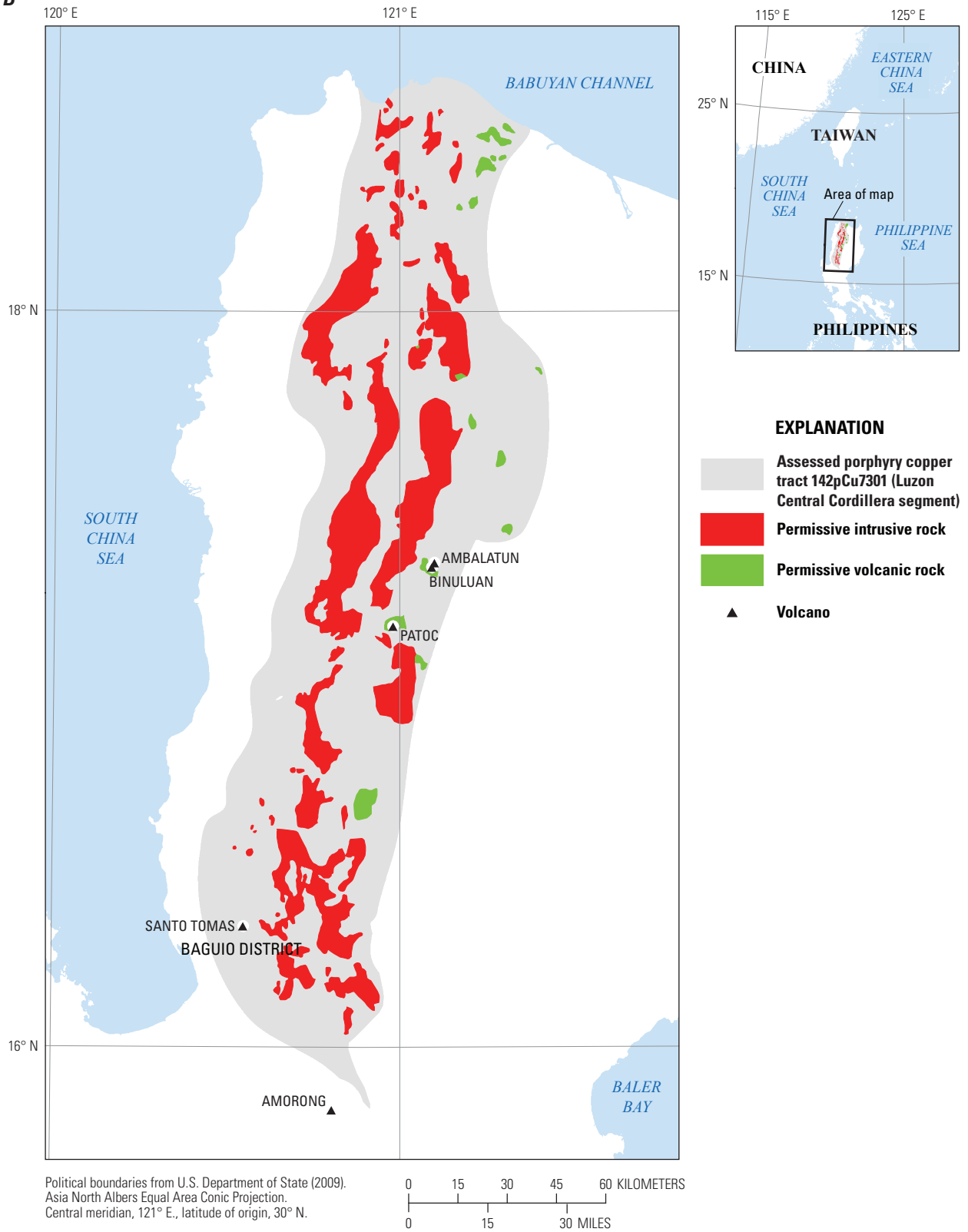
In some areas, the 1:50,000-scale geological maps of the Philippines were scanned and georectified to check the tract areas that were developed using the smaller scale digital map. Larger scale geologic maps are available in topical studies, such as a geologic map of the Baguio district (Waters and others, 2011), and on some Web sites for exploration project areas (RoyalCo Resources, Ltd., 2010).

<sup>6</sup>Refer to figures and tables in main report.



**Figure J2.** Map showing the distribution of permissive igneous rocks for tract 142pCu7301, Luzon Arc, the Philippines and Taiwan (Republic of China). *A*, Taiwan segment. *B*, Luzon Central Cordillera segment. *C*, Western segment. *D*, Eastern segment. TW, Taiwan (Republic of China).

**B**



**Figure J2.**—Continued

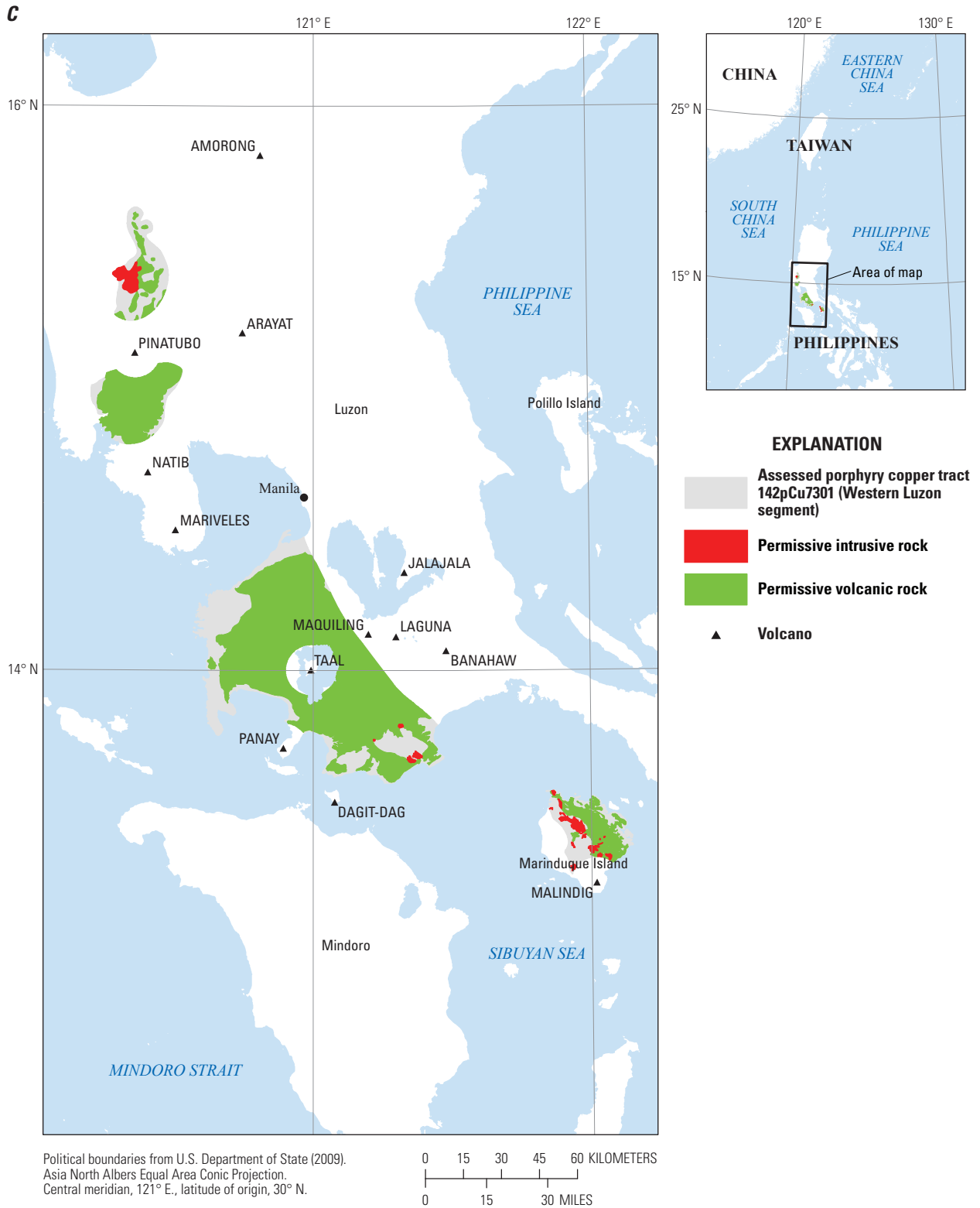
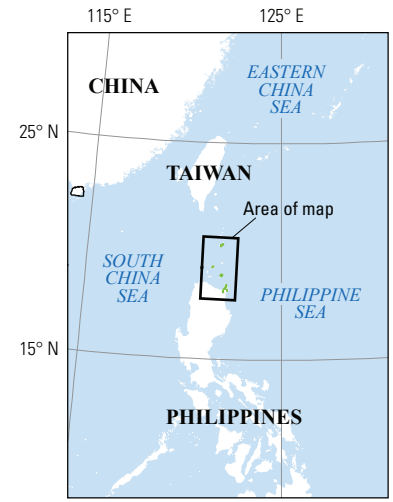


Figure J2.—Continued



D



**EXPLANATION**

- Assessed porphyry copper tract 142pCu7301 (Eastern Luzon segment)
- Permissive volcanic rock
- Volcano

Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 121° E., latitude of origin, 30° N.

0 15 30 45 60 KILOMETERS  
 0 15 30 MILES

Figure J2.—Continued

**Table J2.** Map units that define tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).

[Map unit, age range, and principal lithologies are based on a digital version of the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines, 1963) and the 1:500,000-scale map of Taiwan. NA, not applicable]

Map unit	Map symbol	Lithology	Age range
Intrusive rocks			
<u>Taiwan</u>			
NA	$\gamma$	Quartz porphyry	Pre-Miocene
<u>Philippines</u>			
Neogene intrusives	NI	Largely intra-Miocene quartz diorite. Mostly batholiths and stocks, some laccoliths; also sills, dikes, and other minor bodies. Includes granodiorite and diorite porphyry facies and late Miocene dacite. Pervasive in Paleogene and Mesozoic, less widespread in early Miocene rock sequences.	Neogene
Volcanic rocks			
<u>Taiwan</u>			
NA	$\alpha 1$	Andesite, andesitic pyroclastics	Miocene
NA	$\alpha 2$	Andesite, andesitic pyroclastics	Pliocene
Tuluanshan Formation	MPt	Volcanic breccia, tuff	Miocene
<u>Philippines</u>			
Quaternary volcanics	QV	Nonactive cones (generally pyroxene andesite); also dacitic and (or) andesitic plugs. Basaltic dikes in Binga, Mt. Province, Luzon, and in Misamis Oriental, Mindanao.	Pliocene-Quaternary

### Northern Luzon Arc (Taiwan)

The Taiwan segment represents the northernmost part of the Luzon Arc in the Coastal Range of eastern Taiwan (fig. 3A) and offshore islands. Taiwan is at the convergent boundary between the Eurasian Plate subducting (eastward) under the northern Luzon Arc on the Philippine Sea Plate (fig. 10B). The Longitudinal Valley (fig. 4A) of eastern Taiwan marks the suture zone between the two plates. The northern Luzon Arc consists of the Chimei Igneous Complex and the offshore volcanic islands of Lan Yu and Lu Dao (fig. 4A); arc orientation changes from north-northwest to north-northeast (fig. 7) between these two islands (Shyu and others, 1996). The tract delineates Miocene andesitic volcanic rocks of the Tulanshan Formation and the Chimei Intrusive Complex in the Coastal Range of eastern Taiwan (fig. J2A). Facies distributions of volcanic rocks suggest that the Chimei area is a volcanic center. The 30- to 9-Ma Chimei Complex includes hydrothermally altered diorite, diabase, and andesite.

### Luzon Central Cordillera

The Luzon Central Cordillera extends for about 300 km along northern Luzon Island (fig. 3A). The tract segment is bounded on the west and east by deep basins and, locally, by faults at basin margins. The eastern tract boundary lies along the contact of Tertiary rocks with Quaternary basinal sedimentary rocks of the Cagayan Valley to the east of the tract (Philippine Mines and Geosciences Bureau, 2010). The southern boundary

is the Philippine Fault and the northern boundary is the Luzon coast.

The geology of the Central Cordillera is characterized as a north-trending zone containing Cretaceous to Paleogene submarine lava flows of spilite and basalt with some keratophyre and andesite (fig. J2B). These rocks have been intruded by Neogene to Miocene quartz diorite, granodiorite, and diorite porphyry bodies that form north-south elongate batholiths and stocks but also locally form laccoliths, sills and dikes. This central zone also is flanked by Oligocene to Miocene transgressive conglomerate, graywacke, shale, and reef limestone that is locally interlayered with mafic to intermediate volcanic flows and pyroclastic rocks. These rocks are, in turn, overlain by Upper Miocene to Pliocene marine clastics and pyroclastic rocks (Philippine Mines and Geosciences Bureau, 2010). This part of the tract delineates early Miocene through Pliocene composite diorite to tonalite intrusions and coeval hypabyssal rocks selected from a digital versions of the 1:1,000,000-scale geologic map the Philippines (Philippine Bureau of Mines, 1963).

### Western Luzon Arc

The western part of the Luzon Arc includes two areas north and south of Pinatubo volcano and extends for about 300 km along the southwestern coast of Luzon Island and through Marinduque Island (figs. 3A, 4C). The tract delineates Neogene quartz diorites that crop out west and south of the

Philippine Fault and Pliocene-Quaternary volcanic rocks on the flanks of Quaternary volcanic centers (fig. J2C). A 10-km buffer area around mapped intrusions extends the tract under cover of Neogene andesitic flows, tuffs, and volcanoclastic rocks. Porphyry copper deposits in the tract are associated with Miocene-Pliocene rocks in windows in Quaternary volcanic cover. The tract excludes ultramafic rocks, Holocene Natib (1,253 m) and Mariveles (1,388 m) stratovolcanoes on the Bataan Peninsula (fig. 4C), and the active (1993) central part of Pinatubo volcano (1,486 m elevation). The volcanic cover at young, uneroded volcanoes with summits at elevations of 1 km or higher, such as the volcanoes in the Luzon area, would bury any associated porphyry system. Volcanic summits are excluded from surrounding volcanic cover by placing a 10-km “hole” around the topographic high point. The tract also excludes small bodies mapped as Neogene quartz diorite on the northern margins of a large ultramafic body that may represent older arc material, based on a 44.2-Ma age on tonalite; no volcanic rocks were mapped near the quartz diorite.

The southern part of the Mount Pinatubo area hosts several porphyry copper deposits (Dizon, Pisumpan, and Pinpin). Very young and active stratovolcano complexes, such as Pinatubo, can localize porphyry copper deposits when

mantle-derived mafic melts carrying sulfur, other volatiles, and copper are injected repeatedly into shallow crustal felsic magma reservoirs triggering eruptions and fracturing that accommodates deposition of metals from hydrothermal fluids, as described by Hattori and Keith (2001) and Sillitoe (1973).

### Eastern Luzon Arc

The eastern chain of the double island arc system (50 km east of the Luzon Central Cordillera) forms the Eastern Luzon Arc segment (fig. 3A). The eastern chain is younger than, and geochemically distinct from, the western chain; the chains merge into a single chain between Luzon and Taiwan. In northeastern Luzon, the eastern arc segment is the active calc-alkalic Cagua Volcano (elevation 1,133 m) (fig. J2D).

### Known Deposits

Deposit locations (fig. J1) and identified resources are listed in table J3 by arc segment, along with references for individual deposits. No deposits are known in the Taiwan and Eastern Luzon tract segments.

