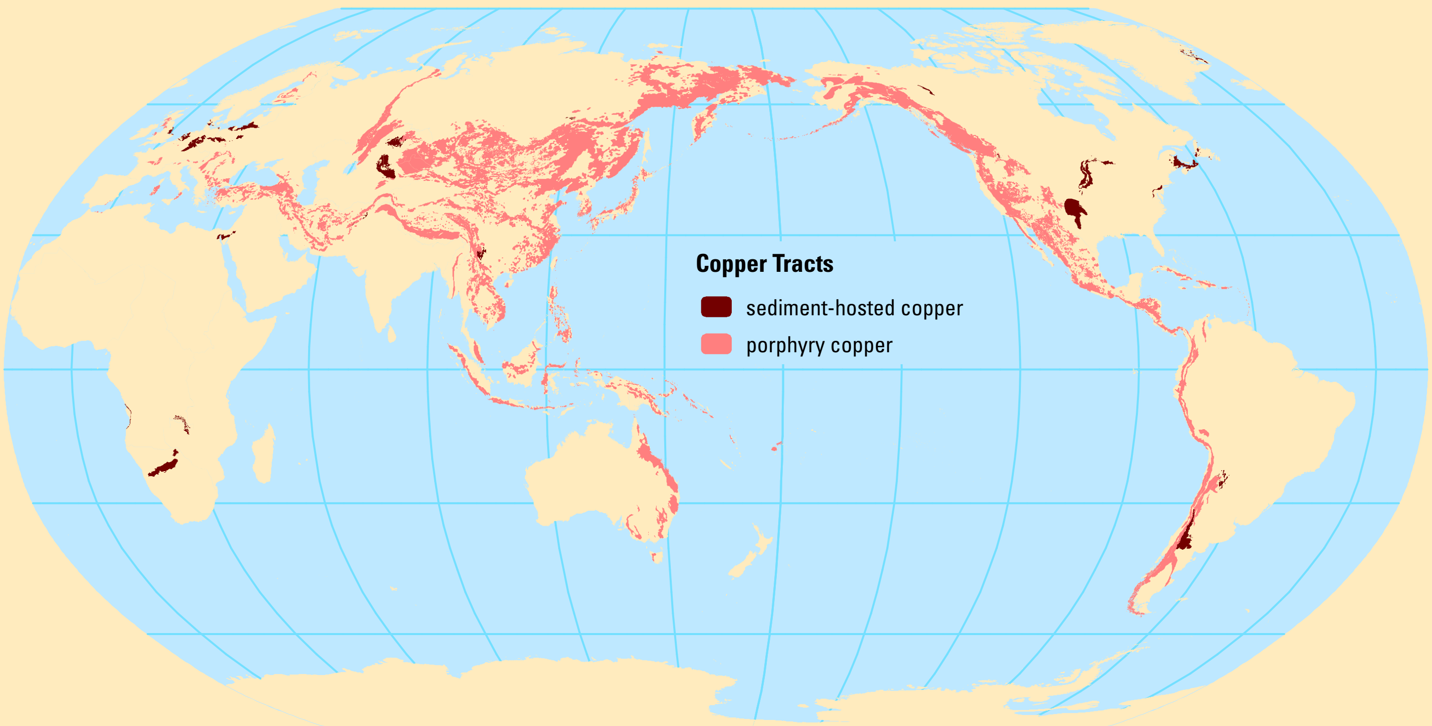
Global Mineral Resource Assessment

Spatial Database for a Global Assessment of Undiscovered Copper Resources



Scientific Investigations Report 2010–5090–Z

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

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

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By Connie L. Dicken, Pamela Dunlap, Heather L. Parks, Jane M. Hammarstrom, and Michael L. Zientek

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Contents

Figure

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)

Datum

Horizontal coordinate information is referenced to the World Geodetic System Datum of 1984 (WGS 1984).

Spatial Database for a Global Assessment of Undiscovered Copper Resources

By Connie L. Dicken, Pamela Dunlap, Heather L. Parks, Jane M. Hammarstrom, and Michael L. Zientek

Abstract

As part of the first-ever U.S. Geological Survey global assessment of undiscovered copper resources, data common to several regional spatial databases published by the U.S. Geological Survey, including one report from Finland and one from Greenland, were standardized, updated, and compiled into a global copper resource database. This integrated collection of spatial databases provides location, geologic and mineral resource data, and source references for deposits, significant prospects, and areas permissive for undiscovered deposits of both porphyry copper and sediment-hosted copper. The copper resource database allows for efficient modeling on a global scale in a geographic information system (GIS) and is provided in an Esri ArcGIS file geodatabase format.

Introduction

In the first-ever global assessment of undiscovered copper resources, the U.S. Geological Survey (USGS) estimated undiscovered copper (Cu) resources for the two most significant sources of global copper supply—porphyry copper deposits and sediment-hosted stratabound copper deposits (Johnson and others, 2014). The purpose of the global assessment was to (1) compile databases of known copper deposits and significant copper prospects for the two deposit types, (2) delineate geology-based permissive areas (tracts) for undiscovered copper deposits at a scale of 1:1,000,000, (3) if possible, estimate numbers of undiscovered deposits within those permissive tracts, and (4) provide probabilistic estimates of amounts of copper and co-product resources that could be contained in those undiscovered deposits. The global assessment was facilitated by incorporating regional reports that describe data sources, methods, and results for each study area and are accompanied by spatial data in the form of a geographic information system (GIS) constructed in Esri[1] ArcGIS. Economic filters were applied to quantitative assessment results for porphyry copper deposits using the economic filter developed by Robinson and Menzie (2012) and are included in this global compilation. See appendix A for description.

This report describes global data that were compiled from regional reports; it includes point data for deposits and prospects and polygon data for areas that represent permissive tracts for undiscovered deposits of porphyry copper and sediment-hosted stratabound copper. The GIS for global copper is a single Esri file geodatabase (*USGS_global_copper.gdb*) composed of feature datasets, feature and relationship classes, and nonspatial tables (fig. 1). These data are packaged along with metadata and a map document[2] file in the compressed archive file *sir20105090z_gis.zip* which is available at http://dx.doi.org/10.3133/sir20105090Z.

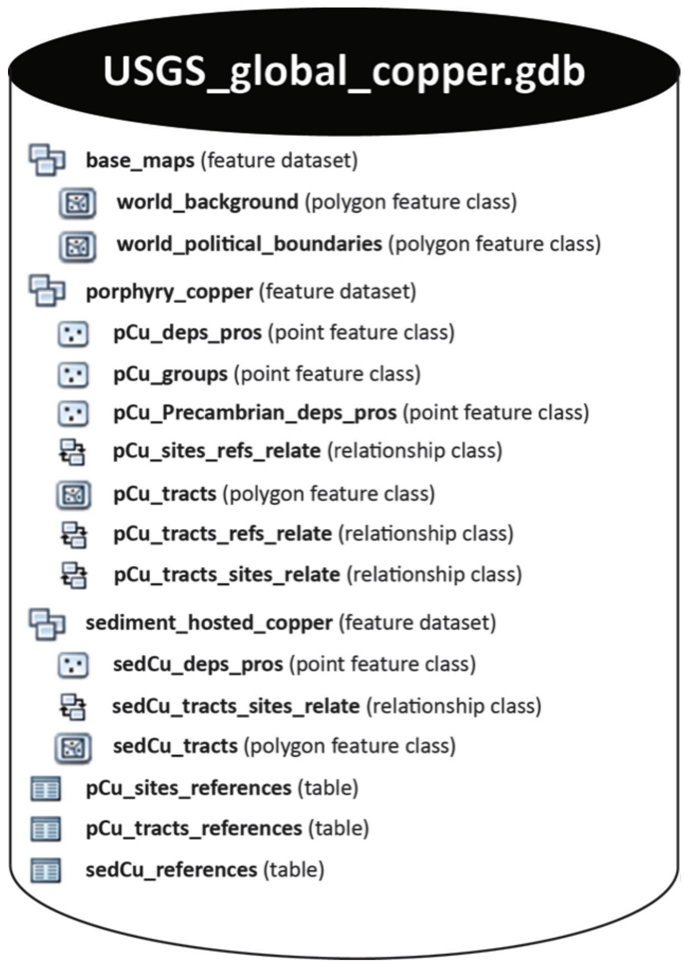

Figure 1. Image showing contents and organization of the data model for the global copper file geodatabase.

[1]Esri is a software development and services company providing geographic information system software and geodatabase management applications.

[2]In this report, the term "map document" refers to an ArcMap document.

Spatial Data for Porphyry Copper

Data for porphyry copper deposits, prospects, and mineral resource tracts were compiled from eighteen regional assessment reports (table 1) into a single global spatial dataset for use in a GIS. These data can be queried in many database management systems as well as a GIS to reveal the distribution, age, geologic setting, and resource potential of porphyry copper deposits and to model resource grade and tonnage.

Table 2 lists the vector features, nonspatial tables, and associated relationship classes that describe porphyry copper assessment outcomes compiled from regional reports and enforce referential integrity. Metadata that describe the spatial data are embedded within the feature classes; they are also provided as standalone files (table 2).

Table 1. Regional assessment reports for the global assessment of undiscovered porphyry copper resources.

Regional report	Reference
Asia	
Afghanistan	Ludington and others (2007)
Central Asian Orogenic Belt and eastern Tethysides—China, Mongolia, Russia, Pakistan, Kazakhstan, Kyrgyzstan, Tajikistan, Afghanistan, India, and Myanmar	Mihalasky, Ludington, Hammarstrom, and others (2015)
East and Southeast Asia—Philippines, Taiwan (Republic of China), Republic of Korea (South Korea), and Japan	Hammarstrom and others (2014)
Mesozoic of East Asia—China, Vietnam, North Korea, Mongolia, and Russia	Ludington, Mihalasky, and others (2012)
Northeast Asia—Far East Russia and northeasternmost China	Mihalasky, Ludington, Alexeiev, and others (2015)
Southeast Asia and Melanesia	Hammarstrom and others (2013)
Tethys Region of western and southern Asia	Zürcher and others (2015)
Tibetan Plateau, China	Ludington, Hammarstrom, and others (2012)
Western Central Asia	Berger and others (2014)
Australia	
Eastern Australia	Bookstrom and others (2014)
Europe	
Europe, exclusive of the Fennoscandian Shield	Sutphin and others (2013)
Finland	Rasilainen and others (2014)
Urals	Hammarstrom (written commun., 2015)
North America	
British Columbia and Yukon Territory, Canada	Mihalasky and others (2011, revised 2013)
Central America and the Caribbean Basin	Gray and others (2014)
Mexico	Hammarstrom and others (2010)
United States	U.S. Geological Survey National Mineral Resource Assessment Team (2002)
South America	
Andes Mountains of South America	Cunningham and others (2008)

Table 2. Description of porphyry copper digital data files within the file geodatabase and supporting metadata files.