**Table J3.** Porphyry copper deposits in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × (Cu grade, % ÷ 100)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Luzon Central Cordillera											
Manag	17.834	121.221	Cu-Au	n.d.	20	0.50	n.d.	1.10	n.d.	100,000	Sillitoe and Gappe (1984), Singer and others (2008)
Boneng Lobo	17.467	120.817	Cu-Au	10.5	225	0.28	0.005	0.26	4	636,750	Almogela (1974), Imai (2002), Jacinto (1977), Sillitoe and Gappe (1984), Singer and others (2008)
Kilongolao	17.387	120.858	NA	n.d.	50	0.35	n.d.	n.d.	n.d.	175,000	Almogela (1974), Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008)
Batong Buhay Group	17.354	121.067	Cu-Au	7.0	87	0.60	0.002	0.31	2	520,531	Fernandez (1986), Philippine Mines and Geosciences Bureau (2007), Saegart and Lewis (1976), Sillitoe and Gappe (1984), Singer and others (2008)

**Table J3.** Porphyry copper deposits in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × (Cu grade, % ÷ 100)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Botilao	17.300	121.010	NA	n.d.	82	0.52	n.d.	0.19	n.d.	426,400	Almogela (1974), Sillitoe and Gappe (1984), Singer and others (2008)
Hale-Mayabo (Dilong project)	17.167	120.733	Cu-Au	n.d.	35	0.50	0.005	0.35	2.5	175,000	Almogela (1974), Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008)
Far Southeast	16.866	120.783	Cu-Au	1.4	657	0.65	n.d.	0.94	0.93	4,270,500	Arribas and others (1995), Claveria (2001), Claveria and others (1999), Disini and others (1998), Garcia (1991), Hedenquist (1999), Hedenquist and others (1998), Lepanto Consolidated Mining Company (2008), Malicdem (1975), Sajona and others (2002), Shinohara and Hedenquist (1997), Singer and others (2008)
Guinaoang (Mankayan Project)	16.864	120.782	Cu-Au	3.5	400	0.38	n.d.	0.42	n.d.	1,520,000	Almogela (1974), Bezant Resources plc (2007), Chang and others (2011), Fernandez (1986), Sillitoe and Angeles (1985), Singer and others (2008), Togashi and others (1989)
San Antonio–Philex	16.750	120.700	Cu-Au	n.d.	170	0.44	0.001	0.07	1.2	748,000	Jacinto (1975), Sillitoe and Gappe (1984), Singer and others (2008)
Santo Niño Group	16.490	120.656	NA	9.5	286	0.35	0.008	0.20	1.7	986,700	Apostol (1974), Bryner (1969), Divis (1983), Govett and Hale (1967), Imai (2002), MMAJ-JICA (1977), Motegi (1977), Sillitoe and Gappe (1984)

**Table J3.** Porphyry copper deposits in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × (Cu grade, % ÷ 100)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Tawi-Tawi	16.387	120.842	NA	4.6	225	0.39	0.008	0.30	1.7	877,500	Mitchell and Leach (1991), MMAJ-JICA (1977), Sillitoe and Gappe (1984), Singer and others (2008), Solfotara Mining Corp. (2010, 2012)
Kennon South East/Black Mountain Group	16.367	120.600	NA	2.1	62	0.38	0.013	0.33	4	234,360	Almogela (1974), Clark and Arancibia (1996), Divis (1983), Fernandez (1986), Imai (2002), Mitchell and Leach (1991), MMAJ-JICA (1977), Philippine Bureau of Mines and Geosciences (1986), Singer and others (2008)
Santo Tomas II Group	16.263	120.623	Cu-Au	1.5	449	0.38	0.001	0.70	1.5	1,683,750	Apostol (1974), Bryner (1969), Imai (2001), Imai and others (1992), MMAJ-JICA (1977), Motegi (1977), Philippine Bureau of Mines and Geosciences (1986), Sillitoe (1997), Singer and others (2008), Takenouchi (1980), Tarkian and Koopmann (1995)
Western Luzon Arc											
Pisumpan	15.008	120.367	Cu-Au	2.1	20	0.41	n.d.	0.60	3	82,000	Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008)
Dizon	14.959	120.336	Cu-Au	2.7	187	0.36	0.003	0.93	2	673,200	Almogela (1974), Anonymous (1997), Hutchinson (1996), Imai (2002), Imai (2005), Imai and others (1992), Malihan (1982), Sillitoe (1989), Sillitoe and Gappe (1984), Singer and others (2008)

**Table J3.** Porphyry copper deposits in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[Ma, million years; Mt, million metric tons; t, metric ton; g/t, gram per metric ton; %, percent; Cu-Au subtype, deposits that have Au/Mo ratios >30 or average Au grades >0.2 g/t; NA, not applicable; n.d., no data. Contained Cu in metric tons is computed as tonnage (Mt × 1,000,000) × (Cu grade, % ÷ 100)]

Name	Latitude	Longitude	Subtype	Age (Ma)	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Ag (g/t)	Contained Cu (t)	Reference
Taysan	13.764	121.211	Cu-Au	7.3	968	0.22	0.003	0.09	0.68	2,129,600	Anonymous (2006), Crazy Horse Resources, Inc. (2012), Delos and Kajiwara (1995), Imai (2002), Leach (1999), McPHAR Geophysical Services (2006), Sillitoe and Gappe (1984), Singer and others (2008) Wolfe and others (1978)
Ino-Capayang	13.500	121.883	NA	n.d.	50	0.50	0.005	0.03	1.3	250,000	Saegart and Lewis (1976), Sillitoe and Gappe (1984), Singer and others (2008)
Marcopper Group (Tapián, San Antonio)	13.446	121.975	Cu-Au	20.5	372	0.55	0.004	0.11	0.7	2,046,000	Clark (1993), Loudon (1976), Loudon (1981), Metal Mining Agency of Japan (1998), Sillitoe and Gappe (1984), Singer and others (2008.) Takenouchi (1980), Walther and others (1981)

### Luzon Central Cordillera

The Luzon Central Cordillera contains 13 copper-gold porphyry deposits that range in age from 11 to 1 Ma (table J3). Deposits and prospects are associated with quartz diorite intrusions and tend to be localized along or near fault intersections (fig. J3). This relation was quantified by Carranza and Hale (2002) in their analysis of the spatial relations among mapped porphyry plutons, known deposits, and strike-slip fault discontinuities in Benguet Province (fig. J3). Their study, which used a digital elevation model (DEM) to interpret fault and fracture patterns combined with weights of evidence modeling, concluded that more than 75 percent of the known porphyry deposits and prospects occurred in belts and clusters localized by regional strike-slip fault systems and within 4 km of a large pluton and that 50 percent of the known deposits are located within 3 km of one another. The clustering and spatial relations of deposits and prospects to the coarser scale fault patterns from the 1:1,000,000-scale geologic map of the Philippines shown in fig. J3 suggest that these relations may continue farther north in western Luzon and provide an exploration guide there as well.

### Mankayan District

The Mankayan district of northern Luzon (fig. J3) contains a variety of deposit types including the Far Southeast and Guanoang-Tirad porphyry copper-gold deposits the Lepanto high-sulfidation epithermal copper-gold deposit, and intermediate sulfidation-state epithermal veins deposits (Chang and others, 2011). The largest porphyry deposit in the segment is the concealed Far Southeast-Bato Tabio deposit with greater than 4 Mt of contained copper (table J3). The most recent resource estimate based on 1995 data for 114 drill holes is 657 Mt of ore having an average grade of 0.65 percent copper and 0.84 g/t gold (cutoff grade of 0.7 percent copper equivalent). The deposit, which is covered by 600 m of volcanoclastic rocks, is hosted by a Pliocene-Pleistocene quartz diorite porphyry stock at the intersection of west-northwest and north-northwest-striking fault systems (Lepanto Consolidated Mining Company, 2008).

The Mankayan district is the premier example of an established genetic relation between a porphyry copper deposit (Far Southeast) and a spatially associated epithermal deposit (Lepanto). Recognition of coupled K-silicate and advanced



argillic (quartz-alunite) alteration in the district established new guidelines for exploration for concealed porphyry deposits based on careful documentation of paleohydrologic regimes that control alteration and ore deposition in some settings (Hedenquist and others, 1998).

#### Baguio District

The world class Baguio district at the southern end of the Cordillera (fig. J3) includes the 2–1.5 Ma diorite-hosted Santo Tomas II palladium-bearing porphyry copper-gold deposit that was mined by block caving from 1958–2003. The Santo Tomas II Group (fig. J1C) includes 2 prospects within 2 km of the deposit. The Kennon and Black Mountain Southeast Group of deposits that are associated with the approximately 3-Ma Black Mountain intrusive complex (Imai, 2001; Philippine Bureau of Mines and Geosciences, 1986; Sillitoe and Gappe, 1984; Waters and others, 2011).

#### Western Luzon Arc

##### Zambales Area, Luzon Island

The 187-Mt Dizon deposit (fig. J1D), 14 km from the current summit of Pinatubo volcano in the same arc, was mined until the eruption of 1991. The 2.7-Ma Dizon deposit is hosted by Pliocene andesitic to dacitic volcanic rocks and quartz diorite porphyry (Malihan, 1982). At Dizon, supergene enrichment occurred to a maximum depth of 50 m; supergene ore accounts for 8 Mt of 0.6 percent copper. In 17 years of mining, the Dizon deposit produced more than 100 Mt of tailings, which contain 0.3 g/t gold, 0.6 g/t silver, 0.074 percent copper, and 4 percent magnetite (Dizon Copper and Silver Mines, Inc., 2012); the company is exploring possible recovery of gold and copper from tailings.

Pisumpan and nearby Pinpin (each 20 Mt at 0.4 percent copper and approximately 1 g/t gold) are hosted by Quaternary dacitic rocks (Hattori and Keith, 2001). No supergene zone was observed at Pisumpan (Sillitoe and Gappe, 1984).

##### Batangas Area, Luzon Island

Taysan (fig. J1D) is a porphyry copper-gold deposit along the western edge of the Taysan batholith in potassically altered

hornblende diorite, quartz diorite, and porphyry-associated hydrothermal breccia (Wolfe and others, 1978; Crazy Horse Resources, Inc., 2012). The deposit has been drilled intermittently since 1968 and in 2012 was a prefeasibility-stage project of Crazy Horse Resources, Inc., (2012) with an expected mine life of 24 years. Based on drilling through 2011, total resources (measured, indicated, and inferred) are reported to be 968 Mt averaging 0.22 percent copper, 0.09 g/t gold, and 0.67 g/t silver (at a 0.1 percent copper cutoff grade), and about 3 percent magnetite.

#### Marinduque Island

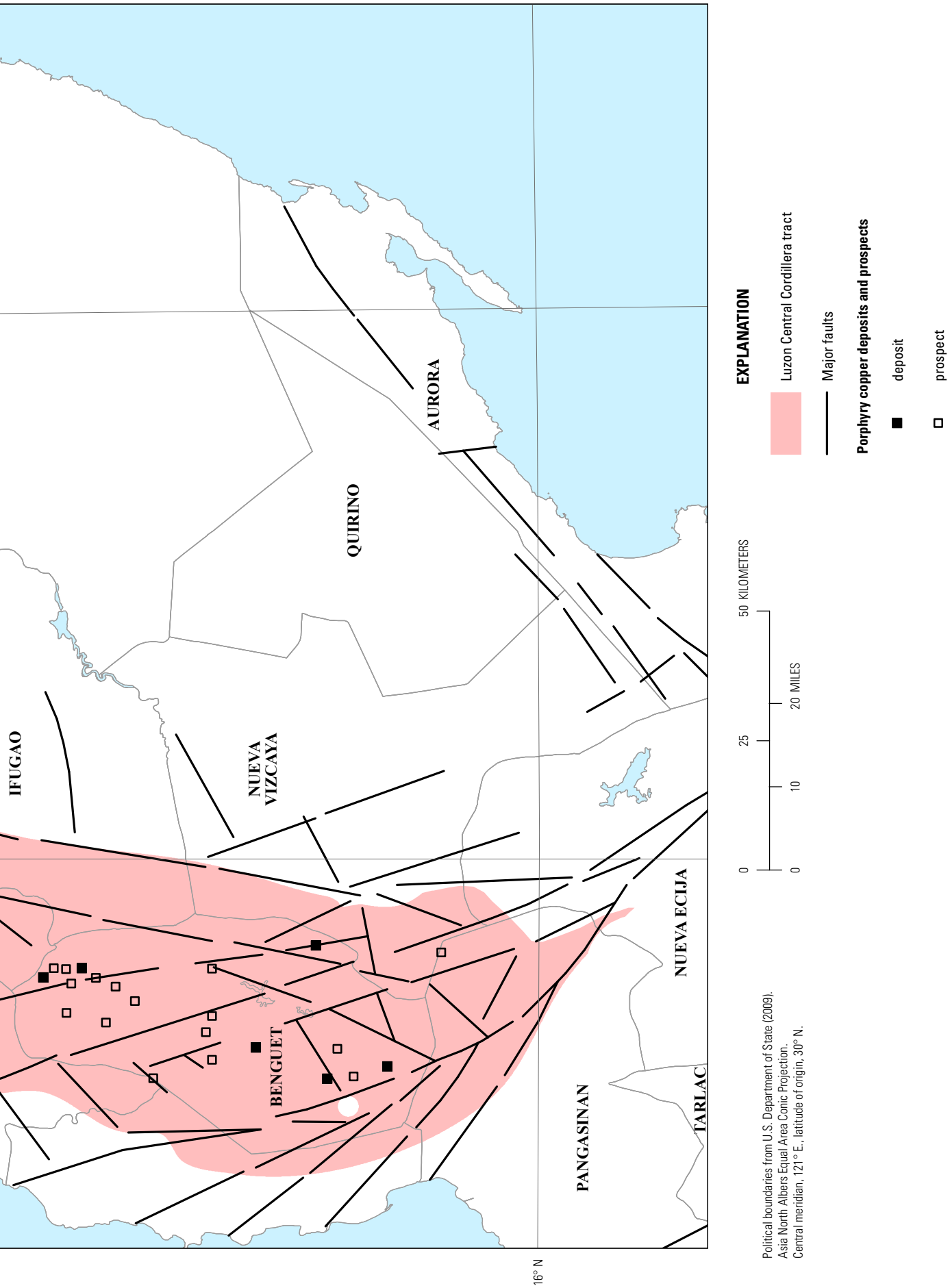
Mining at the 20.9 Ma Marcopper mine on Marinduque Island started in 1969 at the Mount Tapian deposit, which was mined out in 1990. The mining operation continued at the San Antonio ore body, north of the former operations (fig. J1D). Mining operations ceased in 1996 as a result of a tailings impoundment breach which discharged 20 Mt of tailings into the Boac River. Total resources for the Marcopper deposit, including the Tapian and San Antonio ore bodies are 372 Mt at 0.55 percent copper, 0.0035 percent molybdenum, and 0.11 g/t gold (table J3). The deposit is within a granodiorite porphyry phase along the margins of Miocene quartz diorite stock. The upper 30 to 60 m of the deposit was oxidized; hypogene ore minerals included chalcopyrite associated with pyrite and magnetite and minor amounts of bornite and covellite (Loudon, 1976; Philippine Bureau of Mines and Geosciences, 1986).

An open-pit mine was operated at Ino-Capayang (fig. J1D) from 1978 to 1980. The ore zone geometry is described as a steep cylinder, containing 2 volume percent total sulfides. K-silicate alteration is well-developed, with minor development of sericite-chlorite-clay (SCC) alteration, and supergene enrichment to a maximum depth of 80 m (Sillitoe and Gappe, 1984).

### Prospects, Mineral Occurrences, and Related Deposit Types

The tract contains 36 porphyry copper prospects and occurrences. These are listed in table J4, with comments, references, and a ranking of likely significance (4=high, 1=low).





Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 121° E., latitude of origin, 30° N.

**Figure J3.** Map showing the relation of porphyry copper deposits and prospects to major faults in the Luzon Central Cordillera, northern Luzon, Philippines. Major faults are from the 1:1,000,000-scale geologic map of the Philippines (Philippine Bureau of Mines and Geology, 1963).

**Table J4.** Significant prospects and occurrences in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares. MRDS, Mineral Resources Data System record available at <http://mrdata.usgs.gov>; LS, low-sulfidation epithermal; HS, high-sulfidation epithermal; SCC, sericite-chlorite-clay; IP, induced polarization. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
<b>Northern Luzon Arc (Taiwan)</b>						
Chimei	23.433	121.450	21.5	Resource: 10 Mt at 0.3 to 0.9% Cu; 7.3 Mt at 0.3% Cu, 0.4–0.5 g/t Au	Fan (1986), Song and Lo (2002), Tan (1976), Tan and Yu (1970), Wei and Tan (2001)	4
Dulanshan	22.883	121.192	n.d.	Copper prospect Cu, Au	Wei and Tan (2001)	1
Lanyu	22.030	121.580	n.d.	Copper prospect Cu, Au	Wei and Tan (2001)	1
<b>Luzon Central Cordillera</b>						
Sinipsip	16.733	120.767	n.d.	Exploration 1974–1977, 0.08 Mt at 0.02 to 0.51% Cu, 0.035% Mo (73 m), <0.02 g/t Au	Almogela (1974), Fernandez (1986), Sillitoe and Gappe (1984), Singer and others (2008)	4
Suluakan	16.577	120.684	n.d.	Porphyry Cu-Au exploration project (324 ha) of Philippine Metals Corp. in Ilocos Sur and Abra to reevaluate historical exploration data (drill logs, assays, samples, and maps) to target new drilling and develop a current resource estimate. Prospected 1975–1981 with estimate of 123 Mt, 0.35% Cu, 0.007% Mo, 0.13 g/t Au. and 2.4 g/t Ag.	Carranza and Hale (2002), Sillitoe and Gappe (1984)	4
Balatoc	17.382	121.149	n.d.	Exploration area (50.7 km <sup>2</sup> ) in andesite porphyry intruded by Neogene diorite. Along western flank of a northern extension of the Philippine Fault. Cluster of prospects associated with epithermal gold veins. Historical small-scale copper production. Historical reserve estimates 80 Mt at 0.60% Cu, 0.2 g/t Au. Location for municipality of Pasil.	Indophil Resources (2010)	4
Palidan-Mohong Hill	16.821	120.798	1.7	Porphyry lithocap prospect in the Mankayan district ~3 km southwest of the Guinaoang porphyry deposit; estimated resources of 100 Mt at 0.4 percent Cu, 0.5 g/t Au; alunite in the lithocap dated at 1.66 Ma.	Chang and others (2011)	4
Gambang Copper/Gold Project	16.767	120.782	n.d.	Exploration since 1995 (stream sediment and soil geochemical sampling, geological mapping, and geophysical survey) delineated seven target areas with porphyry copper-gold style mineralization	RoyalCo Resources, Ltd. (2010)	3
Dilong Hale	16.567	120.800	n.d.	Porphyry Cu-Au exploration project (324 ha) in Ilocos Sur and Abra to re-evaluate historical exploration data (drill logs, assays, samples, and maps) to target new drilling and develop a current resource estimate.	Philippine Metals Corp. (2010)	2

**Table J4.** Significant prospects and occurrences in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares. MRDS, Mineral Resources Data System record available at <http://mrdata.usgs.gov>; LS, low-sulfidation epithermal; HS, high-sulfidation epithermal; SCC, sericite-chlorite-clay; IP, induced polarization. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenched with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Ampucao (Acupan South)	16.350	120.654	0.5	Prospect associated with Miocene-Pliocene Ampucao dacite exploration drilling in southern part of the Acupan mine area (closed 1992) showed intercepts averaging 0.1–0.2% Cu, 0.9–1.0 g/t Au; associated with northwest- and northeast-trending splays of the Philippine fault. Alteration styles present include K-silicate, SCC, and propylitic. Prospect is 10 km from nearest known porphyry (Santo Tomas II).	Benguet Corp. (2010), Cooke and Bloom (1990)	2
Conner Copper-Gold Project	17.703	121.395	n.d.	Tenement Exploration permit 037; 7,337 ha claim area. Area of quartz diorite intruding altered basalt flows. Later hornblende andesitic dikes intrude quartz diorite and metavolcanic rocks. Possible LS epithermal gold system associated with porphyry copper. Google Earth® location ~ center of claim area.	Claveria (2001)	1
Baay-Licuan Cu	17.583	120.833	n.d.	Mining claim area	Philippine Mines and Geosciences Bureau (2004b)	1
Bakun Gold/ Copper Project	16.700	120.740	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Bayaosen Cu	17.300	120.839	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Bucloc-Lamao	17.433	120.883	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Camp 4	16.321	120.604	4.0	Two porphyry Cu-Au prospects associated with the Camp 4 intrusive complex: Kidao prospect: diorite porphyry and breccias; potassic alteration zones at surface; rock chip assays avg. 0.27% Cu, 0.25 g/t Au, 2 km <sup>2</sup> geochemical anomaly for Cu, Au. Ubulan prospect, low-grade mineralization indicated by drilling a hornblende diorite porphyry in the 1960s.	Carranza and Hale (2002), Durkee and Pederson (1961), Waters and others (2011)	2
Carmen	16.567	120.633	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004a)	1
Claveria Copper/Gold Project	18.538	121.108	n.d.	Exploration project at Praxedes, Cagayan Province. Magnetic anomaly several km long associated with high-grade copper-gold float (up to 9% Cu and 31 g/t Au) in magnetite skarn. Location from Google Earth®.	Oceana Gold (2010)	1
KM24 Tubkay-Atok	16.567	120.713	n.d.	Copper occurrence in metavolcanic rock	U.S. Geological Survey (2012)	1

**Table J4.** Significant prospects and occurrences in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares. MRDS, Mineral Resources Data System record available at <http://mrdata.usgs.gov>; LS, low-sulfidation epithermal; HS, high-sulfidation epithermal; SCC, sericite-chlorite-clay; IP, induced polarization. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenced with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Lacub Cu	17.683	120.917	n.d.	Copper occurrence in Miocene diorite	U.S. Geological Survey (2012)	1
Lomonan	17.525	120.925	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Masalin	16.818	120.718	n.d.	Benguet. Copper prospect. Quartz diorite. Chalcopyrite, bornite.	Carranza and Hale (2002)	1
Nalbuan	17.575	120.890	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Polar	16.810	120.772	n.d.	Copper-gold prospect	Carranza and Hale (2002)	1
Sakaang Gold/Copper Deposit	16.668	120.599	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Sallapandan Cu	17.433	120.850	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Tibeg Cu	17.617	120.867	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Ud-Udiao Cu	17.467	120.850	n.d.	Copper prospect	Philippine Mines and Geosciences Bureau (2004b)	1
Victoria/Teresa Gold/Copper Operation	16.840	120.800	n.d.	Copper prospect	Lepanto Consolidated Mining Company (2008)	1
Bolo/Tawi Tawi Copper/Gold Project	16.170	120.830	n.d.	Exploration project (Solfotara Mining)	Solfotara Mining Corp. (2010)	1
<b>Western Luzon Arc</b>						
Batangas Regional Copper/Gold Project	13.680	121.200	n.d.	Exploration project southeast of Taysan deposit; Lobo and Archangel epithermal gold prospects; Balibago porphyry Cu-Au system (partially unroofed, silica-chlorite-sericite-clay alteration, copper oxides, Cu soil anomalies). Regional northeast Balabat structural trend includes prospects associated with Pliocene volcanoplutonic complex capped with Quaternary volcanic rocks (Cu-Au skarns, intrusive-related porphyry Cu, LS to HS epithermal veins and breccias).	Ruelo and others (2003)	2



**Table J4.** Significant prospects and occurrences in tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).—Continued

[n.d., no data; %, percent; g/t, grams per metric ton; km, kilometers; m, meters; ha, hectares. MRDS, Mineral Resources Data System record available at <http://mrdata.usgs.gov>; LS, low-sulfidation epithermal; HS, high-sulfidation epithermal; SCC, sericite-chlorite-clay; IP, induced polarization. Rank 4=prospect listed in global database of Singer and others (2008) or <16,000 t of ore established by drilling. Rank 3=drilled, with >20 m of 0.2% or more Cu. Rank 2=drilled or trenced with <20 m of 0.2% Cu, or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age	Comments	Reference	Rank
Calo Copper/ Gold Project	13.700	121.244	n.d.	Reconnaissance drilling (7 widely spaced holes) in 2006 to test cluster of IP anomalies reported up to ~500 m of volcanic cover, weak porphyry-related alteration, and altered diorite clasts. Drill intersections of 213 m of 0.18% Cu and 0.30 g/t Au below advanced argillic alteration cap. Exotic copper in volcanic cover above IP anomalies.	Mindoro Resources, Ltd. (2010)	2
Greenhills	14.955	120.305	n.d.	Zambales copper prospect. Andesite porphyry. Chalcopyrite, bornite.	Philippine Mines and Geosciences Bureau (2004a)	1
Kay Tanda Group (Archangel)	13.630	121.314	Miocene	Altered volcanic rocks intruded by andesitic, dacitic, and dioritic intrusions; partly unexposed. Cluster of epithermal gold-silver and porphyry copper prospects along a 6-km long northeast structural trend. Kay Tanda epithermal Au-Ag deposit telescoped on a porphyry system at depth.	Mindoro Resources, Ltd. (2010), Cox (2010)	2
Calampang- Lobo Group	13.658	121.233	10.5	Exploration based on IP anomalies interpreted as buried porphyry targets. Copper mined in 1960s. Drilled summer of 2010 to test Cu-Au-Mo soil anomaly. Pica prospect drilled in 2005 intersected 213 m at 0.18% Cu, 0.30 g/t. Includes Calumpang Copper/Gold Project, a geophysical target northeast of Pica.	Imai (2002), Mindoro Resources, Ltd. (2010)	2
Talahib Gold/ Copper Project	13.657	121.156	n.d.	Reconnaissance exploration in an area of altered andesitic volcanic rocks intruded by altered diorite and microdiorite intrusion. Stream sediment anomalies for Cu, Au, Pb, and Zn. Altered diorite outcrop sampling (0.74% Cu, 0.15 g/t Au); anomalous Cu and Au in channel samples of hydrothermal breccia.	Mindoro Resources, Ltd. (2010)	2

## Taiwan

Chimei is a porphyry prospect in Miocene hornblende diorite porphyry, characterized by stockwork and disseminated chalcopyrite and stockwork quartz (fig. J1B). The resource at Chimei is estimated at 10 Mt of ore with 0.3–0.9 percent copper; the reliability and basis for this estimate are uncertain and may not be based on drilling, so it is cited as a prospect rather than a deposit (Fan, 1986). Alteration includes sericitization, argillization, chloritization, and pyritization. Exploration in the 1970s showed anomalous copper in stream sediments and soils in a 15-km<sup>2</sup> area near Chimei (Tan and Yu, 1970). Other porphyry prospects in the Taiwan arc segment include Dulanshan (23–1.8 Ma age range) and Lanya (less than 2 Ma) (fig. J1B).

## Luzon Central Cordillera

Twenty-seven porphyry copper prospects are known in the Luzon Central Cordillera (table J4, fig. J1B,C). About a quarter of these prospects have had some recent exploration to reevaluate historical data; the others are reportedly porphyry copper-type occurrences (C. Manipon, written commun., 2004). The porphyry copper deposits and prospects in the Baguio district are subjacent to major producing epithermal gold-silver deposits, such as Acupan and gold and base-metal skarn deposits such the Thanksgiving deposit (Cooke and Bloom, 1990; Waters and others, 2011).

## Western Luzon Arc

The Western Luzon arc segment contains six recently active exploration projects, with some reported drill intercepts (table J4). Weak indications of porphyry copper alteration and copper anomalies in stream sediments are associated with the Kay Tanda and Calampang-Lobo prospect areas (fig. J1D), where buried porphyry systems are exploration targets. The Archangel epithermal gold-silver deposit at Kay Tanda was interpreted as a younger system telescoped on a Miocene porphyry system (Cox, 2010).

## Exploration History

The Luzon Central Cordillera has a long history of exploration and development. Most exploration and discovery of large gold and copper deposits in the Luzon Central Cordillera occurred in the 1970s and 1980s. The Far Southeast-Bato Tabio deposit was known in the 13th Century; gold and copper were mined in the early 1900s. Some of the porphyry copper and gold deposits in the southern part of the Cordillera were discovered in the 1950s and 1960s. Exploration activity included trenching, sampling, geological mapping, prospect-scale geophysical exploration and drilling. Two areas of 30-year-old stream-sediment geochemical surveys were noted during the assessment. New exploration depends heavily on magnetics and drilling to target buried deposits. Stream

sediment and soil sampling, as well as reevaluation of historic exploration data, have been ongoing since 2002 to target drilling. The Assessment Team considered the high frequency of mining claim applications to indicate relatively intense levels of mineral exploration in the southern parts of the tract (see also, Kamitani and Naito, 1998; Sillitoe, 1995; and regional mining tenement maps for the Philippines available at <http://www.mgb.gov.ph/lmtp.aspx>).

## Sources of Information

Table J5 lists the sources of information used in the assessment.

## Grade and Tonnage Model Selection

Most of the known deposits in the tract are classified as Cu-Au subtype, as defined by greater than 0.2 g/t gold or Au:Mo ratios greater than 30. Statistical tests (*t*-tests) of deposits in the tract against the porphyry Cu-Au subtype model indicated that the model is appropriate for the assessment (table 4).

## Estimate of the Number of Undiscovered Deposits

### Rationale for the Estimate

In 2005, an assessment team made preliminary estimates of nine undiscovered deposits for the Luzon Central Cordillera. In 2010, another team considered the area in the context of the entire Luzon Arc system, along with an update of the deposits and prospects data compilation. The Taiwan, Luzon Central Cordillera, and Western Luzon tract segments of the Luzon Arc system all contain prospects, at least one of which might, if fully explored, be a deposit. The tract segments on Luzon span numerous fault intersections that might provide conduits for porphyry-related magmas and hydrothermal fluids. Outcropping plutons in the Central Luzon Cordillera define an axis of voluminous porphyry-related magmatism that might also be present at depth, beneath postmineralization cover rocks.

The 2010 tract estimate of a mean of 10 undiscovered deposits (table J6) represents the mean for a 90-percent chance of 2 or more deposits, a 50-percent chance of 9 deposits, and a 10-percent chance of 20 or more deposits (table J6). Recent exploration focus on buried targets that have yet to be tested by drilling, and changes in Philippine mining policies that are more open to exploration than in the recent past were considered in the analysis.