Feature dataset name	Description
porphyry_copper	Feature dataset that contains feature classes and relationship classes, stored in geographic coordinates using the world geodetic system datum of 1984 (GCS WGS 1984).
Feature class name	**Description**
pCu_deps_pros	Feature class (points) of 2,199 Phanerozoic porphyry copper and related deposits and prospects of the world.
pCu_groups	Feature class (points) of select groups of Phanerozoic porphyry copper and related deposits and prospects of the world.
pCu_Precambrian_deps_pros	Feature class (points) of Precambrian porphyry copper and related deposits and prospects of the world.
pCu_sites_references	Nonspatial table of references for abbreviated citations used in the feature class *pCu_d*eps_pros associated with Short_ref field; full reference for Short_ref field can be found in nonspatial table pCu_tracts_references.
pCu_sites_refs_relate	Relationship class that manages the association between objects in the nonspatial table *pCu_sites_references* to objects in the feature class *pCu_d*eps_pros.
pCu_tracts	Feature class (polygons) of permissive tracts of porphyry copper.
pCu_tracts_references	Nonspatial table of full references for abbreviated citations used in the feature class *pCu_t*racts.
pCu_tracts_refs_relate	Relationship class that manages the association between objects in the nonspatial table *pCu_tracts_references* to objects in the feature class *pCu_tracts*.
pCu_tracts_sites_relate	Relationship class that manages the association between objects in the *pCu_tracts* feature class to objects in the *pCu_deps_pros* feature class.
Adobe Acrobat Portable Document Format (.pdf) files for Federal Geographic Data Committee (FGDC) metadata	
pCu_deps_pros_metadata.pdf	Information about the spatial and descriptive data in the file geodatabase feature class *pCu_deps_pros*.
pCu_groups_metadata.pdf	Information about the spatial and descriptive data in the file geodatabase feature class *pCu_groups*.
pCu_Precambrian_deps_pros_metadata.pdf	Information about the spatial and descriptive data in the file geodatabase feature class *pCu_Precambrian_deps_pros*.
pCu_tracts_metadata.pdf	Information about the spatial and descriptive data in the file geodatabase feature class *pCu_t*racts.
Extensible markup language (.xml) files for metadata	
pCu_deps_pros_metadata.xml	Metadata for file geodatabase feature class *pCu_deps_pros*.
pCu_groups_metadata.xml	Metadata for file geodatabase feature class *pCu_groups*.
pCu_Precambrian_deps_pros_metadata.xml	Metadata for file geodatabase feature class *pCu_Precambrian_deps_pros*.
pCu_tracts_metadata.xml	Metadata for file geodatabase feature class *pCu_tracts*.

Porphyry Copper Deposits and Prospects

The feature class *pCu_deps_pros* contains vector data (points) for 2,199 Phanerozoic deposits and significant prospects with porphyry copper or porphyry-related mineralization. Attributes are listed and described in table 3.

The feature class *pCu_groups* contains vector data (points) for a small select set of 47 records, each of which represents a group of related deposits and (or) prospects; data were compiled from the feature class *pCu_deps_pros*. Location coordinates can represent a generalized location or a specific mineralized site; for all of the deposits in the group, “grade” represents a weighted average whereas “tonnage” represents total ore tonnage. Data field names for *pCu_groups* are identical to those for *pCu_deps_pros*; however, definitions of some fields were revised to account for the group nature of the data (table 4).

Table 3. Description of user-defined fields in the feature class *pCu_deps_pros*.

Field name	Field alias	Description
GMRAP_ID	GMRAP ID	Unique identifier for each record. [GMRAP, Global Mineral Resource Assessment Project.]
Coded_ID	Tract identifier	Coded, unique identifier assigned to permissive tract within which the site is located; corresponds to Coded_ID in the feature class *pCu_tracts*.
Tract_name	Tract	Name of permissive tract in which the site is located; corresponds to *Tract_name* in the feature class *pCu_tracts*.
Name	Site	Site name.
Name_other	Other site names	Other names used for the site.
Name_group	Group name	Group name, applied when 2-kilometer rule was used to cluster deposits and (or) prospects for the purpose of calculating grades and tonnages.
Includes	Includes	Names of deposits and (or) prospects that have been combined with the primary deposit as a result of the 2-kilometer spatial aggregation rule used for calculating grades and tonnages, or sites described in the original source reference(s) as being included in the description of primary site.
SiteStatus	Site status	Type of site; “deposit” is a site for which grade and tonnage are reported; “prospect” is a site for which grade and tonnage are not reported.
Country	Country	Country in which the site is located.
State_Prov	State/Province	State, province, or region in which the site is located.
Latitude	Latitude	Latitude, in decimal degrees; positive number represents latitude north of the equator; negative number represents latitude south of the equator.
Longitude	Longitude	Longitude, in decimal degrees; positive number represents longitude east of the Greenwich meridian; negative number represents longitude west of the Greenwich meridian.
Dep_type	Deposit type	Type of mineral deposit.
Dep_subtype	Deposit subtype	Subtype of porphyry copper (Cu) deposit type based on ratio of gold (Au) in grams per metric ton (g/t) to molybdenum (Mo) (weight percent); entries include Cu-Au, Cu-Mo, and NA (not applicable).
Age_Ma	Age date	Age of mineralization; in millions of years before present; based on reported absolute ages, or midpoints of ranges of absolute ages, or midpoints of geologic time scale units.
Age_method	Age method	Method used to determine age reported in field *Age_Ma*.
Age_range	Age range	Range of ages, listed from oldest to youngest; in absolute ages or in geologic time scale units.
Age_ref	Age references	Abbreviated citation, in author and year format, for reference(s) for age information; full references are listed in the file geodatabase nonspatial table *pCu_sites_references*.
Comm_major	Major commodities	Major commodities, listed in decreasing order of economic importance. Chemical symbols are used for commodities; multiple commodities are comma-delimited.
Comm_minor	Minor commodities	Minor commodities, listed in decreasing order of economic importance; queried where uncertain. Chemical symbols are used for commodities; multiple commodities are comma-delimited.
Comm_trace	Trace commodities	Trace commodities, listed in decreasing order of economic importance. Chemical symbols are used for commodities; multiple commodities are comma-delimited.
Tonnage_Mt	Tonnage ore rock	Ore tonnage, for deposit, in millions of metric tons (Mt); -9,999 indicates no data.
Cu_pct	Copper grade	Average copper grade, for deposit, in weight percent; -9,999 indicates no data.

Field name	Field alias	Description
Mo_pct	Molybdenum grade	Average molybdenum grade, for deposit, in weight percent; -9,999 indicates no data.
Au_g_t	Gold grade	Average gold grade, for deposit, in grams per metric ton (g/t); -9,999 indicates no data.
Ag_g_t	Silver grade	Average silver grade, for deposit, in grams per metric ton (g/t); -9,999 indicates no data.
Con_Cu_t	Contained copper	Contained copper, for deposit, in metric tons (t), rounded to nearest significant figure; -9,999 indicates no data.
Au_Mo	Au/Mo (ratio)	Ratio of Au (g/t) to Mo (weight percent), for deposit, rounded to nearest significant figure; -9,999 indicates no data.
Comments	Comments	Significant comments; may include grade and tonnage information for prospects, name of magmatic arc or belt, and other significant comments.
Minerals	Minerals	Minerals present, as reported in literature cited; listed in alphabetical order. Most rock-forming minerals such as feldspar and quartz are not reported.
Assd_rock	Associated rocks	Associated rocks in the deposit and on regional source map.
Dev_Status	Development status	The status or nature of operations at the time the record was entered or this field was last modified; entries include “Occurrence,” “Prospect,” “Producer,” “Past Producer,” or “Unknown.”
Ref_list	References	List of abbreviated citations, in author and year format, for references used in compiling information for site, delimited by semicolons; full references are listed in the file geodatabase nonspatial table *pCu_sites_references*.
Short_ref	Regional report short reference	Abbreviated citation for author and year of the U.S. Geological Survey (USGS) regional report from which data were originally compiled; full reference located in the lineage section of the metadata and listed in file geodatabase nonspatial table *pCu_tracts_references*.
Strat_age	Stratigraphic age (Eon/Era/Period)	Stratigraphic age; Eon, Era, or Period (Cohen and others, 2013, revised 2015).
Setting	Tectonic setting	Tectonic setting in which mineralization was emplaced; entries include continental margin, island arc, mixed, or postconvergence.
Study_area	Study area	Geographic area of USGS report from which data were originally compiled.

Table 4. Description of group-specific, user-defined fields in the feature class *pCu_groups*.

Field name	Field alias	Description
Name_group	Group name	Group name, applied when 2-kilometer rule was used to cluster deposits and (or) prospects for the purpose of calculating grades and tonnages.
Includes	Includes	Names of deposits and (or) prospects that have been grouped as a result of the 2-kilometer spatial aggregation rule used for calculating grades and tonnages.
Latitude	Latitude	Latitude, in decimal degrees, for a general location of the group; positive number represents latitude north of the equator; negative number represents latitude south of the equator.
Longitude	Longitude	Longitude, in decimal degrees, for a general location of the group; positive number represents longitude east of the Greenwich meridian; negative number represents longitude west of the Greenwich meridian.
Tonnage_Mt	Tonnage ore rock	Total ore tonnage for all deposits in the group, in millions of metric tons (Mt); -9,999 indicates no data.
Cu_pct	Copper grade	Weighted average copper grade, for all deposits in the group, in weight percent; -9,999 indicates no data.
Mo_pct	Molybdenum grade	Weighted average molybdenum grade, for all deposits in the group, in weight percent; -9,999 indicates no data.
Au_g_t	Gold grade	Weighted average gold grade, for all deposits in the group, in grams per metric ton (g/t); -9,999 indicates no data.
Ag_g_t	Silver grade	Weighted average silver grade, for all deposits in the group, in grams per metric ton (g/t); -9,999 indicates no data.
Con_Cu_t	Contained copper	Total contained copper, for all deposits in the group, in metric tons (t), rounded to nearest significant figure; -9,999 indicates no data.

The feature class *pCu_Precambrian_deps_pros* contains vector data (points) for 21 Precambrian significant deposits and prospects for porphyry copper from Singer and others (2002) and is included for reference only. Precambrian deposits and prospects were not used to delineate permissive tracts except in the Finland regional report. Deposits and prospects for the Finland report are included with the *pCu_deps_pros* feature class. Attribute field names and descriptions are described in table 5.

Permissive Tracts for Undiscovered Porphyry Copper Deposits

The feature class *pCu_tracts* contains vector data (polygons) for 192 tracts permissive for porphyry copper mineralization. The tracts outline principal areas of the world that have potential for undiscovered porphyry copper resources; the tracts were used to estimate the probable amounts of those resources at depths within 1 kilometer (km) below the Earth's surface. Attributes are listed and described in table 6.

Table 5. Description of user-defined fields in the feature class *pCu_Precambrian_deps_pros*.

Field name	Field alias	Description
Name	Site	Site name.
Name_other	Other site names	Other names used for the site.
Includes	Includes	Names of deposits and (or) prospects that have been combined with the primary deposit as a result of the 2-kilometer spatial aggregation rule used for calculating grades and tonnages, or sites described in the original source reference(s) as being included in the description of primary site.
SiteStatus	Site status	Type of site; deposit is a site for which grade and tonnage are reported; prospect is a site for which grade and tonnage are not reported.
Country	Country	Country in which the site is located.
State_Prov	State/Province	State, province, or region in which the site is located.
Latitude	Latitude	Latitude, in decimal degrees; positive number represents latitude north of the equator; negative number represents latitude south of the equator.
Longitude	Longitude	Longitude, in decimal degrees; positive number represents longitude east of the Greenwich meridian; negative number represents longitude west of the Greenwich meridian.
Dep_type	Deposit type	Type of mineral deposit.
Dep_subtype	Deposit subtype	Subtype of porphyry copper (Cu) deposit type based on ratio of gold (Au) in grams per metric ton (g/t) to molybdenum (Mo) (weight percent); entries include Cu-Au, Cu-Mo, and NA.
Age_Ma	Age date	Age of mineralization; in millions of years before the present; based on reported absolute ages, or midpoints of ranges of absolute ages, or midpoints of geologic time scale units.
Tonnage	Tonnage ore rock	Ore tonnage, for deposit, in millions of metric tons (Mt); -9,999 indicates no data.
Cu_pct	Copper grade	Average copper grade, for deposit, in weight percent; -9,999 indicates no data.
Mo_pct	Molybdenum grade	Average molybdenum grade, for deposit, in weight percent; -9,999 indicates no data.
Au_g_t	Gold grade	Average gold grade, for deposit, in grams per metric ton (g/t); -9,999 indicates no data.
Ag_g_t	Silver grade	Average silver grade, for deposit, in grams per metric ton (g/t); -9,999 indicates no data.

Table 6. Description of user-defined fields in the feature class *pCu_tracts*.

Field name	Field alias	Description
Coded_ID	Tract identifier	Coded, unique identifier assigned to permissive tract.
Tract_name	Tract	Informal name of permissive tract.
Unregcode	United Nations Region code	Three-digit United Nations (2013) code for the region that underlies most of the permissive tract.
Country	Country	Country(ies) in which the permissive tract is located.
Commodity	Commodity	Primary commodity being assessed.
Study_area	Study area	Geographic area of U.S. Geological Survey (USGS) report from which data were originally compiled.
Quant	Quantitative	Dichotomous variable for whether a quantitative resource assessment was performed for tract.

Table 6. Description of user-defined fields in the feature class *pCu_tracts*.—Continued

Field name	Field alias	Description
Region	Region	Name of large geographic region used for reporting copper resources in Johnson and others (2014).
Dep_type	Deposit type	Type of mineral deposit.
GT_model	Grade/tonnage model	Grade-tonnage model used for the undiscovered resource simulation.
Geology	Geology	Geologic feature assessed.
Age	Age	Age of the assessed geologic feature.
Age_group	Age group	Generalized geologic age.
Asmt_date	Assessment date	Year assessment was conducted.
Asmt_depth	Assessment depth	Maximum depth beneath the Earth's surface used for the assessment, in kilometers.
N90	90th percentile deposit estimate	Estimated number of deposits associated with the 90th percentile (90 percent chance of at least the indicated number of deposits); -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N50	50th percentile deposit estimate	Estimated number of deposits associated with the 50th percentile (50 percent chance of at least the indicated number of deposits); -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N10	10th percentile deposit estimate	Estimated number of deposits associated with the 10th percentile (10 percent chance of at least the indicated number of deposits); -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N05	5th percentile deposit estimate	Estimated number of deposits associated with the 5th percentile (5 percent chance of at least the indicated number of deposits); -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N01	1st percentile deposit estimate	Estimated number of deposits associated with the 1st percentile (1 percent chance of at least the indicated number of deposits); -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N_expected	Expected number of deposits	Expected (mean) number of deposits, where $N\_expected = (0.233 \times N90) + (0.4 \times N50) + (0.225 \times N10) + (0.045 \times N05) + (0.03 \times N01)$; -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
s	Standard deviation	Standard deviation, where $s = 0.121 - (0.237 \times N90) - (0.093 \times N50) + (0.183 \times N10) + (0.073 \times N05) + (0.123 \times N01)$; -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
Cv_percent	Coefficient of variance	Coefficient of variance, in percent, where $Cv = (s/N\_expected) \times 100$; -9,999 indicates no data. <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
Est_levels	Percentile estimate levels	The set of percentile (probability) levels at which undiscovered deposit estimates were made.
N_known	Known deposits	Number of known deposits in the tract; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
N_total	Total deposits	Total number of deposits, where $N\_total = N\_expected + N\_known$; <Null> indicates segment data (partial tract); data recorded in main tract so it would not be duplicated.
Area_km2	Tract area in square kilometers	Area of permissive tract, in square kilometers, calculated in a locally appropriate equal-area projection; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
DepDensity	Deposit density	Deposit density (total number of deposits per square kilometer), where $DepDensity = N\_total/Area\_km2$; -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
DepDen10E5	Deposit density per 100,000 square kilometers	Deposit density per 100,000 square kilometers, where $DepDen10E5 = DepDensity \times 100{,}000$; -9,999 indicates no data; <Null> indicates segment data (partial tract); data were recorded in main tract and were not duplicated.
Estimators	Estimators	Names of people on the estimation team.
Mean_Cu_t	Mean copper resources	Mean copper resources, in metric tons, based on Monte Carlo simulation.

Table 6. Description of user-defined fields in the feature class *pCu_tracts*.—Continued

Field name	Field alias	Description
Mean_Mo_t	Mean molybdenum resources	Mean molybdenum resources, in metric tons, based on Monte Carlo simulation.
Mean_Au_t	Mean gold resources	Mean gold resources, in metric tons, based on Monte Carlo simulation.
Mean_Ag_t	Mean silver resources	Mean silver resources, in metric tons, based on Monte Carlo simulation.
Mean_Rock_Mt	Mean ore tonnage	Mean ore tonnage, in metric tons, based on Monte Carlo simulation.
Cu_95	Copper resource estimate at 95th percentile	Undiscovered copper resource estimate, 95th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_90	Copper resource estimate at 90th percentile	Undiscovered copper resource estimate, 90th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_50	Copper resource estimate at 50th percentile	Undiscovered copper resource estimate, median (50th percentile) value, in metric tons (t); -9,999 indicates no data.
Cu_10	Copper resource estimate at 10th percentile	Undiscovered copper resource estimate, 10th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_05	Copper resource estimate at 5th percentile	Undiscovered copper resource estimate, 5th percentile value, in metric tons (t); -9,999 indicates no data.
Prob_mean	Probability of mean copper	Probability of the mean value, undiscovered copper resource estimate; -9,999 indicates no data.
Prob_0_Cu	Probability of no copper resources	Probability of no copper, based on Monte Carlo simulation.
Ident_Cu	Known copper resources	Known copper resources, in metric tons (t).
N_prospects	Number of prospects	Number of identified porphyry copper prospects in tract.
Scales	Map scales used	List of map scales used, by denominator, to delineate tract boundary.
Begin_age	Oldest age	Oldest age of permissive rocks in the tract, from geologic source maps, in millions of years before the present.
End_age	Youngest age	Youngest age of permissive rocks in the tract, from geologic source maps, in millions of years before the present.
Duration	Age range	Age range of permissive rocks in the tract, from geologic source maps.
Short_ref	Regional report short reference	Abbreviated citation for source reference; full reference located in the lineage section of the metadata and listed in file geodatabase nonspatial table *pCu_tracts_references*.
MeanCu_km2	Mean copper resource per square kilometers	Mean copper resources per square kilometer (km^2), in metric tons (t).
CtryFraser	Country used for Fraser ranking	Country used for infrastructure rankings as compiled by the Fraser Institute (McMahon and Cervantes, 2012); <Null> indicates no economic evaluation.
Fras_typ	Fraser typical	Percentage of categories 1 and 2, from quality of infrastructure table (McMahon and Cervantes, 2012), used to classify cost setting; <Null> indicates no economic evaluation.
Fras_high	Fraser high	Percentage of categories 3, 4, and 5, from quality of infrastructure table (McMahon and Cervantes, 2012), used to classify cost setting; <Null> indicates no economic evaluation.
Typ_cost	Typical cost	Ranking for typical cost, in percent; <Null> indicates no economic evaluation.
High_cost	High cost	Ranking for high cost, in percent; <Null> indicates no economic evaluation.
Infra_set	Infrastructure setting	Mine cost setting based on infrastructure development; <Null> indicates no economic evaluation.
Depth_dist	Depth distribution	Comments on rationale for assignment of depth distributions categories; <Null> indicates no economic evaluation.