**Table J5.** Principal sources of information used for tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of China).

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Geology and mineral resources of the Philippines, v. 1—Geology	1:1,000,000	Philippine Bureau of Mines and Geosciences (1981), Philippine Mines and Geosciences Bureau (2010)
	Digital geologic map of the Philippines	1:1,000,000	Philippine Mines and Geosciences Bureau (2004a)
	Tectonic map of the Philippines	1:2,000,000	Anonymous (1995)
	Resources map of metallic minerals of Taiwan	1:500,000	Wei and others (2006)
	Geologic map of the Philippines	1:1,000,000	Philippine Bureau of Mines (1963)
Mineral occurrences	Porphyry copper deposits of the world—Database, map, and grade and tonnage models	NA	Singer and others (2008)
	Geology and mineral resources of the Philippines, v. 2—Mineral Resources	NA	Philippine Bureau of Mines and Geosciences (1986)
	Digital data base of mineral occurrences of the Philippines	NA	Philippine Mines and Geosciences Bureau (2004b)
	Mining places in the Philippines (kml file)	NA	GoogleEarth® (2013)
	Philippine porphyry copper deposits	NA	Sillitoe and Gappe (1984)
	Taiwan economic minerals	NA	
	U.S. Geological Survey On-Line Mineral Resources Spatial Data (MRDS)	NA	Wei and Tan (2001)
Exploration	Philippine Mines and Geosciences Bureau Web site	NA	<a href="http://www.mgb.gov.ph/">http://www.mgb.gov.ph/</a>
	Company Web sites and technical reports	NA	See tables J3 and J4

**Table J6.** Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of 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; area, area of permissive tract in square kilometers ( $\text{km}^2$ ); density, deposit density reported as the total number of deposits per 100,000  $\text{km}^2$ .  $N_{und}$ ,  $s$ , and  $C_v\%$  are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract Area ( $\text{km}^2$ )	Deposit density ( $N_{total}/100,000 \text{ km}^2$ )
$N_{90}$	$N_{50}$	$N_{10}$	$N_{05}$	$N_{01}$	$N_{und}$	$s$	$C_v\%$	$N_{known}$	$N_{total}$		
2	9	20	20	20	10	6.4	63	18	28	23,700	118

### Probabilistic Assessment Simulation Results

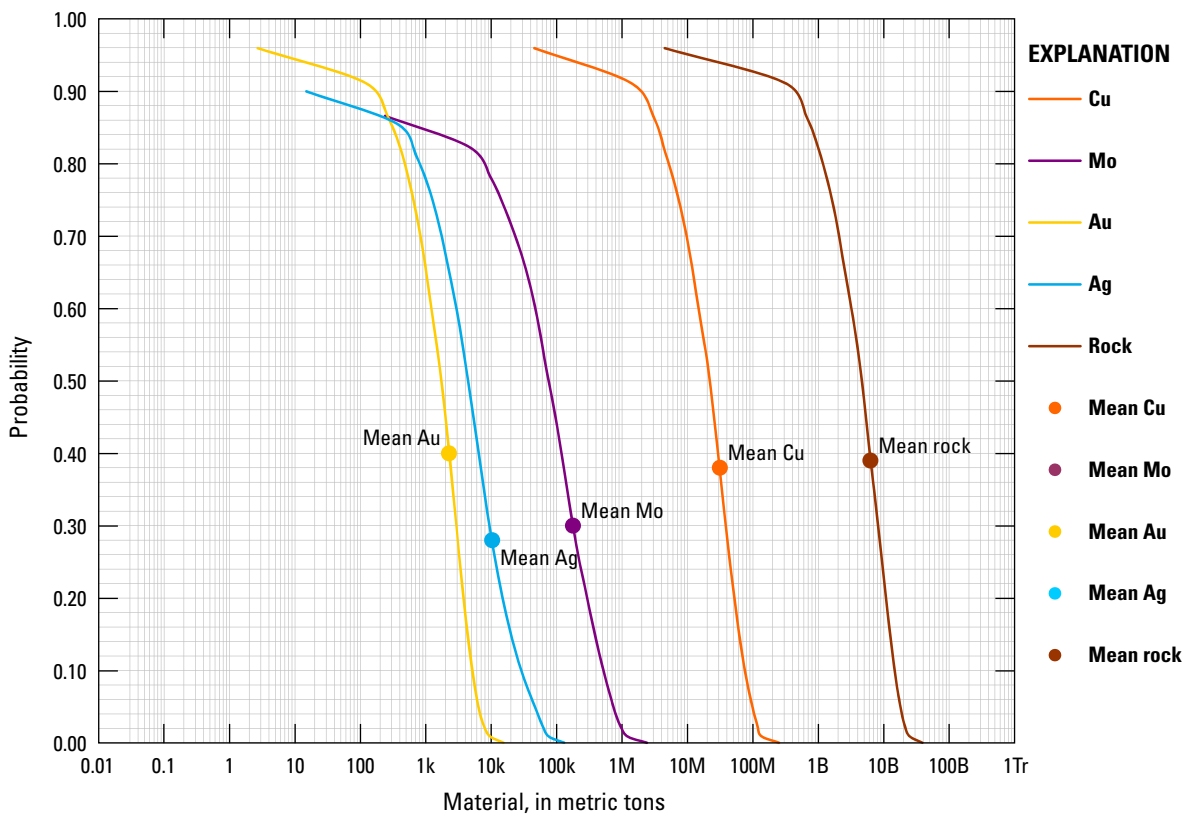
Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered porphyry copper deposits with the porphyry copper model of Singer and others (2008) using the EMINERS program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Selected simulation results are reported in table J7. Results of

the Monte Carlo simulation are presented as a cumulative frequency plot (fig. J4). The cumulative frequency plot shows the estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for each commodity and for total mineralized rock. The mean amount of copper (31 Mt) estimated for undiscovered deposits represents about twice the identified resources (17 Mt). The median expected value is 22 Mt (table J7).

**Table J7.** Results of Monte Carlo simulation of undiscovered resources for tract 142pCu7301, Luzon Arc—Philippines and Taiwan (Republic of 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	200,000	1,700,000	22,000,000	75,000,000	98,000,000	31,000,000	0.38	0.04
Mo	0	0	75,000	520,000	720,000	180,000	0.30	0.13
Au	21	160	1,700	5,100	6,400	2,300	0.40	0.04
Ag	0	0	4,400	29,000	46,000	10,000	0.28	0.10
Rock	49	400	4,600	15,000	18,000	6,300	0.39	0.04



**Figure J4.** Cumulative frequency plot showing the results of Monte Carlo computer simulation of undiscovered resources in tract 142pCu7301, Luzon Arc, the Philippines and Taiwan (Republic of China). k, thousands; M, millions; B, billions; Tr, trillions.

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## Appendix K. Porphyry Copper Assessment for Tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea)

By Jane M. Hammarstrom<sup>1</sup>, Steve Ludington<sup>2</sup>, Michael DeMarr<sup>1</sup>, and Connie L. Dicken<sup>1</sup>

### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Berger and others, 2008; Cox, 1986; John and others, 2010)

Table K1 summarizes selected assessment results.

**Table K1.** Summary of selected resource assessment results for tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea).

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric ton; NA, not applicable]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2012	1	46,300	0	NA	NA

### Location

Gyeongsang<sup>3</sup> Basin and adjacent areas in southern South Korea (fig. K1).

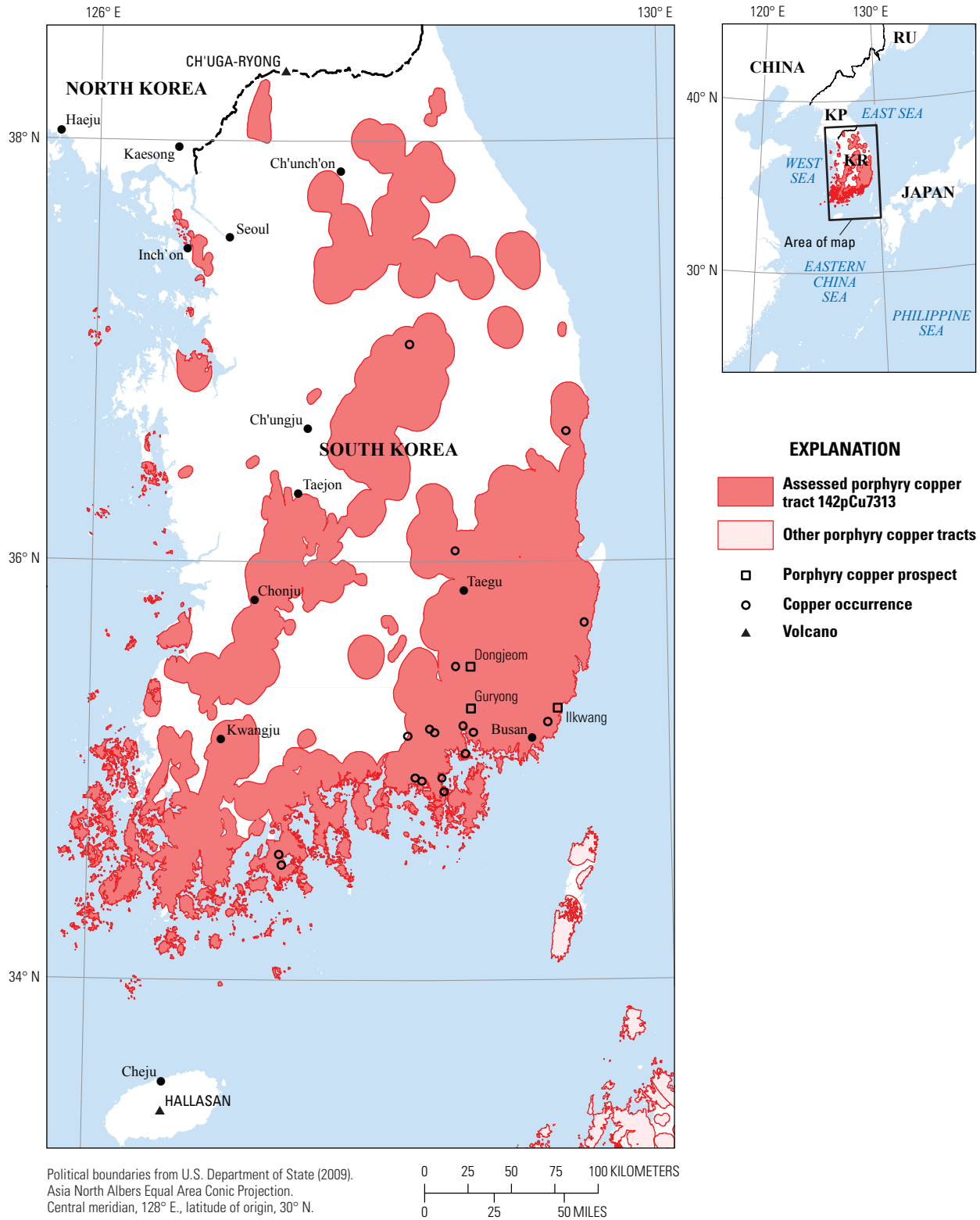
### Geologic Feature Assessed

Korean segment (Gyeongsang Arc) of the Cretaceous-Paleogene continental margin arc along the East Asian craton.

<sup>1</sup>U.S. Geological Survey, Reston, Virginia, United States.

<sup>2</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>3</sup>Also spelled as Gyeongsong and Kyongsang.



**Figure K1.** Map showing tract location and significant prospects and occurrences (open squares) for tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea). RU, Russia; JP, Japan; KP, Democratic People’s Republic of Korea (North Korea); KR, Republic of Korea (South Korea).



## Delineation of the Permissive Tract

### Tectonic Setting

Before the opening of the Sea of Japan in the Miocene, Korea was part of an active, Andean-type continental margin along East Asia that encompassed what is now southeastern China, western Japan, and the Sikhote-Alin area of Russia (fig. 9<sup>4</sup>). Northward (oblique) subduction of the Izanagi Plate (see fig. 10A) during the Cretaceous caused back-arc strike-slip basins to form, including the Gyeongsang Basin (Maruyama and others, 1997). The nonmarine Gyeongsang Basin preserves late Cretaceous volcano-sedimentary complexes and calc-alkalic I-type subvolcanic intrusions (Bulgusa or Bulguksa magmatism) that have been interpreted as marking the trace of a subduction-related continental arc system that extends from eastern China through southeastern Korea to the Japan Arc (Zhang and others, 2012). The Bulgusa granitoids were emplaced at relatively shallow levels (approximately 3 km) and cooled rapidly from intrusion to about 72 Ma, after which cooling rates slowed as the basin was inverted by regional uplift and exhumation, as indicated by fission track cooling rates and sedimentological studies (Lim and Lee, 2005; Chough and others, 2000). Tertiary inversion of the strike-slip basin in South Korea is attributed to collision of the Indian Plate with Eurasia (Chough and others, 2000).

### Geologic Criteria

The Late Cretaceous igneous and volcanic rocks of South Korea are exposed in the Gyeongsang Basin and along the Ogcheon Belt (fig. 11A). Rocks of the Gyeongsang Supergroup, a 9-km-thick sequence of volcanic and sedimentary rocks, including the 2,000–3,000-m-thick volcanic-dominant Yucheon Group, fill the basin. The Yucheon Group is comprised of andesitic and rhyolitic subgroups of high-K

calc-alkalic volcanic rocks. The granitoids range in age from 120–40 Ma, occur as small stocks and volcano-plutonic complexes, and predominantly are porphyritic, I-type diorites to granodiorites that have textures and miarolitic cavities indicative of a shallow level of emplacement (Zhang and others, 2012).

The permissive tract was constructed by selecting Cretaceous igneous rocks from a digital version of the 1:1,000,000-scale geologic map of Korea. Map units used to delineate the tract are shown in figure K2 and listed in table K2. A 10-km buffer was created around intrusive rocks, and a 2-km buffer was created around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock.

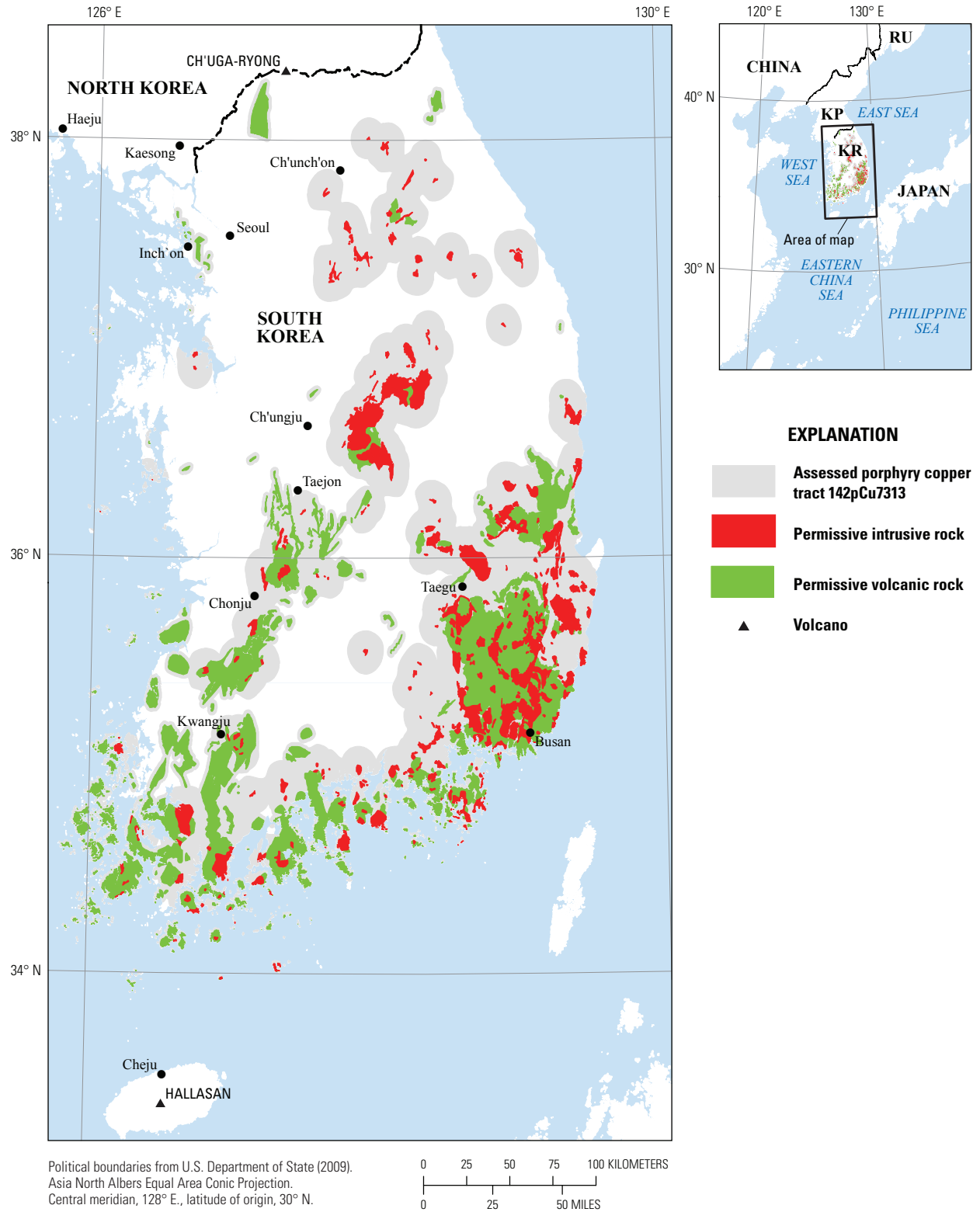
### Known Deposits

None.