Table 6. Description of user-defined fields in the feature class *pCu_tracts*.—Continued

Field name	Field alias	Description
D_0_250m	Surface to 250 meters	Proportion of undiscovered deposits occurring in the interval between the surface and 250 meters in depth; <Null> indicates no economic evaluation.
D_250_500m	250-500 meters	Proportion of undiscovered deposits occurring in the interval 250–500 meters in depth; <Null> indicates no economic evaluation.
D_over500m	Over 500 meters	Proportion of undiscovered deposits occurring in the interval 500–1,000 meters in depth; <Null> indicates no economic evaluation.
Ec_Cu	Economic copper	Estimated amount of economically recoverable copper, in metric tons (t); <Null> indicates no economic evaluation.
Ec_Mo	Economic molybdenum	Estimated amount of economically recoverable molybdenum, in metric tons (t); <Null> indicates no economic evaluation.
Ec_Au	Economic gold	Estimated amount of economically recoverable gold, in metric tons (t); <Null> indicates no economic evaluation.
Ec_Ag	Economic silver	Estimated amount of economically recoverable silver, in metric tons (t); <Null> indicates no economic evaluation.
Ec_0_prob	Probability of no economic resources	Probability of no economic resources occurring in the tract, in percent; <Null> indicates no economic evaluation.
Ec_NPV	Economic net present value	Net present value of simulated economic deposits in the tract, in million U.S. dollars; <Null> indicates no economic evaluation.
EV_ID	Expected value	Expected value of simulated resources in the tract, in million U.S. dollars/100,000 km^2; <Null> indicates no economic evaluation.
EV_class	Expected value classification	Qualitative classification of expected value of simulated resources in the tract; <Null> indicates no economic evaluation.
Tect_set	Tectonic setting	Tectonic setting.
Econ_ref	Economic reference	Abbreviated citation for economic source reference; full reference is listed in file geodatabase nonspatial table *pCu_tracts_references*; <Null> indicates no economic evaluation.

Spatial Data for Sediment-Hosted Stratabound Copper

Data were compiled from nine regional assessment reports (table 7) into a single feature dataset. Similar to the porphyry copper compilation, the two feature classes and associated relationship class contain spatial and descriptive data for deposits, prospects, and other mineralized sites, and for permissive tracts. These data can be queried in many database management systems as well as a GIS to reveal the distribution, geologic setting, and resource potential of sediment-hosted copper deposits and to model grade and resource tonnage.

The sediment-hosted stratabound copper data are briefly described in table 8 and include two feature classes and a relationship class. Metadata that describe the spatial data are embedded within the feature classes; they are also provided as standalone files (table 8).

Sediment-Hosted Stratabound Copper Deposits, Prospects, and Mineralized Sites

The feature class *sedCu_deps_pros* contains vector data (points) and documents locations and descriptive data for 1,200 sites around the world. Abbreviated source references (*Short_ref*) are listed in the feature attribute table of *sedCu_deps_pros*; full source citations are provided in the nonspatial table *sedCu_references*. Attributes and their descriptions are listed in table 9.

Permissive Tracts for Undiscovered Sediment-Hosted Stratabound Copper Deposits

The feature class *sedCu_tracts* contains vector data (points) for 48 sediment-hosted copper permissive tracts of the world, which were used to outline the principal areas in the world that have potential for undiscovered sediment-hosted copper resources. Those tracts with a quantitative estimate were assessed to depths of 1 to 2.5 km below the Earth's surface. Attributes and their descriptions are listed in table 10.

Spatial Data for Basemaps

Base data have been included, as a courtesy, to assist users with spatial references (table 11). The *world_background* feature class provided by Esri (2007) contains polygons that represent grid cells of 30 by 30 degrees for the world. The second dataset contains vector data (polygons) which represent political boundaries of the world (*world_political_boundaries*) compiled by the U.S. Department of State (2009).

Table 7. Regional assessment reports for the global assessment of undiscovered sediment-hosted stratabound copper resources.

Regional report	Reference
Africa	
Neoproterozoic Roan Group, Central African Copperbelt, Katanga Basin, Democratic Republic of the Congo and Zambia	Zientek, Bliss, and others (2014)
Asia	
Afghanistan	Ludington and others (2007)
Chu-Sarysu Basin, Central Kazakhstan	Box and others (2012)
Kodar-Udokan area, Russia	Zientek, Chechetkin, and others (2014)
Teniz Basin, Kazakhstan	Cossette and others (2014)
Europe	
Permian Kupferschiefer, Southern Permian Basin, Europe	Zientek, Oszczepalski, and others (2015)
North America	
Greenland	Stensgaard and others (2011)
United States national assessment	Ludington and Cox (1996)
World	
Qualitative assessment for selected areas: (1) Mesoproterozoic Belt-Purcell Basin, United States and Canada; (2) Cretaceous Benguela and Cuanza Basins, Angola; (3) Cretaceous Chuxiong Basin, China; (4) Paleo- to Mesoproterozoic Dongchuan Group rocks, China; (5) Cambrian Egypt-Israel-Jordan Rift, Egypt, Israel, and Jordan; (6) Carboniferous Maritimes Basin, Canada; (7) Cretaceous Neuquen Basin, Argentina; (8) Neoproterozoic Northwest Botswana Rift, Botswana and Namibia; (9) Upper Proterozoic Redstone Copperbelt, Canada; and (10) Upper Cretaceous Salta Rift System Argentina.	Zientek, Wintzer, and others (2015)

Table 8. Description of sediment-hosted stratabound copper digital data files within the file geodatabase and supporting metadata files.

Feature dataset name	Description
sediment_hosted_copper	Feature dataset that contains feature classes, stored in geographic coordinates using the world geodetic system datum of 1984 (GCS WGS 1984).
Feature class name	**Description**
edCu_deps_pros	Feature class (points) of 1,200 sediment-hosted copper deposits and prospects of the world.
sedCu_references	Nonspatial table of references for abbreviated citations used in the feature classes sedCu_deps_pros and *sedCu_t*racts.
sedCu_tracts	Feature class (polygons) of sediment-hosted copper permissive tracts of the world.
sedCu_tracts_sites_relate	Relationship class that manages the association between objects in the *sedCu_tracts* feature class to objects in the *sedCu_deps_pros* feature class.
Adobe Acrobat Portable Document Format (.pdf) files for Federal Geographic Data Committee (FGDC) metadata	
sedCu_deps_pros_metadata.pdf	Metadata for *sedCu_deps_pros* file.
sedCu_tracts_metadata.pdf	Metadata for *sedCu_tracts* file.
Extensible markup language (.xml) files for metadata	
sedCu_deps_pros_metadata.xml	Metadata for file geodatabase feature class *sedCu_deps_pros*.
sedCu_tracts_metadata.xml	Metadata for file geodatabase feature class *sedCu_tracts*.

Table 9. Definitions of user-defined attribute fields in the feature class *sedCu_deps_pros*.

Field name	Field alias	Description
GMRAP_ID	GMRAP ID	Unique identifier for each record. [GMRAP, Global Mineral Resource Assessment Project.]
Coded_ID	Tract identifier	Coded, unique identifier assigned to permissive tract within which the site is located; corresponds to Coded_ID in the feature class *sedCu_tracts*.
Tract_name	Tract	Name of permissive tract in which the site is located; corresponds to Tract_name in the feature class *sedCu_tracts*.
Name	Site	Site name.
Name_other	Other site names	Other names used for the site.
Name_group	Group name	Group name, applied when 500-meter (m) rule was used to cluster deposits and (or) prospects for the purpose cacluating grades and tonnages.
Includes	Includes	Names of deposits that have been combined with the primary deposit as a result of the 500-m spatial aggregation rule used for calculating grades and tonnages.
SiteStatus	Site status	Type of site; “deposit” is a site for which grade and tonnage are reported; “historic mine-19th century or earlier” is a site that is no longer an active historic mine; “prospect” is a site with no grade and tonnage values provided; “prospect - mineralized material estimated” is a site that has estimated mineralized material; and “site” is a site that occurs in sedimentary rock but has no other descriptive information.
SiteStatus2	Site status 2	Additional information on the status of the site.
Country	Country	Country in which the site is located.
State_Prov	State/Province	State, province, or region in which the site is located.
Latitude	Latitude	Latitude, in decimal degrees; positive number represents latitude north of the equator; negative number represents latitude south of the equator.
Longitude	Longitude	Longitude, in decimal degrees; positive number represents longitude east of the Greenwich meridian; negative number represents longitude west of the Greenwich meridian.
Dep_type	Deposit type	Type of mineral deposit.
Dep_subtype	Deposit subtype	Subtype of sediment-hosted copper. Subtype based on host lithology.
Age_host	Age host	Age of host rock, in geologic time scale units.
Age_Ma	Age date	Age, in millions of years before present. Age may be an average for geologic era, period, or epoch listed.
Unit	Unit	Geologic unit in which site is located.
Host_rocks	Host rocks	Simplified lithologic description of host rocks.
Comm_major	Major commodities	Major commodities, listed in decreasing order of economic importance. Chemical symbols are used for commodities; multiple commodities are comma-delimited.
Tonnage_Mt	Tonnage ore rock	Ore tonnage, for deposit, in millions of metric tons (Mt); -9,999 indicates no data.
Cu_pct	Copper grade	Average copper grade, for deposit, in weight percent; -9,999 indicates no data.
Co_pct	Cobalt grade	Average cobalt grade, for deposit, in weight percent; -9,999 indicates no data.
Ag_g_t	Silver grade	Average silver grade, for deposit, in grams per metric ton (g/t); -9,999 indicates no data.
Con_Cu_t	Contained copper	Contained copper, for deposit, in metric tons (t), rounded to nearest significant figure; -9,999 indicates no data.
Comments	Comments	Significant comments; may include grade and tonnage information for prospects, mineral alteration, and other significant comments.
Minerals	Minerals	Ore and gangue minerals, listed in approximate order of abundance.
Ref_list	References	List of abbreviated citations, in author and year format, for references used in compiling information for site, delimited by semicolons; full references are listed in the file geodatabase nonspatial table *sedCu_references*.
Short_ref	Regional report short reference	Abbreviated citation for author and year of the U.S. Geological Survey (USGS) regional report from which data were originally compiled; full reference located in the lineage section of the metadata and listed in file geodatabase nonspatial table *sedCu_references*.

Table 10. Definitions of user-defined attribute fields in the feature class *sedCu_tracts*.

Field name	Field alias	Description
Coded_ID	Tract identifier	Coded, unique identifier assigned to permissive tract.
Tract_name	Tract	Informal name of permissive tract.
Unregcode	United Nations Region code	Three-digit United Nations (2013) code for the region that underlies most of the permissive tract.
Country	Country	Country(ies) in which the permissive tract is located.
Commodity	Commodity	Primary commodity being assessed.
Region	Region	Name of large geographic region used for reporting copper resources in Johnson and others (2014).
Basin	Basin	Name of sedimentary basin in which the permissive tract is located.
Dep_type	Deposit type	Type of mineral deposit.
Dep_model	Deposit model	Model used to classify deposit type.
Dmodel_ref	Deposit model reference	Deposit type model short reference; full reference is provided in the nonspatial table *sedCu_references*.
GT_model	Grade/tonnage model	Grade-tonnage model used for the undiscovered deposit estimate.
GATM_ref	Grade/tonnage model short reference	Abbreviated citation for grade and tonnage model; full reference is provided in the nonspatial table *sedCu_references*.
Geology	Geology	Geologic feature assessed.
Age	Age	Age of the assessed geologic feature.
Asmt_date	Assessment date	Year assessment was conducted.
Asmt_depth	Assessment depth	Maximum depth beneath the Earth's surface used for the assessment, in kilometers.
Est_levels	Percentile estimate levels	The set of percentile (probability) levels at which undiscovered deposit estimates were made; -9,999 indicates no data.
N90	90th percentile deposit estimate	Estimated number of deposits associated with the 90th percentile (90 percent chance of at least the indicated number of deposits); -9,999 indicates no data.
N50	50th percentile deposit estimate	Estimated number of deposits associated with the 50th percentile (50 percent chance of at least the indicated number of deposits); -9,999 indicates no data.
N10	10th percentile deposit estimate	Estimated number of deposits associated with the 10th percentile (10 percent chance of at least the indicated number of deposits); -9,999 indicates no data.
N05	5th percentile deposit estimate	Estimated number of deposits associated with the 5th percentile (5 percent chance of at least the indicated number of deposits); -9,999 indicates no data.
N01	1st percentile deposit estimate	Estimated number of deposits associated with the 1st percentile (1 percent chance of at least the indicated number of deposits); -9,999 indicates no data.
N_expected	Expected number of deposits	Expected (mean) number of deposits, where *N_expected* = (0.233×N90) + (0.4×N50) + (0.225×N10) + (0.045×N05) + (0.03×N01); -9,999 indicates no data.
s	Standard deviation	Standard deviation, where *s* = 0.121 − (0.237×N90) − (0.093×N50) + (0.183×N10) + (0.073×N05) + (0.123×N01); -9,999 indicates no data.
Cv_percent	Coefficient of variance	Coefficient of variance, in percent, where *Cv* = (*s/N_expected*) × 100; -9,999 indicates no data.
N_known	Known deposits	Number of known deposits in the tract.
N_total	Total deposits	Total number of deposits, where *N_total* = *N_expected* + *N_known*.
Area_km2	Tract area in square kilometers	Area of permissive tract, in square kilometers.
DepDensity	Deposit density	Deposit density (total number of deposits per square kilometer), where *DepDensity* = *N_total*/ *Area_km2*; -9,999 indicates no data.
DepDen10E5	Deposit density per 100,000 square kilometers	Deposit density per 100,000 square kilometers, where *DepDen10E5* = *DepDensity*×100,000; -9,999 indicates no data.
Estimators	Estimators	Names of people on the estimation team.

Table 10. Definitions of user-defined attribute fields in the feature class *sedCu_tracts*.—Continued

Field name	Field alias	Description
Ident_Cu	Known copper resources	Known copper resources, in metric tons (t).
Cu_95	Copper resource estimate at 95th percentile	Undiscovered copper resource estimate, 95th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_90	Copper resource estimate at 90th percentile	Undiscovered copper resource estimate, 90th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_50	Copper resource estimate at 50th percentile	Undiscovered copper resource estimate, median (50th percentile) value, in metric tons (t); -9,999 indicates no data.
Cu_10	Copper resource estimate at 10th percentile	Undiscovered copper resource estimate, 10th percentile value, in metric tons (t); -9,999 indicates no data.
Cu_05	Copper resource estimate at 5th percentile	Undiscovered copper resource estimate, 5th percentile value, in metric tons (t); -9,999 indicates no data.
Mean_Cu_t	Mean copper resources	Undiscovered copper resource estimate, mean value, in metric tons (t); -9,999 indicates no data.
Prob_mean	Probability of mean copper	Probability of the mean value, undiscovered copper resource estimate; -9,999 indicates no data.
Prob_0_Cu	Probability of no copper resources	Probability of no undiscovered copper resources; -9,999 indicates no data.
Study_area	Study area	Geographic area of U.S. Geological Survey (USGS) report from which data were originally compiled.
Quant	Quantitative	Dichotomous variable for whether a quantitative resource assessment was performed for tract.
Short_ref	Regional report short reference	Abbreviated citation for source reference; full reference located in the lineage section of the metadata and listed in file geodatabase nonspatial table *sedCu_references*.

Table 11. Description of basemap digital data files within the file geodatabase and map document.

Feature class name	Description
world_background	Feature class (polygons) of world map background represents grid cells of 30 by 30 degrees that cover the world (Esri, 2007).
world_political_boundaries	Feature class (polygons) of countries of the world (U.S. Department of State, 2009).
Esri map document (.mxd)	
Global_copper.mxd	ArcMap document used for querying and viewing data.

Using the Data

The Esri ArcGIS map document format (.mxd) allows users to view and query data in a map format. *Global_copper.mxd* displays site and tract data in the Robinson map projection. Custom spatial bookmarks are included and identify specific geographic regions for quick and easy reference. Data in the spatial databases can be viewed by opening their attribute tables from the "Table of Contents" window. Nonspatial tables containing references can be viewed when their attribute table is opened in the "List By Source" view of the "Table of Contents" window. One way the data can be queried is by using the tools available in the attribute tables and within the "Definition Query" tab in the "Layer Properties" window accessed by right-clicking on an individual layer and selecting "Properties." Points and polygons can also be selected in the map view window using the "Identify" tool, which allows the user to view the data in the form of a list of fields and values.

When working with the *pCu_deps_pros* feature class, the outcome of having selected a deposit or prospect will display both a hierarchical catalog of deposits and prospects in one frame of the "Identify" window and a list of fields and values for the selected site(s) in the other frame. There are three hierarchical catalogs associated with each porphyry copper deposit and prospect. The first is *pCu_site_references* in which one can view full references by expanding the catalog and selecting the desired abbreviated source reference; hyperlinks provide access to the referenced article on the Internet where available. The second catalog is *pCu_tracts*; expanding this catalog for the tract in which the deposit occurs displays the third catalog, *pCu_tract_references*, and one can view the tract reference information in the same manner as for deposits and prospects. Similarly, there are three hierarchical catalogs associated with each porphyry copper tract: *pCu_tract_references*, *pCu_deps_pros*, and *pCu_site_references*.

When working with the *sedCu_deps_pros* and *sedCu_tracts* feature classes, using the “Identify” tool will display one hierarchical catalog for each file; one that lists deposits and prospects within each tract and one that lists the name of the permissive tract in which the site occurs.

These two hierarchical catalogs are the result of relationship classes stored in the file geodatabase. Another way to determine if relationships exist is to click on the “Related Tables” icon within the table view of a feature class or nonspatial table; all relationship classes in which the current table participates will appear in a list.

Summary

This final compilation of spatial and nonspatial data for all twenty-seven regional reports in the Global Mineral Resource Assessment Project describing the two most significant sources of global copper supply resulted in a single Esri file geodatabase, *USGS_global_copper.gdb*. It contains three feature datasets: (1) porphyry copper, (2) sediment-hosted stratabound copper, and (3) basemap data. Within the two feature datasets for copper are feature classes and relationship classes pertaining to a specific deposit type. The final feature dataset includes elements for a political boundary feature class (*world_political_boundaries,* U.S. Department of State, 2009) and a world map background feature class (*world_background,* Esri, 2007), which are used to display a single background color fill and lines of latitude and longitude in the map document *USGS_global_copper.mxd.* Additional elements included in the file geodatabase are three nonspatial tables of source references, two of which are used in the relationship classes.

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Appendix

Appendix A. Mineral Resource Assessment Methods and Procedures Used in the Global Mineral Resource Assessment[1]

By Michael L. Zientek[2] and Jane M. Hammarstrom[3]

Introduction

When evaluating mineral potential, geologists distinguish rocks that are barren from those that could contain valuable concentrations of useful minerals or materials. Exploring for minerals is expensive; therefore, mineral potential is evaluated in a series of steps that minimize the cost of excluding barren areas while increasing knowledge about the possible existence of undiscovered mineral resources (Singer and Menzie, 2010). Initially, geologists use regional-scale datasets to discriminate geologic settings that are barren from those that may be mineralized. Next, targets or prospective areas that may contain mineralized rock are defined. If mineralization is found at a target area, then systematic sampling is conducted to determine if an economic volume of rock is present. If an economic volume can be defined, then economic and feasibility studies are conducted to determine how much of the volume can be developed. After a mine is developed, detailed geologic information guides the application of mining technology that will be used to separate ore from waste material in the mining process.

U.S. Geological Survey (USGS) mineral resource assessments generally correspond to the early regional reconnaissance step in the process of determining mineral potential and address two basic questions: (1) where are undiscovered mineral resources likely to exist? and (2) how much undiscovered mineral resource may be present? Results are presented as mineral potential maps and as frequency distribution of in-place, undiscovered metal.

We can make inferences about undiscovered mineral resource potential because natural accumulations of useful minerals or rocks ("mineral deposits") can be classified using common characteristics and associations into groups or "deposit types" that reflect processes of formation. Using the deposit-type paradigm, we can predict the geologic settings in which various types of deposits may be found and as well as anticipate the distribution and concentration of ore materials at the scale of the deposit.

The USGS strives to conduct consistent and unbiased assessments by applying a methodology[4] to select areas having mineral resource potential and to probabilistically estimate the amount of mineral resources likely to be present. Integrated models and procedures reduce the likelihood of introducing bias in the assessment process.

USGS mineral assessment protocols are based on science practices derived from the fields of economic geology[5], mineral inventory estimation, and undiscovered mineral resource appraisal. The assessments are based on our fundamental understanding of the geologic processes that concentrate valuable mineral materials near the surface of the earth. The method extends the scientific and engineering principles that are used to establish mineral inventories. The science and mathematics of making forecasts and predictions are an essential part of the assessment process.

This document summarizes the technical language used in mineral assessments, the underlying principles, and an outline of operational procedures used for USGS mineral resource assessment.

Technical Language and the Assessment Process

Successful assessments require consistent use of technical language in order to reduce bias. The use of technical language comes at a cost, however, because economic geologists take common terms and restrict their meaning in order to communicate precisely with each other. Mineral assessment scientists may understand each other but the general user community may not understand the subtle distinctions between terms. So, it is necessary to discuss technical terms used in mineral resource assessment studies before considering mineral resource assessment methodology.

Mineral Resources and Reserves

Bodies of mineralized rock are classified according to (1) their geological, physical, and chemical properties; (2) their profitability; and (3) the level of certainty associated with the estimates of mineral potential. For estimation and assessment studies, the words "deposit," "resource," "reserve," "discovered," and "undiscovered" are used, but with specialized meanings. "Mineral inventories" are formal quantifications of the amounts of naturally occurring materials estimated by a variety of empirically or theoretically based procedures using the spatial distribution of grade and the particular locations

[1]Reprinted from Zientek and Hammarstrom (2014).