### Prospects, Mineral Occurrences, and Related Deposit Types

The tract includes the Dongjeom porphyry copper prospect, the Guryong copper-molybdenum prospect, and the Ilkwang copper-tungsten breccia-pipe (fig. K1, table K3), as well as skarns, polymetallic deposits, and copper occurrences. No economic porphyry copper deposits have been documented to date. Yang and Bodnar (1994) concluded that exposed permissive rocks in the Gyeongsang Basin represent the root zones of porphyry copper systems; any ores that existed higher in the system have eroded off. They interpreted fluid- and silicate-melt inclusion data of the granitoids as indicative of a higher pressure of emplacement (1.9–2.5 kbar) than that of typical porphyry systems. Those pressures, along with a lack of water saturation until very late in the crystallization history suggests that the only subeconomic, low-grade, deeper parts of porphyry systems are preserved.

<sup>4</sup>Refer to figures and tables in main report.



**Figure K2.** Map showing igneous rocks used to delineate tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea). RU, Russia; JP, Japan; KP, Democratic People’s Republic of Korea (North Korea); KR, Republic of Korea (South Korea).

**Table K2.** Map units that define tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea).

[Map unit, age range, and principal lithologies are based on a digital compilation of maps listed in table K4]

Map unit	Lithology	Age range
Intrusive rocks		
Kgr	Bulgugsa granite	Cretaceous
Volcanic rocks		
K3	Yucheon and Jaedok Groups of the Gyeongsang Supergroup	Cretaceous and Paleogene

**Table K3.** Significant prospects and occurrences in tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea).

[% , percent; m, meters; Ma, million years. Rank 2=drilled or trenched with &lt;20 m of 0.2% Cu or past or ongoing exploration. Rank 1=copper occurrence that may be related to porphyry-type mineralization based on stream sediment or magnetic anomaly or location along structural trend]

Name	Latitude	Longitude	Age (Ma)	Comments	Reference	Rank
Dongjeom (Red Hill, Baegwol)	35.503	128.633	Cretaceous	Low-grade ( $\leq 0.1\%$ Cu) porphyry copper prospect associated with a 1,400 by 500 m exposed granodiorite porphyry stock. Explored by drilling, IP, geochemical surveys in the 1970s.	Sillitoe (1980)	2
Ilkwong	35.301	129.233	69	Cu-W tourmaline breccia pipe associated with an 81 Ma quartz monzonite stock. Level of emplacement appropriate for porphyry; no potassic alteration.	Fletcher (1977), Yang and Bodnar (2004)	1
Guryong	35.301	128.634	~85	Cu-Mo in hydrothermally altered (pyrophyllite) andesite. Quartz veinlets with chalcopyrite, molybdenite, and pyrite in a propylitized zone at depth.	Sillitoe (1980)	1

### Dongjeom (Red Hill, Baegwol)

The Red Hill porphyry copper prospect at Dongjeom (fig. K1) is a partly covered, fine-grained biotite-hornblende granodiorite stock that intrudes mudstones of the Cretaceous Gyeongsang Supergroup (Sillitoe, 1980). Potassic and sericitic alteration affected the stock; propylitic alteration developed in the mudstone. The potassic alteration zone is sulfide-rich (as much as 10 percent sulfides), mainly pyrite, with chalcopyrite, pyrrhotite, and molybdenite; calcite, chlorite, and tourmaline also are present (Sillitoe, 1980). Five holes were drilled in the 1970s, following an exploration plan for a vein-type deposit; evaluation of drill core and surface exposures led to a reinterpretation as a porphyry-type deposit, albeit of low average grade (0.1 percent copper or less, local higher-grade zones) with negligible supergene enrichment (Sillitoe, 1980).

### Guryong

Guryong is not a recognizable porphyry copper prospect but rather represents one of a number of pyrophyllite deposits developed in advanced argillic alteration zones in Cretaceous

andesite near intrusions in South Korea (Sillitoe, 1980). Some characteristics of the upper parts of porphyry systems are present at Guryong, as well as minor amounts of copper and molybdenum minerals. Quartz stockworks cut argillic alteration; molybdenite occurs with pyrite and chalcopyrite in quartz veinlets and as disseminations in the argillic alteration zone and to a lesser extent in an underlying propylitic zone. However, the observed apparent stratigraphic control and downward decrease in alteration and sulfide content are atypical of porphyry systems. Sillitoe (1980) suggested that the annular intrusion at Guryong might indicate cauldron subsidence, which would have perturbed the more stable subvolcanic conditions necessary to develop porphyry systems.

### Ilkwong

Ilkwong is a 100 by 70 m altered copper-tungsten breccia pipe in an elliptical Cretaceous stock that shares some characteristics with tourmaline-bearing breccia pipes associated with porphyry copper systems elsewhere (Yang and Bodnar, 2004). The deposit was mined from 1937 to 1945, and produced 3,500 metric tons of copper and 40 metric tons of tungsten.

The Ilkwang stock was dated at  $81 \pm 3$  Ma (K-Ar on hornblende), whereas sericite in altered breccia fragments from the pipe were dated at 69 Ma (Fletcher, 1977). Fluid inclusion and stable isotope data indicate that the deposit formed from magmatic hydrothermal fluids that evolved from high to low pressure as crystallization and water pressure buildup within the pipe eventually fractured and formed the breccia. Ilkwang was apparently formed at lower pressure or shallower emplacement depths than most of the noneconomic granitoids in the basin (Yang and Bodnar, 2004).

### Andong Area

Copper-bearing polymetallic vein occurrences in the Andong area (fig. K3) in the northern part of the Gyeongsang Basin were described as Cretaceous hydrothermal copper-lead-zinc-silver deposits that may represent a type of vein system transitional between epithermal and porphyry types of deposits (So and others, 1997). The quartz- and calcite veins fill fractures in Cretaceous sedimentary rocks; the veins may be related to spatially associated Cretaceous quartz porphyry (Bulgugsa series granitoids). A K-Ar age of  $91.4 \pm 4.2$  Ma was obtained on sericite alteration from one of the veins. High-temperature (greater than 320 °C), high-salinity early stage fluid inclusions, and decreasing sulfur and oxygen isotopes with decreasing temperature through the multistage vein paragenesis were interpreted as a magmatic hydrothermal system that was progressively mixed with meteoric water. The economically significant stage I veins evolved from pyrite (with pyrrhotite, chalcopyrite, sphalerite, and minor wolframite and magnetite) through base-metal sulfide to sulfosalt-bearing veins.

The exact location of the two mines developed along the veins, the Dongwha (3.2 percent copper and 160 ppm Ag) and Daesong mines studied by So and others (1997), could not be confirmed. On the basis of their sketch map, however, the mines appear to be in the vicinity of the prospects in the Andong area, as shown on figure K3.

### Other Deposits

South Korea is best known for production of tungsten, molybdenum, and lead-zinc from skarns associated with Cretaceous felsic intrusions. The Sangdong tungsten-molybdenum deposit, one of the largest tungsten resources in the world, produced tungsten until 1992, when low metal prices led to mine closure; the mine was approved to reopen in 2010, and a feasibility study was completed in April 2012 (Woulfe Mining Corp., 2012). These types of skarns typically are associated with coarse-grained equigranular batholiths rather than with porphyritic intrusions, and may indicate a deeper level of emplacement than porphyry-copper-related skarns, in accord with the results of Yang and Bodnar's 1984 study.

A copper-molybdenum prospect near the eastern coast of South Korea called Kampo (Gumnyong) was described by Sillitoe (1980) as an alteration zone in mainly rhyolitic volcanic and volcanoclastic rocks associated with a hornblende-biotite granodiorite of probable Cretaceous age. The location of this prospect could not be confirmed, but it was reportedly drilled in the 1970s.

The southwestern corner of South Korea (Jeollanam-do<sup>5</sup> Province and Gasa Island, figs. 8, K3) host epithermal gold-silver veins in clay deposits (advanced argillic alteration) associated with Cretaceous tuffs, rhyolites, and andesite (Eunsun (Silver Hill), Moisan deposits); these do not appear to have any association with porphyry copper deposits. Mining at Eunsun ceased in 2004. Exploration in the area from about 2003 to 2004 failed to discover additional high-grade precious metal veins (Asia Gold Corp., 2004).

### Exploration History

The Korea Mining Promotion Corporation and other groups explored for porphyry copper and molybdenum deposits in the 1970s (Sillitoe, 1980). A few prospects were drilled, and geophysical and geochemical surveys were done. In 2009, the Korean Institute of Geoscience and Mineral Resources (KIGAM, previously called the Korea Institute of Geology, Mining and Materials) (KIGAM, 2012) initiated a 3-year domestic exploration project for epithermal gold deposits in hydrothermally altered Cretaceous volcanic rocks in Jeollanam-do Province, southwesternmost South Korea (fig. K3). KIGAM is also doing an assessment of domestic reserves of metallic mineral resources that includes stream-sediment surveys and drilling for extensions of tungsten skarns in Gangwon-do Province (fig. K3) (KIGAM, 2011).

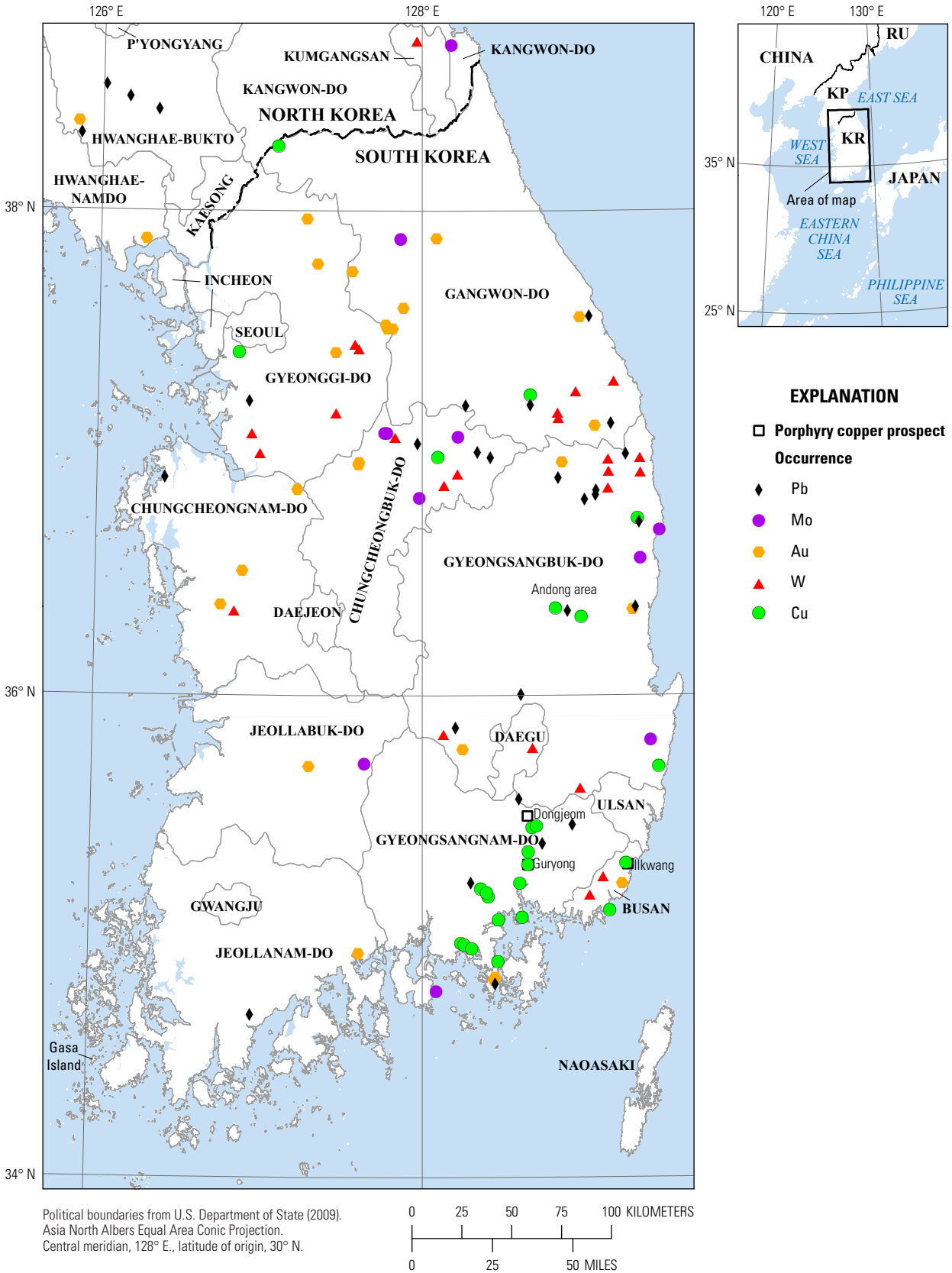
### Sources of Information

Table K4 lists the sources of information used in the assessment.

### Qualitative Assessment

Although Cretaceous continental margin arcs host significant porphyry copper deposits in many parts of the world, the Gyeongsang Basin area has not proven to be prospective for the deposit type. The basin preserves permissive rocks in volcanoplutonic complexes. However, existing data suggest that the uplift and erosion that accompanied basin inversion may have eroded any porphyry systems, if they ever existed. None of the available data suggest that undiscovered porphyry copper deposits that would have grades and tonnages described by the global models used for this assessment are likely to be present within the upper kilometer of the surface. Therefore, no estimate of numbers of undiscovered deposits was made.

<sup>5</sup>Chollanam-Do.



**Figure K3.** Map showing the distribution of copper, molybdenum, gold, tungsten and lead occurrences in South Korea. See table K4 for data sources. RU, Russia; JP, Japan; KP, Democratic People’s Republic of Korea (North Korea); KR, Republic of Korea (South Korea).



**Table K4.** Principal sources of information used for tract 142pCu7313, Gyeongsang Basin Area—Republic of Korea (South Korea).

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Geological map of Korea	1:1,000,000	Korea Institute of Geology, Mining and Materials (1995a)
	Isotope age map of volcanic rocks in Korea	1:1,000,000	Korea Institute of Geology, Mining and Materials (1995b)
	Isotope age map of plutonic rocks in Korea	1:1,000,000	Korea Institute of Geology, Mining and Materials (1995b)
	Mesozoic episodic magmatism in South Korea and its tectonic implication	NA	Sagong and others (2005)
	Late Cretaceous volcanic rocks and associated granites in Gyeongsang Basin, SE Korea	NA	Zhang and others (2012)
Mineral occurrences	Metallogenic map of Korea	1:1,000,000	Hwang and Kim (1983)
	Isotope age map of ore deposits in Korea	1:1,000,000	Korea Institute of Geology, Mining and Materials (1995d)
	Mineral resources map of East Asia	1:3,000,000	Kamitani and others (2007)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
	Evidence for porphyry-type mineralization in South Korea	NA	Sillitoe (1980)
	Mineralization characteristics and structural controls of hydrothermal deposits in the Gyeongsang Basin, South Korea	NA	Koh and others (2003)
Exploration	Evidence for porphyry-type mineralization in South Korea	NA	Sillitoe (1980)
	Korea Institute of Geosciences and Mineral Resources (KIGAM) Web site	NA	Korea Institute of Geosciences and Mineral Resources (KIGAM) (2012)

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## Appendix L. Porphyry Copper Assessment for Tract 142pCu7314, Western Honshu Area—Japan

By Yashushi Watanabe<sup>1</sup> with contributions from Dennis Cox<sup>2</sup>, Jane M. Hammarstrom<sup>3</sup>, and Michael DeMarr<sup>3</sup>

### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Cox, 1986; John and others, 2010)

Table L1 summarizes selected assessment results.

**Table L1.** Summary of selected resource assessment results for tract 142pCu7314, Western Honshu Area—Japan.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric ton; NA, not applicable]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2005	1	27,600	0	NA	NA

### Location

Western Honshu Island.