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

[3]U.S. Geological Survey, Reston, Virginia, United States.

[4]A system of interrelated, internally consistent, and integrated models and procedures.

[5]The study and analysis of geologic bodies and materials that can be used profitably by man, including fuels, metals, nonmetallic minerals, and water; the application of geologic knowledge and theory to the search for and the understanding of mineral deposits (AGI Glossary Online).

of volumes of mineralized rock that are above cutoff grade[6] (Sinclair and Blackwell, 2002). "Mineral inventories" include mineral resources and mineral reserves. "Mineral resources" are defined as concentrations or occurrences of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity, and other geological characteristics of a mineral resource are known, estimated, or interpreted from specific geological evidence, sampling, and other knowledge (Committee for Mineral Reserves and Reporting Standards, 2006). The term "mineral reserve" is restricted to the economically mineable part of a mineral resource. On the basis of the level of confidence in the estimates, mineral resources are divided into "measured," "indicated," and "inferred" categories, and mineral reserves are subdivided into "proven" and "probable" groupings.

Mineral Deposit

"'When I use a word,' Humpty Dumpty said, in rather a scornful tone, 'it means just what I choose it to mean—neither more nor less.'" –Lewis Carroll

"Deposit" has more than one meaning for most people, but "a layer or mass of accumulated matter" is close to how it is used by earth scientists. The following definitions are examples of how earth scientists may enhance the meaning of "mineral deposit":

"geologic bodies which consist mainly of a single useful mineral or which contain, throughout or in places, valuable minerals which can be profitably extracted" (Lindgren, 1933).

"natural concentrations of useful minerals or rocks, which can be economically exploited" (Pohl, 2011).

"a mass of naturally occurring mineral materials, e.g. metal ores or nonmetallic minerals, usually of economic value, without regard to mode of origin" (Bates and Jackson, 1987).

"a mineral occurrence of sufficient tonnage and grade that it might, under the most favorable of circumstances, be considered to have economic potential" (Cox and others, 1986).

"an accumulation of associated mineralized bodies that constitute a single mineralizing event, including subsequent processes (e.g., oxidation and supergene enrichment) affecting part or all of the accumulation" (Barton and others, 1995).

Almost all agree that a deposit is an accumulation of potentially economic material, but some include additional constraints on size and genesis. For USGS mineral resource assessments, "mineral deposit" refers to natural accumulations of minerals or mineral materials that (1) formed by the same mineralizing event, (2) might have economic potential, (3) have a formally defined mineral inventory based upon a sampling density that is appropriate for the deposit type, and (4) are well explored. In order to be well explored, a mineral inventory based on mapping, drilling, and sampling should encompass most of the potentially economic mineralized rock at the site. Accumulations of minerals or mineral materials that lack a mineral inventory or are incompletely explored are referred to as "prospects."

Deposit Type

The concept of deposit type underlies the geologically based mineral resource assessments conducted by the USGS. Geologists, engineers, and miners have long recognized that mineral deposits can be classified into groups or types based on common characteristics and associations (Skinner and Barton, 1973). According to Eckstrand (1984), "a mineral deposit type is defined as a hypothetical composite of the geological characteristics common to a group of similar mineral deposits." Mineral deposit types are defined as follows:

Characteristic ore body[7] geometries
Distributions of tonnage and grade
Rock and mineral properties that determine the potential value of the deposit
Amount of sampling that will be required to delimit mineral resources
Amount of valuable material that can be mined and processed
Furthermore, each deposit type has a specific impact on the environment, whether through natural weathering processes or mining.

When referring to deposits that are members of a type, Eckstrand (1984) states, "It is implicit that such deposits, because of their similarities, are expected to have a common mode of genesis, whether or not that mode of genesis is well understood." The genetic foundation of deposit types allows a scientific approach to assessing mineral resources. Scientific investigations of mineral deposits show they are extraordinary geologic features, formed by rare conjunctions of ordinary geologic processes. Even though mineral deposits are rare events, the principle of uniformity allows us to make predictions about their location and potential value based on geologic observations. The association of deposits to types gives even greater predictive capability.

Undiscovered Mineral Resources and Mineral Deposits

"Undiscovered" is a term that also has specific usage in USGS mineral resource assessments. To most people, an undiscovered resource would refer to a quantity of material that is completely unknown. In assessments, the terms "undiscovered mineral resources" refer to a variety of situations in which location, grade, quality, and quantity of mineralized

[6]Cutoff grade is the lowest grade, or quality, of mineralized material that qualifies as economically mineable and available in a given deposit (Committee for Mineral Reserves and Reporting Standards, 2006).

[7]A continuous, well-defined mass of material of sufficient ore content to make extraction economically feasible (AGI Glossary Online). Ore is a naturally occurring solid material from which a metal or valuable mineral can be profitably extracted (Oxford English Dictionary).

material are not constrained by specific geologic evidence. The presence of mineralized rock might be recognized at a site (location is known) but the grade, quality, and quantity of mineralized material is not sufficiently characterized to estimate mineral resources using industry-standard practices. In this example, the location of mineralized rock is discovered but the amount of mineral resource is unknown; therefore, any mineral resources that exist are undiscovered. In a similar situation, a well-characterized volume of mineralized rock with a resource estimate is surrounded by mineralized rocks for which the sample density is too sparse to classify the material as mineral resource. Undiscovered mineral resources may be present in the poorly characterized material. Finally, undiscovered mineral resources may be associated with a completely unknown, undiscovered mineral deposit, in which location, grade, quality, and quantity of mineralized rocks are unknown.

Assessment Methodology—Parts and Procedures

An assessment method consists of “parts,” each of which incorporates appropriate scientific theories, methods, and findings into the process. Rigorous reasoning integrates the parts into a consistent system or method that will indicate the possible location and potential value of undiscovered mineral resources in a form that can be consistently replicated and compared to other assessments. Parts of a method are usually models, but can also be subjective information provided by experts, or a product.

For example, for quantitative mineral resource assessments, the USGS uses the three-part form of assessment (Singer, 1993; Singer and Menzie, 2010). The first part consists of models of grades and tonnages of deposits used to estimate the amount of metal; the second is a mineral resource map in which areas are delineated according to the types of deposits permitted by the geology; and the third provides estimated numbers of undiscovered deposits of each type. These parts are essential for a quantitative assessment but do not completely describe an assessment method; in other words, they are not steps in an assessment method.

Assessing Location

The USGS mineral potential maps show geographic areas where undiscovered mineral resources may be present. For most USGS mineral resource assessments, mineral potential maps show “permissive tracts,” where geology permits the existence of deposits of one or more types. However, some studies create prospectivity maps, which delineate mineral exploration targets by combining various evidential layers in a geographic information system (GIS). Mineral potential maps can be represented cartographically as figures or plates in reports or as digital files that can be incorporated into a GIS.

Permissive tracts represent the surface projection of part of the Earth’s crust and overlying surficial materials to a predetermined depth where undiscovered mineral resources may be present. The criteria used to select the permissive volume of rock, or assessment unit, are provided by descriptive mineral deposit models and mineral systems models, as described below. The assessment geologist determines how to apply the criteria in the models to the specific datasets available for the assessment. Boundaries of the rock volume are defined such that the occurrence of deposits of the type being assessed outside the volume is negligible. According to Singer and Menzie (2010), negligible means a chance of less than 1 in 100,000. Areas are excluded from these tracts only on the basis of geology, knowledge about unsuccessful exploration, or the presence of barren overburden exceeding some predetermined thickness (Singer and Menzie, 2010). In assessment reports, maps commonly show the permissive tracts along with mineral deposits, prospects, and occurrences of the deposit type being assessed.

Mineral prospectivity analysis is a predictive tool used for regional- to camp-scale exploration targeting (Porwal and Kreuzer, 2010). Mineral systems models are used to synthesize ideas about the processes related to mineralization. Critical processes act together to form mineral deposits; although processes cannot be directly observed, expressions of the processes can be mapped. The probabilities of occurrence of the critical mineralization processes can either be assigned subjectively based on expert assessment of available spatial and nonspatial geoscience information (knowledge-driven approach) or estimated empirically from the distribution of known mineral deposits (data-driven approach). From this information, resource potential maps can be generated in which each cell is attributed with a favorability value that represents the probability that the cell contains a deposit of the targeted type.

Descriptive Mineral Deposit Models

A mineral deposit model is systematically arranged information describing the essential attributes (properties) of a class of mineral deposits (Cox and others, 1986). Descriptive models used in USGS studies focus on observations and use theories of origin only to guide what to observe (Singer and Menzie, 2010). The function of the model is to provide assessment geologists with information that they can interpret and use to discriminate (1) possible mineralized environments from barren environments, and (2) types of known deposits from each other.

Descriptive models used in USGS assessments, such as those in Cox and Singer (1986), have two parts. The first lists characteristics of the geologic environments in which the deposits are found; the second gives identifying characteristics of deposits. The information in the first part can be interpreted by the assessment geologist and used to delineate tracts of land geologically permissive for the occurrence of undiscovered deposits. The second part of the descriptive model, the deposit description, includes information on host rocks, mineralogy, alteration, and geochemical and geophysical anomalies that are used by the assessment geologist to recognize the deposit type and to discriminate one deposit type from another.

The descriptive models are lists of information. Therefore, the theory of ore formation that guided what was included in the list is not explicitly stated. The models also do not provide any suggestions on how the information can be used to delineate tracts or to identify deposits by type. Information needed to assess the potential economic value of the deposit type, such as typical mining, beneficiation, and remediation methods, are not usually included.

Mineral Systems Model

The concept of a mineral system can be used to incorporate concepts of regional ore genesis into mineral resource assessment and exploration targeting studies (Wyborn and others, 1994; Knox-Robinson and Wyborn, 1997; Cox and others, 2003; Hronsky, 2004; Hitzman and others, 2005; Barnicoat, 2006; Hronsky and Groves, 2008; Blewett and others, 2009). Mineral systems models use components and processes to organize ideas about how different mineral deposit types relate to regional-scale movements of energy and mass in the Earth. For example, hydrothermal ore deposits can be understood by considering the source of the ore-forming fluid, its physical and chemical character, the mechanisms for dissolving and transporting ore-forming components, and the causes of precipitation from it (Skinner and Barton, 1973). Sites where appropriate combinations of structural, chemical, and physical conditions that force ore mineral precipitation reactions are called ore traps (Reed, 1997). Variations of the source-transport-trap paradigm are used to define both petroleum and mineral systems models (Magoon and Dow, 1994; Wyborn and others, 1994; Magoon and Schmoker, 2000). All proponents of mineral systems models agree that deposition of ore minerals will not occur unless all essential components are present and processes occur in the correct sequence and location (Magoon and Dow, 1994; Kreuzer and others, 2008; McCuaig and others, 2010).