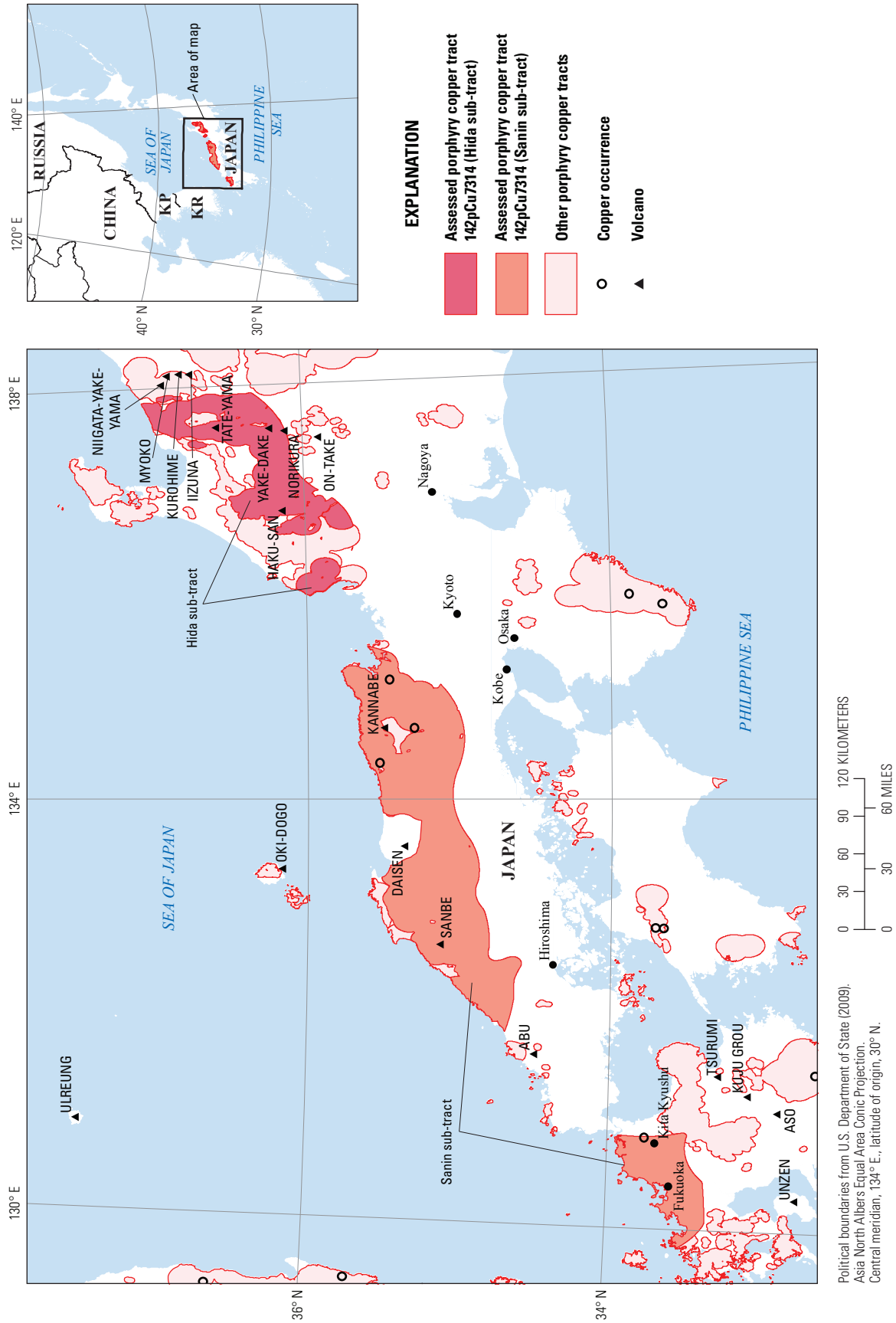
### Geologic Feature Assessed

Cretaceous to Paleogene calc-alkalic magnetite-series igneous rocks that formed part of the continental arc along the East Asia craton margin.

<sup>1</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.

<sup>2</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>3</sup>U.S. Geological Survey, Reston, Virginia, United States.



**Figure 11.** Map showing the location of permissive tract 142pCu7314, Western Honshu Area—Japan. KP, Democratic People’s Republic of Korea (North Korea); KR, Republic of Korea (South Korea).

## Delineation of the Permissive Tract

### Tectonic Setting

Japan was part of an active Cretaceous Andean-type continental margin along East Asia that encompassed what is now southeastern China, western Japan, and the Sikhotealin area of Russia (fig. 9<sup>4</sup>). Subduction of the (now extinct) Izanagi Plate (fig. 10A) brought the paleo-Pacific Plate into contact with proto-Japan. Subsequently, an extensional regime developed along the northern Asian continental margin in Eocene time as convergence rates decreased. Continued extension led to the Miocene opening of the Japan Sea as a back-arc basin and resulted in a separation of Japan from the continent. Clockwise rotation of southwestern Japan and counterclockwise rotation of northeastern Japan in the Miocene led to the modern configuration of the archipelago (fig. 10B), which is situated on four different tectonic plates: Eurasia, Okhotsk (North America), the Philippine Sea Plate, and the Pacific Sea Plate (Maruyama and others, 1997). The Japan Arc evolved from a Cretaceous Eurasian continental margin arc through a continental rifting stage (approximately 24 Ma), followed by an arc rifting stage (16–13 Ma) to the modern island arc (less than 14 Ma). The tract delineates Cretaceous and Paleogene granitoids and volcanic rocks that formed when Japan was part of the Eurasian continental margin.

### Geologic Criteria

The tract delineates a permissive area for porphyry copper deposits consisting of Cretaceous to Paleogene calc-alkalic magnetite-series granodiorite and granite, as depicted on geologic maps of Japan (Yamada and others, 1990; Ishihara and others, 1992). This tract is large having dimensions of about 70 by 600 km, and is separated into the eastern Hida and western Sanin segments by the Sea of Japan (fig. L1). The eastern margin of the tract is cut by the Itoigawa-Shizuoka tectonic line (ISTL on fig. 12A), a major fault that separates tectonic provinces (Ishihara and others, 1992). The tract is part of the Cretaceous to Paleogene Inner Zone Southwest Japan metallogenic belt (Nokleberg and others, 2004). The belt is interpreted as forming during the generation of granitoids along the East Asia magmatic arc related to subduction of the Kula and Pacific Plates. Mineral deposits in the belt are interpreted as forming during siliceous granitoid magmatism.

The permissive tract was constructed by selecting Cretaceous to Eocene igneous rocks from a digital version of the 1:1,000,000-scale geologic map of Japan (fig. L2, table L2).

A 10-km buffer was created around intrusive rocks, and a 2-km buffer was created around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. The buffered map polygons were edited by hand to restrict the tract to areas of magnetite-series rocks west of the Itoigawa-Shizuoka tectonic line.

The 65- to 30-Ma host granitoids in the Sanin sub-tract (figs. L1, L2) have initial strontium isotope ratios of 0.704 to 0.706. The granitoids consist of magnetite-series granite and granodiorite associated with rhyolite-dacite lava and felsic pyroclastic rock (Rezanov and others, 1994). Some of the granitoids are associated with cauldrons and intense sericitic and pyrophyllitic hydrothermal alteration (Imaoka and others, 2001). The granitoids associated with polymetallic vein deposits or occurrences in the eastern part of the Sanin segment are quartz diorite, granodiorite, and biotite granite whereas granitoids associated with molybdenum-tungsten vein and skarn deposits in the Hida and Sanin segments are biotite granite and granodiorite that are rich in mafic enclaves (Ishihara, 2002b). The exception is a stock in the Shirakawa region of molybdenum-mineralized granitoids (fig. L2) in Gifu Prefecture, where the Mirase molybdenite deposit occurs (Ishihara and Tani, 2004). The high concentration of molybdenum in the Hirase stock is attributed to a high degree of magmatic fractionation that produced MoS<sub>2</sub>-rich residual melts (Ishihara and Tani, 2004).

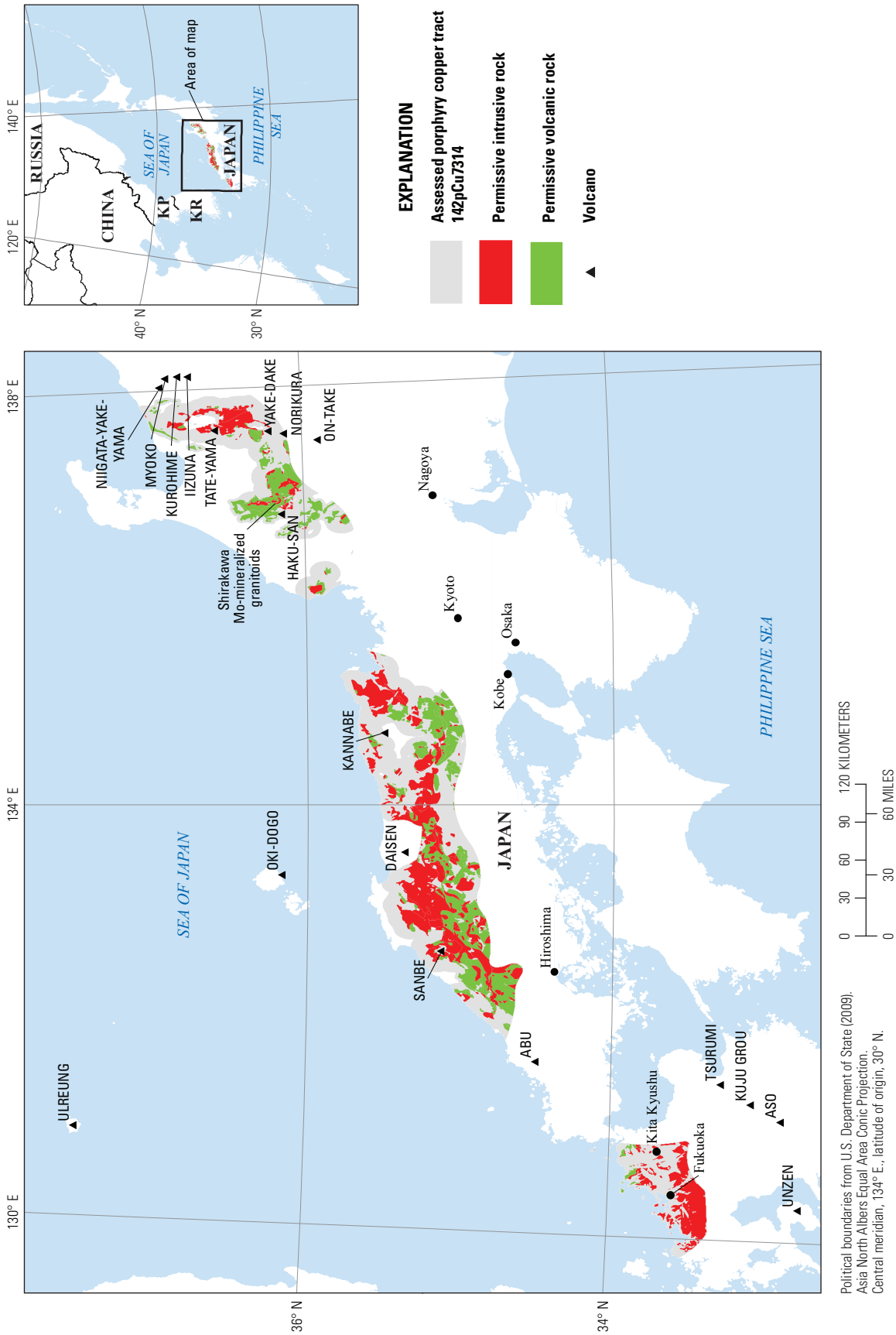
The Hida sub-tract (fig. L1) corresponds to the Hida belt of basement rock that consists of high-grade gneiss that is intruded by granitoids. This segment is intruded by latest Cretaceous to Paleogene magnetite-series granites and granodiorites and overlain by granitoids that are associated with rhyolite and andesite volcanic rock (Harayama, 1988).

The Sanin sub-tract corresponds to basement belts that represent several pre-Jurassic accretionary prisms (Isozaki, 1997). Late Cretaceous (79–58 Ma) andesite and rhyolite lavas and pyroclastic rock (Ishihara, 2002a), and latest Cretaceous to Paleogene (68–30 Ma) magnetite-series granitoids are present along the southern margin of the Sanin sub-tract (Rezanov and others, 1994; Ishihara, 2002a, b). Early Miocene tholeiitic volcanic rock that erupted in a rift graben (Inoue, 1994), Pliocene-Pleistocene sedimentary rocks (Uno, 1994), and Pliocene-Quaternary volcanic rocks (Uto and others, 1994) overlie the permissive rocks that define the Sanin sub-tract. The formation of the rift graben is interpreted to be related to spreading in the Sea of Japan.

### Known Deposits

None.

<sup>4</sup>Refer to figures and tables in main report.



**Figure L2.** Map showing the distribution of Cretaceous and Paleogene permissive rocks in the Inner Zone of southwest Japan. KP, Democratic People’s Republic of Korea (North Korea); KR, Republic of Korea (South Korea).



**Table L2.** Map units that define tract 142pCu7314, Western Honshu Area—Japan.

[Map unit, age range, and principal lithologies are based the 1995 digital geologic map of Japan. Felsic rocks predominate over mafic rocks; mafic rocks are spatially associated with felsic rocks at the 1:1,000,000 map scale]

Map unit	Lithology	Age range
Intrusive rocks		
K1	felsic, mafic intrusive rocks	Early Cretaceous
K1-K2	felsic, mafic intrusive rocks	Early and Late Cretaceous
K2	felsic, mafic intrusive rocks	Late Cretaceous
PG1	felsic, mafic intrusive rocks	Paleocene to early Eocene
PG2	felsic, mafic intrusive rocks	Eocene
PG3	felsic, mafic intrusive rocks	Late Eocene to early Oligocene
PG4	felsic, mafic intrusive rocks	Late Oligocene to early Miocene
Volcanic rocks		
K1	felsic, mafic volcanic rocks	Early Cretaceous
K1-K2	felsic, mafic volcanic rocks	Early and Late Cretaceous
K2	felsic, mafic volcanic rocks	Late Cretaceous
PG1	felsic, mafic volcanic rocks	Paleocene to early Eocene
PG2	felsic, mafic volcanic rocks	Eocene
PG3	felsic, mafic volcanic rocks	Late Eocene to early Oligocene
PG4	felsic, mafic volcanic rocks	Late Oligocene to early Miocene

## Prospects, Mineral Occurrences, and Related Deposit Types

No porphyry copper prospects are known in the tract area. Other types of deposits known within the tract include molybdenum deposits (48–65 Ma) and lead-zinc-silver vein and skarn deposits (Ishihara and others, 1988). The largest metallic deposit in the tract is the Kamioka (fig. 8) clinopyroxene skarn with sphalerite, galena, chalcopyrite, magnetite, pyrite, and pyrrhotite, and minor molybdenite and scheelite.

The tract also includes an antimony vein deposit, a few gold-silver mesothermal vein deposits, and four major sericite and pyrophyllite deposits that are hosted in granite (Sudo and Murao, 2004).

## Exploration History

The tract has been explored in detail for more than 1,000 years. Shallow drilling, to about 100 m, has occurred in and around sericite mines, and to 500 m at other types of mines. The Metal Mining Agency of Japan conducted exploration projects for lead and zinc skarn deposits in Hida (fig. 8) and in other areas. Many detailed geologic, geochemical and geophysical studies have been conducted at scales of 1:50,000 and larger.

## Sources of Information

Principal sources of information used by the assessment team for delineation of 142pCu7314 are listed in table L3.

## Qualitative Assessment

Qin and Ishihara (1998) discussed the potential for porphyry copper deposits in Japan and concluded that although such deposits could possibly exist, the absence of thick crust, an extensional setting that produced volcanogenic massive sulfide deposits rather than a compressional setting that would favor porphyry formation, low copper abundance in granitoids, and the overall low percentages of magnetite-series relative to ilmenite-series granitoids compared with productive arcs elsewhere, all are negative factors for porphyry systems. They suggested that the most likely target areas are volcano-plutonic magnetite series rocks in uplifted areas of the Inner Zone of southwestern Japan.

The lack of porphyry copper deposits most likely reflects the fact that the oxygen and sulfur fugacities of magnetite-series magmas in Japan were not high enough to form porphyry copper deposits, as shown by Takagi and Tsukimura (1997) and Takagi (2004) based on considerations of volatile compositions of source magmas.

This assessment was developed by the Geological Survey of Japan in consultation with the U.S. Geological Survey. The Assessment Team chose not to record an estimate of the number of undiscovered porphyry copper deposits in the tract because the available data do not support the assumption that undiscovered porphyry copper deposits are likely to be present within the upper kilometer of the surface that would have grades and tonnages described by the global models used for this assessment.

**Table L3.** Principal sources of information used for tract 142pCu7314, Western Honshu Area—Japan.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Computer-generated geologic map of Japan	1:1,000,000	Yamada and others (1990)
	Geological map of Japan (digital)	1:1,000,000	Geological Survey of Japan (1995)
	Regional geology of Japan	1:1,000,000	Karakida and others (1992)
Mineral occurrences	Geology, geochemistry, and origin of high sulfidation Cu-Au mineralization in the Nansatsu district, Japan.	NA	Hedenquist and others (1994)
	Metallogenic map of Japan	1:2,000,000	Ishihara and others (1992)
	Ore deposits related to granitic magmatism in Japan.	NA	Ishihara and Sasaki (1991)
	Overview of epithermal gold mineralization in Kyushu, Japan.	NA	Izawa and Watanabe (2001)
	Geologic setting of the Kuroko deposits, Japan.	NA	Ohmoto and others (1983)
	Mineral resources map of Tohoku	1:500,000	Sudo and Igarashi (1997)
	Mineral resources map of Tohoku	1:500,000	Sudo and Morao (2004)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Geochemistry	Unpublished data	NA	Geological Survey of Japan Assessment Team, this report
Exploration	Unpublished data	NA	Geological Survey of Japan Assessment Team, this report
	Korea Institute of Geosciences and Mineral Resources (KIGAM) Web site	NA	Korea Institute of Geosciences and Mineral Resources (KIGAM) (2012)

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## Appendix M. Porphyry Copper Assessment for Tract 142pCu7315, Subaerial Neogene Arcs of Japan

By Yashushi Watanabe<sup>1</sup>, with contributions from Dennis Cox<sup>2</sup>, Takehiro Sakimoto<sup>1</sup>, Jane M. Hammarstrom<sup>3</sup>, and Michael W. DeMarr<sup>3</sup>

### Deposit Type Assessed: Porphyry copper

**Descriptive model:** Porphyry copper (Cox, 1986; John and others, 2010)

Table M1 summarizes selected assessment results.

**Table M1.** Summary of selected resource assessment results for tract 142pCu7315, Subaerial Neogene Arcs of Western Japan.

[km, kilometers; km<sup>2</sup>, square kilometers; t, metric ton; NA, not applicable]

Date of assessment	Assessment depth (km)	Tract area (km <sup>2</sup> )	Identified copper resources (t)	Mean estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)
2005	1	120,590	0	NA	NA

### Location

Most of Japan.

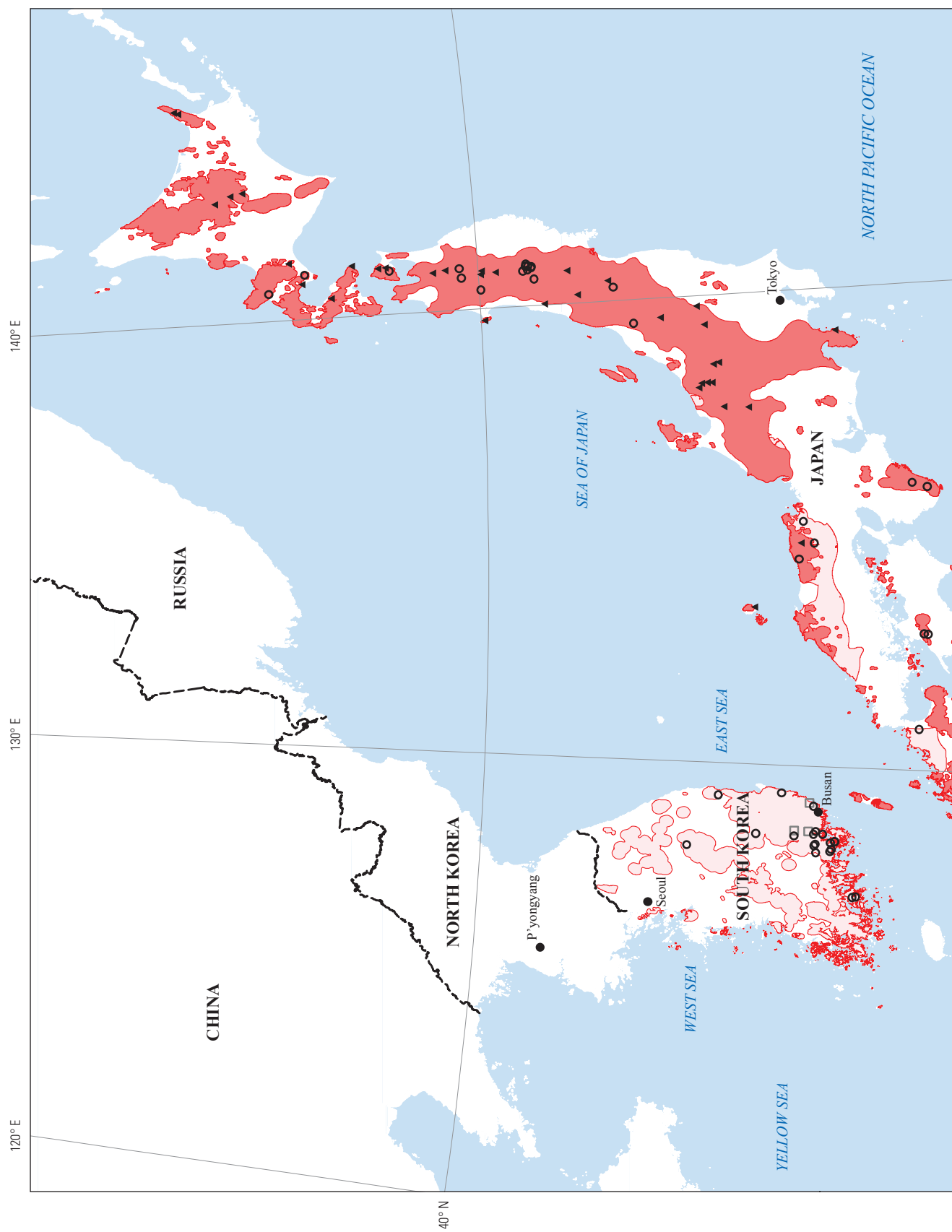
### Geologic Feature Assessed

Subaerial parts of the Miocene and younger Kurile, Northeast Japan, Izu, Southwest Japan, and Ryukyu Arcs (fig. M1).

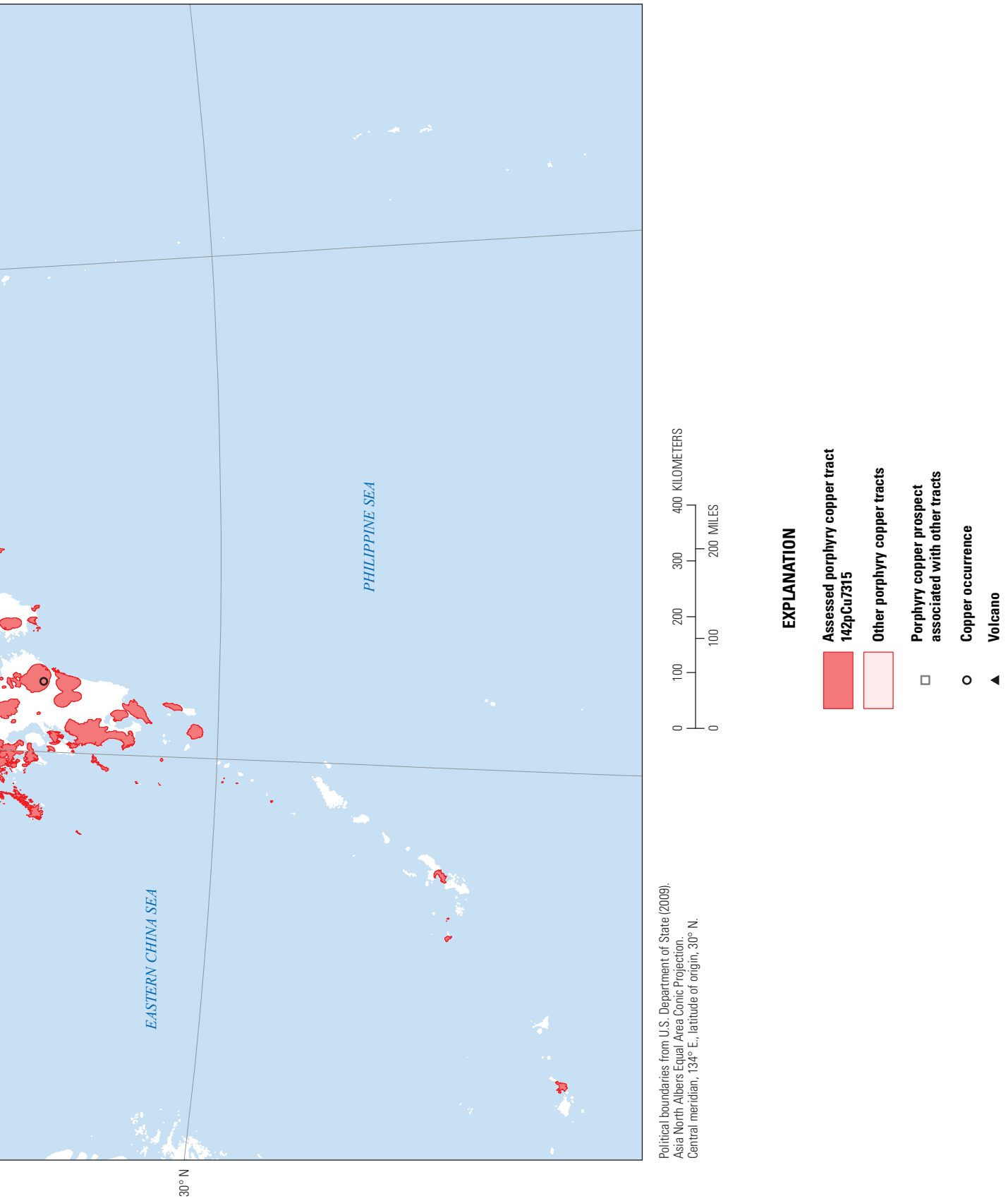
<sup>1</sup>Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Ibaraki, Japan.

<sup>2</sup>U.S. Geological Survey, Menlo Park, California, United States.

<sup>3</sup>U.S. Geological Survey, Reston, Virginia, United States.







Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 134° E., latitude of origin, 30° N.

**Figure M1.** Map showing the location of permissive tract 142pCu7315, Neogene arcs of Japan.

## Delineation of the Permissive Tract

### Tectonic Setting

The Neogene island arcs of Japan include the Japan Arc, the Ryukyu Arc, the Izu-Bonin Arc, and the Kurile Arc (fig. 2<sup>4</sup>). Rift-related bimodal arc volcanism accompanied the Miocene opening of the Sea of Japan, followed by subduction-related andesite-dacite volcanism starting in the late Miocene (Garwin and others, 2005). The northeastern and southwestern segments of the Japan Arc are separated by a fault zone (Itoigawa-Shizuoka tectonic line, ISTL on fig. 12A) that forms the boundary between the North American and Eurasian Plates (Garwin and others, 2005; Uyeda, 1991). The northeastern Japan Arc is related to subduction of the Pacific Plate beneath the North America Plate along the Japan Trench. The 1,800-km-long modern continental Japan Arc connects the Ryukyu Arc to the south with the Kurile Arc to the north (fig. 2B). The Ryukyu Arc resulted from subduction of the Philippine Sea Plate beneath Eurasia. The Kurile Arc formed by subduction of the Pacific Plate beneath the Okhotsk Plate along the Kurile Trench. The oceanic Izu-Bonin Arc results from northwestward subduction of the Pacific Plate along the Philippine Sea Plate (fig. 10B). During the middle Miocene, the Okhotsk (North America) continental block and the Izu-Bonin Arc collided with the Japan Arc. Most of the Izu-Bonin arc is submerged.

### Geologic Criteria

The tract delineates the subaerial parts of the Miocene and younger-age Kurile, Northeast Japan, Izu, Southwest Japan, and Ryukyu Arcs, as depicted on the geologic map of Japan (Yamada and others, 1990). The tract is very large, about 1,800 km long by 100 km wide, and occurs in parts of Hokkaido Island, Northeast Japan, the Sanin district in Southwest Japan, and Kyushu Island (fig. M1).

The host rocks that are permissive for undiscovered deposits in the tract are Miocene to Quaternary volcanic rocks (fig. M2, table M2), including calc-alkaline andesite and dacite with minor rhyolite and basalt. The tract contains many Miocene and Pliocene shallow-level intrusions that are variable in

size, ranging from a few meters to several kilometers in diameter. The shallow-level intrusions are generally fine-grained or porphyritic, and vary from andesite to rhyolite. Also occurring locally in the tract are late Miocene granitoid intrusions.

The permissive tract was constructed by selecting Miocene and younger igneous rocks from a digital version of the 1:1,000,000-scale geologic map of Japan. A 10-km buffer was created around intrusive rocks, and a 2-km buffer around volcanic rocks. These distances are considered appropriate to allow for inaccuracies in mapped contacts and extensions under adjacent cover rock. Volcanoes were not excluded from the tract; their locations are shown on fig. M2.

### Known Deposits

None.

### Prospects, Mineral Occurrences, and Related Deposit Types

Although no porphyry copper deposits or occurrences are known in the tract, abundant advanced argillic alteration occurs around late Miocene and Pliocene shallow intrusions in the Nagano and Kagoshima Prefectures (fig. 8). Many detailed geologic, geochemical, and geophysical studies have been conducted at a scale of 50,000 and larger. Porphyry granitoid systems probably are present beneath the epithermal deposits; some may contain copper. No porphyry molybdenum, porphyry tungsten, or porphyry tin deposits are known in Japan. The age range of host rocks for undiscovered deposits is middle Miocene to Quaternary.

The tract includes several metallogenic provinces that contain gold-silver epithermal vein, polymetallic and epithermal veins, sulfur-sulfide (S, FeS<sub>2</sub>), and related deposits (Nokleberg and others, 2004). Metallic mineral deposits of the Japan Arc include middle Miocene copper-lead-zinc (silver-gold) Kuroko deposits and late Miocene to Pleistocene copper-lead-zinc and gold-silver epithermal deposits (Watanabe, 2002). More than 40 Miocene, low-sulfidation epithermal gold and mercury deposits and prospects occur on northeast Hokkaido Island in the southwestern Kurile Arc. About 70 Kuroko deposits, including massive gypsum and barite deposits, occur in the 800-km-long Northeast Japan Arc (Sato, 1974). These

<sup>4</sup>Refer to figures and tables in main report.

deposits are associated with monogenetic rhyolite volcanism of the middle Miocene back-arc bimodal assemblage that formed in a submarine environment. A few middle (or early) Miocene epithermal gold-silver deposits in the Northeast Japan Arc are related to felsic volcanism (Watanabe, 1995, 1996, 2002). The metallic mineral deposits along the Izu Arc are Kuroko massive sulfide and epithermal gold-silver deposits. The northern end of the Ryukyu Arc hosts the Pliocene and Pleistocene Southern Kyushu epithermal low-sulfidation gold province.

## Exploration History

The tract has been explored in detail for more than 400 years. Various epithermal gold-silver mines have been drilled at depths of hundreds to thousands of meters. Small volcanic islands in the middle and northeastern parts of the Kurile Arc have not been thoroughly explored. The middle and northeastern parts of the tract contain mainly polymetallic base-metal vein prospects of middle and late Miocene age and associated with intrusive rocks (Ishihara, 1994). The Metal Mining Agency of Japan conducted the following exploration projects in the tract (see fig. M2 for general locations): Northern Hokkaido area for gold (1989–2002), the Kunitomi area for base metals (1967–73), the Chitose area for gold (1978–86), the Shakotan area for base metals (1984–1988), the Southern Hokkaido area for gold (1998–2003), Kudo area for

base metals (1977–86), the Oshima-Shimokita area for gold (1991–97), and the Northern Hidaka area for gold and rare metals (1992–96).