Mineral systems models serve two functions in mineral resource assessments. All components and processes that relate to ore deposit type can be systematically evaluated to identify areas where a mineral-forming system could be present and to create prospectivity maps that identify target areas for exploration. Another function of these models is to use the components and processes of the mineral system model to define the assessment unit in areas where the existence of a mineral-forming system is known from the presence of deposits and prospects.

Assessing Probable Amounts of Undiscovered Metal

Mineral resource assessments should be in a form that allows for comparison of potential value and benefit of mineral resource development with other socioeconomic benefits and consequences. Uncertainty of assessment results must also be indicated. Mineral potential can be expressed qualitatively, for example, high, medium, and low; however, this form of valuation cannot be related to other types of information, such as the value of other natural resources or the integrity of ecosystem function and process. Therefore, USGS mineral resource assessments express amounts of undiscovered mineral resources using probabilistic estimates of the amount of in-place metal. This form of assessment result can then be filtered economically to give some idea of the potential value of the mineral resource.

At least two strategies are used by the USGS to assess undiscovered mineral resources. The first is to estimate the number of undiscovered deposits; this approach has been widely used in USGS mineral resource assessments since the 1970s. A second approach uses geostatistical methods to estimate undiscovered mineral resources associated with incompletely explored extensions of stratabound ore deposits.

Estimating Undiscovered Resources by Estimating Undiscovered Deposits

Mineral resource assessments completed by the USGS during the past three decades express geologically based estimates of numbers of undiscovered mineral deposits as probability distributions. Numbers of undiscovered deposits of a given type are estimated in geologically defined regions. Using Monte Carlo simulations, these undiscovered deposit estimates are combined with grade and tonnage models to derive a probability distribution describing amounts of commodities and rock that could be present in undiscovered deposits within a study area.

Grade and Tonnage Models

Mineral deposits of a given type have characteristic distributions of size and grade that can be used to constrain the probable size and grade of undiscovered deposits of the same type. Frequency distributions of tonnages and average grades of well-explored deposits of each type are used as models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings (Singer and Menzie, 2010). These models are based on the average grades of each metal or mineral commodity of possible economic interest and the associated tonnage, prior to mining. Data used in the models should represent an estimate of the total endowment of each of the known deposits so that the final models can accurately represent the endowment of undiscovered deposits. In order to be consistent, the deposits used to estimate tonnages and grade in a model should (1) form by the same mineralizing event and be the same deposit type as other sites used in the same model (Barton and others, 1995); (2) be well explored (Singer and Menzie, 2010); (3) be an estimate of pre-mining, in-place mineral endowment (Singer and Menzie, 2010); (4) be based on sampling consistent with industry practices for defining mineral resources and reserves; (5) use similar cutoff grades;

(6) use consistent rules for defining how ore bodies are spatially grouped into a deposit (Singer and Menzie, 2010); and (7) be developed on the basis of similar mining and processing methods as other sites in the model (Bliss and others, 1987).

The stipulation that the data used in a grade and tonnage model should represent total endowment affects what is considered a deposit or a prospect for assessment purposes. In the USGS three-part form of assessment (Singer and Menzie, 2010), deposits must be (1) described in published literature (including grades and tonnages), (2) well explored in three dimensions, and (3) completely delineated (not open in any part). Mineral deposits that do not meet these three criteria are classified by Singer and Menzie (2010) as "undiscovered" for the sake of mineral resource assessment. For example, if there is any indication that an ore body is open, they count the site as an undiscovered deposit for assessment purposes (Singer and Menzie, 2010). Or, if a mineral deposit is well explored and completely delineated, but the mineral resource information is not published, then the deposit is considered undiscovered, but with a high probability for occurrence.

Number of Undiscovered Deposits

An estimate of some fixed, but unknown, number of undiscovered deposits of each type that are inferred to exist in the delineated tracts is another part of the three-part form of assessment (Singer and Menzie, 2010). Ore tonnages and metal grades of the undiscovered deposits are assumed to be distributed similarly to those of identified deposits of the same types. Expert panels estimate the number of undiscovered deposits at several confidence levels, usually the 90th, 50th, and 10th percentiles. An algorithm converts these estimates into a continuous distribution for use in the simulation of undiscovered mineral resources (Root and others, 1992). Two strategies typically are used when estimating 90th, 50th, and 10th percentiles. In one scenario, an expert chooses a "best estimate" (for example, the median) and then adjusts up or down from that estimate in order to get the extreme percentiles (Clemen, 2001). In another scenario, the expert decides on the extremes first, assessing the 10th and 90th percentiles, and then selects the 50th.

Singer and Berger (2007) and Singer and Menzie (2010) offer guidelines for estimating numbers of undiscovered deposits. Estimates at the 90th and 50th percentile can be guided by counting and ranking prospects and mineral occurrences or by visualizing exploration targets based on data such as geochemical or geophysical anomalies or the presence of hydrothermal alteration. Probabilities can be assigned to each "target" and then combined to give an overall probability. Estimates are also guided by analogy with well-explored areas that are geologically similar to the study area. If a quantitative deposit density model is available, some estimators will use a predicted density from the model to guide their estimates (Singer and others, 2005; Singer, 2008).

Monte Carlo Simulation

Monte Carlo simulation is used to combine grade and tonnage distributions with the probability distribution of undiscovered deposits to obtain probability distributions of undiscovered metals in each tract (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). USGS software uses a number of techniques to avoid introducing bias into Monte Carlo simulation results. For example, dependencies between grades and tonnages of deposits and between grades of different metals in the same deposit are preserved. In addition, grades and tonnages are approximated by piecewise linear distributions to avoid unrealistically large values.

Simulation results are reported at select quantile levels, together with the mean expected amount of metal, the probability of the mean, and the probability of no deposits being present. The amount of metal reported at each quantile represents the least amount of metal expected.

Estimating Undiscovered Resources using Geostatistical Methods

Estimating undiscovered resources for some stratabound[8] and stratiform[9] deposit types by estimating the number of undiscovered deposits is problematic. Examples of stratabound deposit types include iron formations; beds of halite or potash-salt; layers rich in chromitites and platinum group element reefs in a layered igneous complex (Schulte and others, 2012; Zientek, 2012); and sediment-hosted stratabound copper deposits (Cox and others, 2003; Hitzman and others, 2005; Zientek, Hayes, and Hammarstrom 2013; Zientek, Hayes, and Taylor, 2013; Hayes and others, 2015). The difficulty in making such estimates arises because valid grade and tonnage models cannot be constructed because most deposits are open at depth. In addition, deposit tonnage correlates with the extent of basin or layered igneous intrusion; a global tonnage model could have values that are geologically impossible for the size of a particular basin or intrusion.

Metal Surface Density

Probabilistic estimates can be made for undiscovered mineral resources in incompletely explored extensions of large, stratabound deposits if appropriate data are available to calculate metal surface density surfaces. The justification for using metal surface density in layered ore bodies follows.

In-place contained metal in an ore body is given by this relation:

$$M = T \times g \quad (1)$$

[8]A mineral deposit confined to a single stratigraphic unit.

[9]A special type of stratabound deposit in which the desired rock or ore constitutes, or is strictly coextensive with, one or more sedimentary, metamorphic, or igneous layers.

where

M is contained metal, in metric tons;
T is the mass (tonnage) of the ore body, measured in metric tons; and
g is the average grade of the ore body, measured in grams/metric ton.

Tonnage is determined by this equation:

$$T = V \times \rho_b \quad (2)$$

where

V is the volume of the ore body, measured in cubic meters; and
ρ_b is the bulk density of the ore, measured in metric tons/cubic meters.

For tabular ore bodies, the volume can be approximated by:

$$V = t_t \times S \quad (3)$$

where

t_t is the average true thickness of the tabular ore body, in meters; and
S is the surface area, in square meters, measured in the plane of the tabular layer.

Alternatively, for a dipping layer, the volume can be estimated by:

$$V = t_a \times S_h \quad (4)$$

where

t_a is the apparent thickness of the tabular ore body, in meters, measured perpendicular to the horizon; and
S_h is the surface area of the dipping ore body, in square meters, projected to the surface.

Combining equations, the in-place contained metal content of a dipping stratiform ore body is:

$$M = S_h \times (t_a \times \rho_b \times g) \quad (5)$$

This estimation method is a form of the area-averaging method of mineral resource estimation described by Noble (1992), which requires only an interpretation of the shape of the ore body and the average grades within the shape. This formula can be used to estimate the metal that is undiscovered in extensions to known mineral inventory if information is available for all the parameters.

Metal surface density (*MSD*) is calculated by dividing metal content (*M*) for the mineral resource block by its area S_h:

$$MSD = \frac{M}{S_h} \quad (6)$$

Metal surface density can be estimated from samples collected through the mineralized intervals in stratabound or stratiform ore bodies. Mineralized intervals can be sampled in outcrop, drill hole, or underground workings. Metal surface density can also be estimated for a resource or reserve block if the tonnage, grade, and surface extent of the block are known.

Interpolation and Simulation Techniques

A single value of contained metal can be calculated from the kriged metal surface density surface for an assessment area. The spatial variation in metal surface density in the area is represented using geostatistical interpolation techniques (kriging). This approach is used because it quantifies the spatial autocorrelation among measured points and accounts for the spatial configuration of the sample points around the prediction location. From the metal surface density surface, contained metal is calculated by multiplying the value of metal surface density for a cell by the cell, and then summing the values for all cells.

Geostatistical simulation techniques can provide probabilistic estimates of the amount of undiscovered metal. Simulation techniques approximate solutions to uncertain and complex systems through statistical sampling. The system is represented by a model in which uncertainties in inputs, represented by probability distributions, are explicitly and quantitatively propagated into model outputs, also known as a probability distribution. For each simulation, or realization of the system, all of the uncertain parameters are sampled. In geostatistics, each simulation is the realization of a random function (surface) that has the same mean, variance, and semivariogram as the sample data used to generate it. The system is simulated many times, resulting in a large number of separate and independent realizations that represent a range of plausible possibilities, and in this case, the contained metal that can be estimated from metal surface density relations. Gaussian geostatistical simulation is an example of a simulation technique that is available in the geostatistical tools in ArcGIS. Therefore, each metal surface realization can be processed to estimate contained metal and the results from all realizations can then be tabulated to give a probability distribution of contained metal for the model.