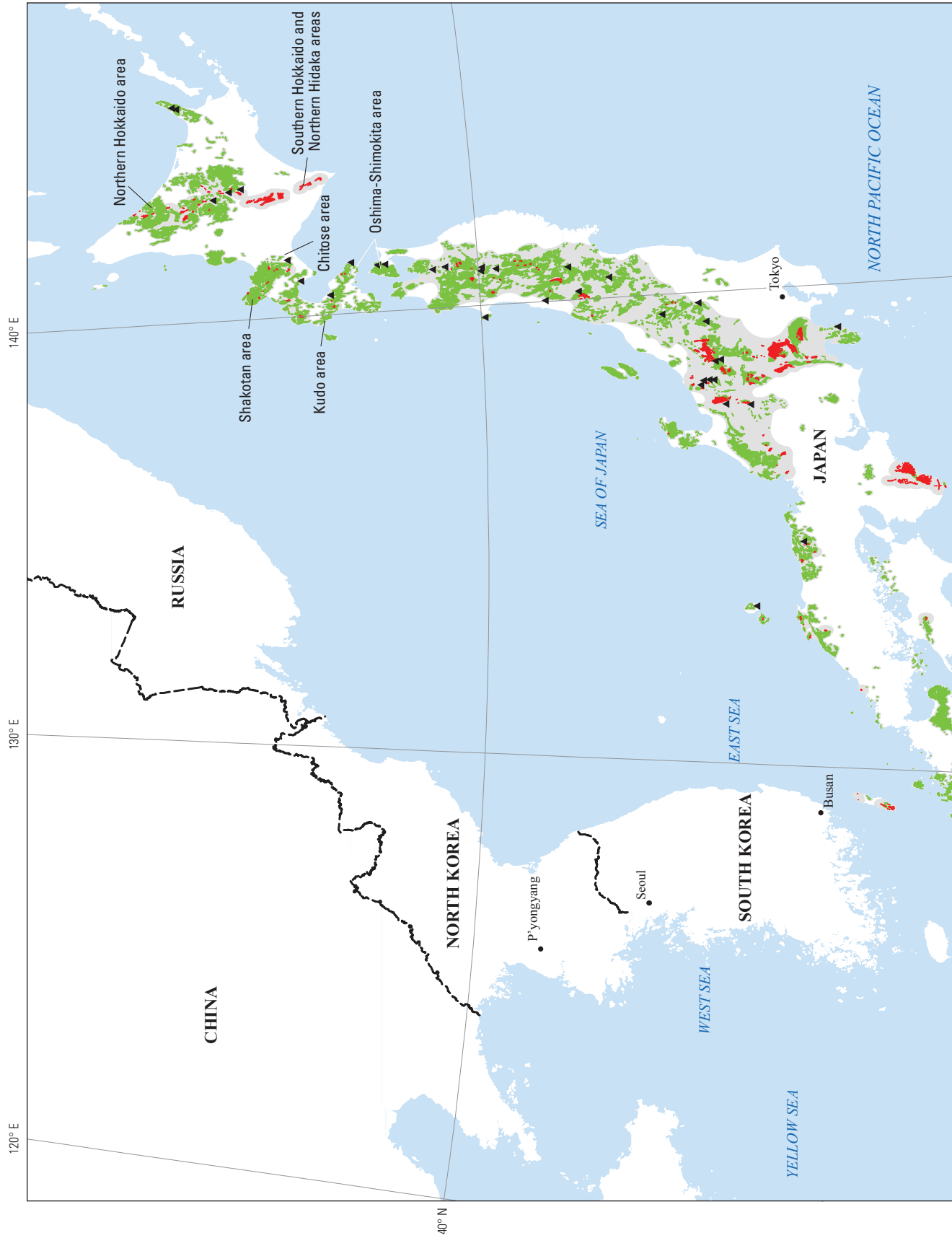
## Sources of Information

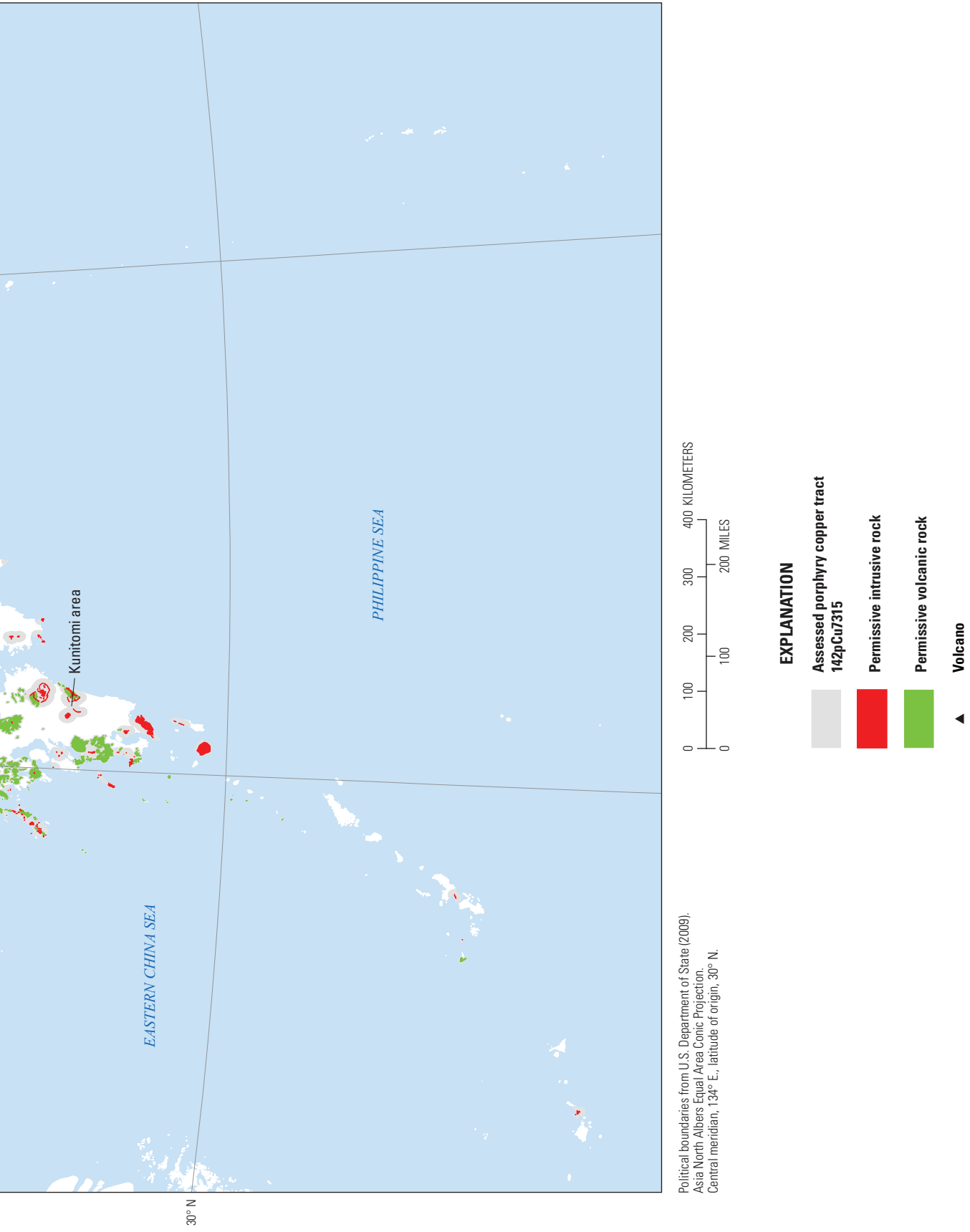
Principal sources of information used by the assessment team for delineation of the tract are listed in table M3.

## Qualitative Assessment

Well-developed, advanced argillic alteration occurs locally around late Miocene and Pliocene shallow intrusions in Japan. Many detailed studies of epithermal deposits are published at 1:50,000 and larger scales. Porphyry granitoid systems may be present beneath epithermal deposits and some may contain copper. No porphyry molybdenum, porphyry tungsten, or porphyry tin deposits are known in Japan.

This assessment was developed by geological surveys of local prefectures and by the Geological Survey of Japan in consultation with the U.S. Geological Survey. The Assessment Team chose not to record an estimate of the number of undiscovered porphyry copper deposits in the tract because the available data do not support the assumption that undiscovered porphyry copper deposits are likely to be present within the upper kilometer of the surface that would have grades and tonnages described by the global models used for this assessment.





Political boundaries from U.S. Department of State (2009).  
 Asia North Albers Equal Area Conic Projection.  
 Central meridian, 134° E., latitude of origin, 30° N.

**Figure M2.** Map showing the distribution of Miocene and younger permissive rocks associated with Neogene arcs in Japan.

**Table M2.** Map units that define tract 142pCu7315, Subaerial Neogene Arcs of Western Japan.

[Map unit, age range, and principal lithologies are based the 1995 digital geologic map of Japan]

Map unit	Lithology	Age range
Intrusive rocks		
N1	felsic, mafic intrusive rocks	Miocene
N2	felsic, mafic intrusive rocks	Miocene
N3	felsic, mafic intrusive rocks	Late Miocene to Pliocene
Volcanic rocks		
N1	felsic, mafic volcanic rocks	Miocene
N2	felsic, mafic volcanic rocks	Miocene
N3	felsic, mafic volcanic rocks	Late Miocene to Pliocene
Q1, Q2, Q3	felsic, mafic volcanic rocks; pyroclastic flows	Pleistocene

**Table M3.** Principal sources of information used for tract 142pCu7315, Subaerial Neogene Arcs of Western Japan.

[NA, not applicable]

Theme	Name or title	Scale	Citation
Geology	Computer-generated geologic map of Japan	1:1,000,000	Yamada and others (1990)
	Geological map of Japan (digital)	1:1,000,000	Geological Survey of Japan (1995)
	Regional geology of Japan	1:1,000,000	Karakida and others (1992)
Mineral occurrences	Geology, geochemistry, and origin of high sulfidation Cu-Au mineralization in the Nansatsu district, Japan	NA	Hedenquist and others (1994)
	Metallogenic map of Japan	1:2,000,000	Ishihara and others (1992)
	Ore deposits related to granitic magmatism in Japan	NA	Ishihara and Sasaki (1991)
	Overview of epithermal gold mineralization in Kyushu, Japan.	NA	Izawa and Watanabe (2001)
	Mineral resources map of Kyushu	1:500,000	Sudo and others (2003)
	Geologic setting of the Kuroko deposits, Japan	NA	Ohmoto and others (1983)
	Mineralization in the Kuril Islands	NA	Ishihara (1994)
	Evolution in space and time of epithermal mineralization in northeastern Hokkaido, Japan	NA	Yahata and others (1999)
	Quaternary gold mineralization and its geologic environments in Kyushu, Japan	NA	Izawa and Urashima (1987)
	U.S. Geological Survey On-Line Mineral Resources Spatial Data	NA	U.S. Geological Survey (2012)
Unpublished data	NA	Geological Survey of Japan Assessment Team, this report	
Geochemistry	Unpublished data	NA	Geological Survey of Japan Assessment Team, this report
Exploration	Unpublished data	NA	Geological Survey of Japan Assessment Team, this report



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## Appendix N. Description of Spatial Data Files

Three ESRI shapefiles (.shp), a file geodatabase (.gdb) and an ESRI map document (.mxd) are included with this report. The file geodatabase contains four feature classes and two data tables. These may be downloaded from the USGS Web site as zipped file **GIS\_SIR2010-5090-P.zip**.

The file geodatabase is **E\_SE\_Asia\_pCu** and contains the following four feature classes and two tables:

**E-SE\_Asia\_pCu\_Tracts**—a polygon feature class that represents permissive tracts for East and South East Asia. Attributes include the tract identifiers, tract name, a brief description of the basis for tract delineation, and assessment results. Attributes are defined in the metadata that accompanies the feature class.

**E\_SE\_Asia\_pCu\_Deposits\_prospects**—point feature class for locations of known deposits (identified resources that have well-defined tonnage and copper grade) and prospects. Feature class attributes include the assigned tract, alternate site names, information on grades and tonnages, age, mineralogy, associated igneous rocks, site status, comments fields, data sources, and references. Attributes are defined in the metadata that accompanies the feature class. Note that tonnage and grade information are numeric fields; entries of –9999 in these fields mean that no data are available. Entries of 0 in the Age\_Ma field mean that no data are available.

**E-SE\_Asia\_political\_boundaries**—polygon feature class showing countries within and adjacent to the study area. The feature class is extracted from the country and

shoreline boundaries maintained by the U.S. Department of State (2009).

**SSIB\_Borders**—line feature class showing internal country boundaries. The feature class is maintained by the U.S. Department of State (2009).

Probabilistic assessment results are included in two tables in the GIS map document.

**Means** data table—shows the mean expected amount for each commodity by tract in East and South East Asia.

**Quantiles** data table—shows the probabilistic assessment results as quantiles for each commodity by tract.

Four shapefiles are included (**E\_SE\_Asia\_pCu\_Tracts.shp**, **E\_SE\_Asia\_pCu\_Deposits\_prospects.shp**, **E\_SE\_Asia\_political\_boundaries.shp** and **SSIB\_Borders.shp**). The shapefiles have been created from the feature classes. They represent an exact copy of the feature class in shapefile format.

These four feature classes are included in an ESRI map document (version 10 Service Pack 5): **E\_SE\_Asia\_pCu.mxd**. Probabilistic assessment results are included in two related tables in the GIS package; Excel versions of these tables also are provided. Mean, shows the mean amount for each commodity by tract. Quantiles, shows probabilistic assessment results as quantiles for commodity by tract.

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## Appendix O. Assessment Team

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**Dennis P. Cox**, USGS Geology, Minerals, Energy, and Geophysics Science Center, Menlo Park, Calif., United States. Dr. Cox is an emeritus scientist with the USGS. Dr. Cox is an expert on porphyry copper deposits. He participated in project workshops in 2005.

**Michael W. DeMarr**, George Mason University, Fairfax, Va. Intern with USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va. Assisted with the GIS compilation and analysis of the data for South Korea.

**Connie L. Dicken**, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. GIS task leader for the USGS Global Mineral Resource Assessment Project. Ms. Dicken compiled the GIS for the project.

**Jane M. Hammarstrom**, USGS Eastern Mineral and Environmental Resources Science Center, Reston, Va., United States. Co-chief, USGS Global Mineral Resource Assessment Project since 2007. Task leader, porphyry copper assessment. Mrs. Hammarstrom led the 2009 workshop in Busan, South Korea.

**Steve Ludington**, USGS Geology, Minerals, Energy, and Geophysics Science Center, Menlo Park, Calif., United States. Economic geologist with expertise on porphyry copper and mineral resource assessment. Dr. Ludington participated in the 2009 workshop in Busan, South Korea, and provided estimates for final quantitative assessment of the Philippines.

**Claro C. Manipon**, Mines and Geosciences Bureau, Department of Environment and Natural Resources, Republic

of the Philippines. Mr. Manipon provided information on porphyry copper deposits and prospects in the Philippines and participated in the 2005 workshop in Kunming, China.

**Lilian A. Rollan**, Supervising science research specialist, Mines and Geosciences Bureau, Department of Environment and Natural Resources, Republic of the Philippines. CCOP representative for the Philippines at the 2009 Busan workshop.

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**Yashushi Watanabe**, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST). Dr. Watanabe served as the Group Leader for the AIST Mineral Resources Research Group and was the CCOP representative for Japan and leader of the Japan assessment at the 2005 workshop in Kunming, China.

**Michael L. Zientek**, USGS Geology, Minerals, Energy, and Geophysics Science Center, Spokane, Wash., United States. Co-chief, USGS Global Mineral Resource Assessment Project since 2007. Dr. Zientek provided estimates for the final quantitative assessment of the Philippines.

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