Working with Assessment Results

Using deposit types, assessment geologists define areas in which undiscovered resources may be present and derive a frequency distribution of undiscovered, in-place metal. An assessment study may delineate many permissive tracts and probabilistic estimates of undiscovered resource. In order to integrate mineral assessment results with other types of information, it may be necessary to aggregate mineral assessments results into a single mineral resource theme and to indicate what proportion of the undiscovered mineral resource could potentially be economic.

Aggregation of Assessment Results

Permissive tracts are polygons that are represented by using a vector model. Two classes of attributes, spatially intensive and spatially extensive, are associated with the vector model (Longley and others, 2001). These two classes of attributes represent fundamentally different types of information that are governed by different rules for spatial analysis. Spatially intensive attribute values are true for each part of an area. For a vector spatial representation of counties, county name would be an example of a spatially intensive attribute value. No matter how small a part of the county polygon is considered, the county name attribute is always true. Spatially extensive attribute values are true only for entire areas. County population is an example of a spatially extensive attribute value. If the county is subdivided into four parts, the value of county population is not true for each of the subdivisions. Spatially extensive attribute information can be aggregated but not subdivided.

Permissive tracts have spatially extensive and spatially intensive attributes. Attributes like tract name and deposit type assessed are spatially intensive. However, the undiscovered deposit estimate is a spatially extensive attribute; the estimate applies to the entire tract. The results of Monte-Carlo simulation (in-place, undiscovered metal and ore [reported as percentiles and mean values], mean number of deposits, and the probability of zero deposits) are also spatially extensive attributes that apply only to an entire tract. Spatially intensive attributes can be aggregated and applied to a new tract that represents a union of the input tracts in which all the internal boundaries between overlapping areas are removed. The probability distributions of undiscovered metal from several mineral resource assessments can also be aggregated into a single result. However, the degree of association (dependencies) between geologically based assessment regions and tracts must be understood before aggregating assessment results. The mean of the aggregated distributions is the sum of the means of the individual distributions. However, aggregation does affect the spread of the functions because the variance of the combined distribution is affected by the dependency between the random variables. Quantile estimates of distributions can be added if the assumption of complete dependence among tracts can be made. Adding percentiles results in underestimating variance of the joint distribution if the distributions between assessment areas are independent or partially correlated (see, for example, Pike, 2008).

Schuenemeyer and others (2011) published a script that aggregates undiscovered deposit estimates for tracts of a given deposit type, assuming independence, total dependence, or some degree of correlation among aggregated areas, given a user-specified correlation matrix. The aggregated undiscovered deposit estimate, along with appropriate grade and tonnage models, are then input into Monte Carlo simulation software to obtain an aggregated distribution of undiscovered metal.

Economic Filters

Mineral supply, economic, environmental, and land-use planning studies often require an estimate of the amount of undiscovered mineral resources that are likely to be economically recoverable. Economic filters based on simplified engineering cost models provide a method for estimating potential tonnages of undiscovered metals that may be economic in individual assessment areas. For example, Robinson and Menzie (2012) use this approach to perform an economic analysis of undiscovered resources estimated in porphyry copper deposits in six tracts located in North America.

The economic filter developed by Robinson and Menzie (2012) modified and updated mining engineering cost models from the former U.S. Bureau of Mines (Taylor, 1978, 1986) that consider mine capacity, mine life, capital and operating costs to build and operate a mine and mill, metallurgical recovery, and 20-year average metal prices. To apply the economic filter for each permissive tract for porphyry copper deposits, a depth distribution of undiscovered deposits within the upper 1 kilometer (km) of the Earth's crust is specified along with an estimate of the cost setting determined by the country or countries covered by the tract.

Simplified engineering cost models, updated with a cost index, were used to estimate the economic fraction of resources contained in undiscovered porphyry copper deposits as predicted in the USGS assessment of global copper resources (Robinson and Menzie, 2012).

The economic resource is estimated as:

economic resource = *resource* × *economic filter*, where

resource is the mean undiscovered resource estimated by simulation and the *economic filter* is the fraction of the resources estimated to be economic based on the grade and tonnage model used in the simulation, the depth distribution for the undiscovered deposits, and adjustments for cost settings. The economic filters were computed using an Excel workbook developed by Robinson and Menzie (2012). The 20-year (1989–2008) average metal prices and metallurgical recovery rates were used in filter calculations. A number of parameters can be varied, as described here.

Depth Percentages

The depth distribution affects the amount of material that would have to be moved to develop a mine and determines the mining method (open pit or underground mining by block caving). Porphyry systems typically form within 1–4 km of the Earth's surface. Some deposits are exposed at the surface but many are not. The amount of cover material that must be removed to access the ore (overburden) adds to the cost of developing a mine.

For each tract, a subjective estimate was made of a hypothetical depth distribution for undiscovered deposits. These estimates refer to the part of the upper kilometer of the Earth's crust that the tops of any undiscovered porphyry copper deposits are expected to lie within. Three depth distribution scenarios were developed. In the default depth distribution, 25 percent of the undiscovered deposits are accessible in the upper 250 meters (m) of the crust, 25 percent are accessible between 250 and 500 m, and 50 percent lie below 500 m but above 1 km. For areas that have significant amounts of volcanic rocks or other cover, it was assumed that a greater percentage of the undiscovered deposits would lie at deeper depths, so the distribution was skewed to place 10 percent of the undiscovered deposits in the upper 250 m of the crust, 30 percent between 250 and 500 m, and 60 percent below 500 m but above 1 km. For areas that were uplifted and eroded based on tectonic history and relative amounts of volcanic and intrusive permissive rocks, it was assumed that any preserved undiscovered deposits would lie closer to the present surface than the default distribution. The depth distribution adopted for the economic filter for those areas was skewed shallow—35 percent of the deposits would be intersected in the upper 250 m, 25 percent of the deposits would be intersected below 250 m and above 500 m, and 40 percent of the deposits would lie below 500 m and above 1 km depth.

Cost Settings

The economic filter incorporates a parameter for cost setting to express the quality of existing regional infrastructure (Robinson and Menzie, 2012). A “typical cost” setting has existing regional infrastructure to support mining (for example, northern Mexico and southwestern United States or established mining areas in Chile). A “high cost” setting refers to remote areas that lack existing infrastructure to support mining (for example, the Tibetan Plateau or Mongolia).

Country-by-country infrastructure rankings compiled by the Fraser Institute (McMahon and Cervantes, 2012) were used as an independent guide to select appropriate cost settings for mining in each tract. Data from the 2011–2012 quality of infrastructure table (McMahon and Cervantes, 2012, table A10) are expressed in terms of five categories of response: (1) encourages investment, (2) not a deterrent to investment, (3) mild deterrent, (4) strong deterrent, and (5) would not pursue investment due to this factor. The category scores were used to classify cost settings as typical where categories 1 and 2 represent more than 50 percent of the response, as high cost where categories 3, 4, and 5 represent more than 50 percent of the response, and as mixed otherwise.

Many tracts cross jurisdictions, and some tract areas are in jurisdictions that were not evaluated by the Fraser Institute. In these cases we used the jurisdiction most closely associated with the tract as a proxy.

Operational Procedures

Previous text in this appendix describes the various aspects of the USGS mineral resource assessment methodology but does not actually describe how an assessment is conducted. Thus, the following is a list of steps or procedures used to conduct a mineral resource assessment using the three-part form of assessment:

Understand the assignment

- Commodities and deposit types to assess
- Anticipated end use
- Scope of work, including assessment depth
- Available resources (models, procedures, personnel, and budget)
- Required products
- Timeframe for completion

Gather and compile data

- Review literature
- Acquire geologic maps and databases of known mineral deposits and mineral occurrence (all datasets for the assessment should be at a scale appropriate for the study)
- Acquire geochemical, geophysical, and exploration data, if available
- Acquire specialized data required to assess and delineate tracts for a particular deposit type
- Organize digital library and share with project staff

Enhance geologic data

- Add attributes as needed for assessment study based on criteria in deposit and mineral system models
- Process data as needed to delineate tracts

Review and enhance mineral occurrence data

- Classify known mineral deposits and occurrences by deposit type using models
- Verify locations of deposits and prospects
- Update information using literature and technical reports published by exploration companies
- Review and apply spatial rules so that data will correspond to rules used to construct grade and tonnage and spatial density models
- Assess if deposits (sites with grade and tonnage) are well explored and should be classified as known deposits

Select appropriate grade and tonnage model

- Select published grade and tonnage models that might be appropriate for a quantitative assessment
- Use statistical tests to compare known deposits in assessment area with published models. If all the published grade and tonnage models fail statistical tests,

determine if an appropriate model can be developed for the quantitative assessment. If a unique model is developed for the quantitative assessment of an area, it must be published with the assessment

Complete a preliminary study prior to assessment meeting

- Using descriptive and mineral system models, select the assessment unit for tract delineation
- Delineate permissive tracts
- Make preliminary undiscovered deposit estimates

Assemble assessment panel

The assessment team should include a mix of scientists with appropriate backgrounds for the deposit type being assessed. Ideally, the team should include geologists with expertise in (1) the deposit type being assessed, (2) the regional geology of the study area, and (3) the mineral resource assessment methodology.

Conduct a workshop to quantitatively assess the area

- Discuss ground rules, purpose, and goals of the workshop
- Summarize geology of the deposit type, geology of the study area, the characteristics of the grade and tonnage model, and the assessment method
- Present preliminary tracts and revise as needed
- If using grade and tonnage models to estimate undiscovered mineral resources, emphasize that undiscovered deposit estimates must be consistent with the models
- Estimate the number of undiscovered deposits. Each panel member initially determines estimates independently. The independent estimates are then compared and discussed. Regression equations are used to calculate mean of deposits and coefficient of variation. Consensus value for simulation value is determined
- Document assessment information—deposit type assessed; descriptive model used; grade and tonnage model used; the geologic feature being assessed (the assessment unit); geologic criteria used for tract delineation; known deposits, prospects, and occurrences; exploration history; sources of information; estimate of the number of undiscovered deposits; and rationale for the estimate

Estimate undiscovered mineral resources using Monte Carlo simulation

- Check Monte Carlo simulation results to make sure they are consistent with the cited grade and tonnage model

Present results of assessment to Assessment Oversight Committee

- Provide all data used to the committee, in digital format, for their review prior to presentation
- Revise the assessment in response to committee comments

Prepare report with assessment results

- Obtain two or more peer reviews, in addition to coauthor, supervisor, project manager, Science-Center Director reviews, editor input, and Bureau approval.

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