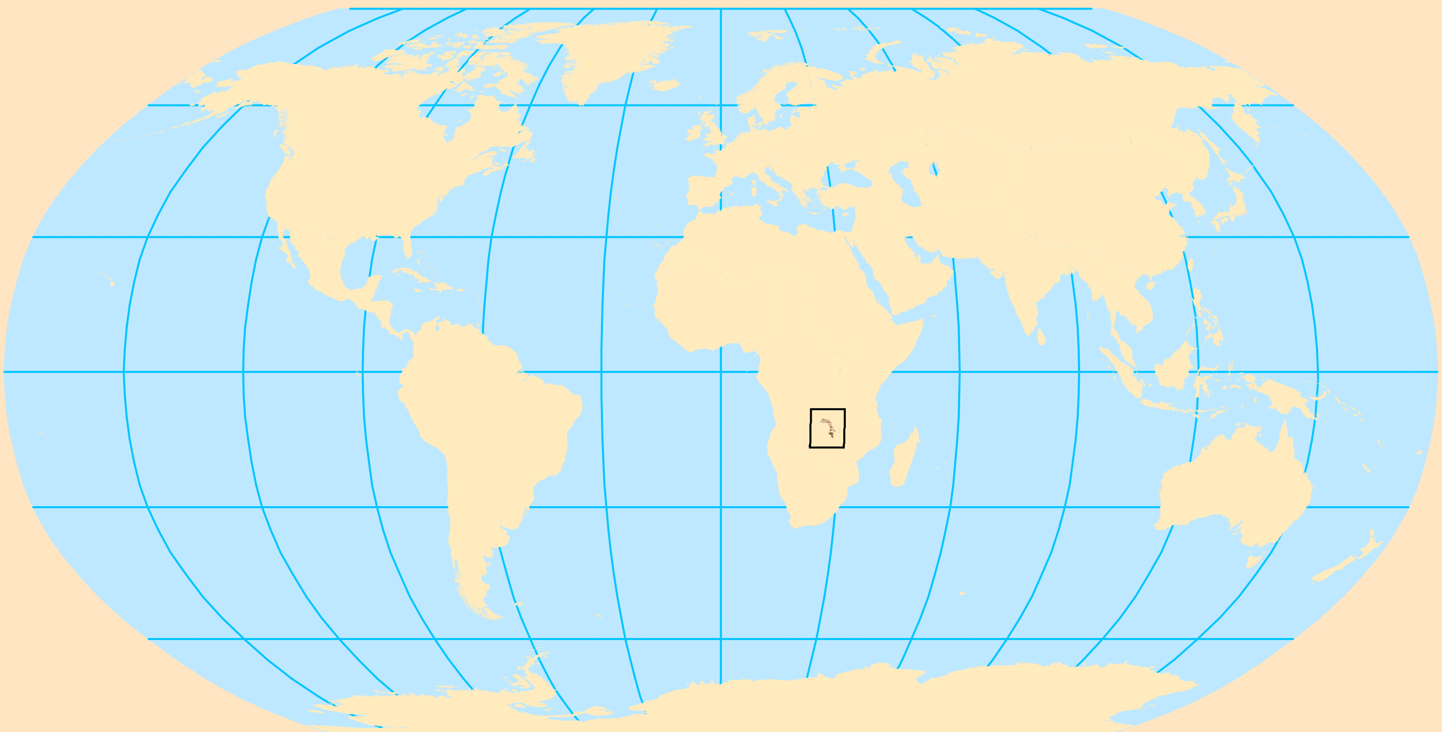
Global Mineral Resource Assessment

Sediment-Hosted Stratabound Copper Assessment of the Neoproterozoic Roan Group, Central African Copperbelt, Katanga Basin, Democratic Republic of the Congo and Zambia



Prepared in cooperation with the Council for Geosciences, South Africa

Scientific Investigations Report 2010–5090–T

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

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

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U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
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)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	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)
megagram (Mg)	0.9842	ton, long (2,240 lb)

Conversion Factors, Abbreviations and Acronymns, and Chemical Symbols

Acronyms and Abbreviations Used

A.D.	Anno Domini—a designation used to label or number years used with the Gregorian calendar
AGI	American Geosciences Institute
Ar-Ar	argon-argon
ArcGIS	Esri's ArcGIS is a geographic information system (GIS) for working with maps and geographic information
ASCII	American Standard Code for Information Interchange
BOMZ	black ore main zone
C.M.N.	Calcaire à Minerais Noiŕ—Kambove Dolomite
CACB	Central African Copperbelt
CAMEC	Central African Mining and Exploration Company
CAMI	Cadastre Minier
Corp.	corporation
CSK	Comite Special du Katanga
D. Strat.	Dolomites stratifies—stratified, fine grained dolomites
DEM	digital elevation model
DRC	Democratic Republic of the Congo
EMINERS	Economic Mineral Resource Simulator
Esri	A software development and services company providing geographic information system software and geodatabase management applications
g/t	grams per metric ton
Gécamines	La Générale des Carrières et des Mines—a state-owned mining company in the Democratic Republic of the Congo
GIS	geographic information system
ID	identifier
Inc.	incorporated
km	kilometer
km^2	square kilometers
kml	keyhole markup language—an extensible markup language notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earthbrowsers
KOV	Kamoto-Oliveira-Virgule area
Ltd	limited
m	meter
Ma	million of years before the present
M.Sc.	Master of Science

Conversion Factors, Abbreviations and Acronymns, and Chemical Symbols

Acronyms and Abbreviations Used

n.b.	nonbrecciated
NGOs	non-governmental organizations
NI 43-101	National Instrument 43-101—guidelines developed by the Canadian Securities Administration for preparation of technical reports that summarize scientific and technical information concerning mineral exploration, development and production activities on a mineral property that is material to an issuer
Plc	public limited company
R.A.T.	Roches Argilo-Talqueuses Subgroup—red, massive- to irregularly bedded, terrigenous and dolomitic rocks
R.S.C.	Roches Siliceuses Cellulaires—massive and generally stromatolitic dolomites
R.S.F.	Roches Siliceuses Feuilletées—siliceous, laminated dolomites
RCM	Roan Consolidated Mines Ltd
Re-Os	rhenium—osmium
S.D.	Shales Dolomitiques—dolomitic shales
S.D.B.	Schistes Dolomitiques De Base—basal dolomitic shales
S.D.S.	Schistes Dolomitiques Supérieures—upper dolomitic shales
Sprl	société privée à responsabilité limitée—private limited liability company
TCL	Tanganyika Concessions Ltd
UMHK	Union Minière du Haut Katanga
U-Pb	uranium-lead
USGS	United States Geological Survey
VTEM	versatile time domain electromagnetic
WGS	World Geodetic System
ZCCM	Zambia Consolidated Copper Mines
ZCCM-IH	ZCCM Investments Holdings Plc.

Chemical Symbols Used

Ag	silver
Au	gold
Co	cobalt
Cu	copper
Ni	nickel
Pd	palladium
Pt	platinum

Sediment-Hosted Stratabound Copper Assessment of the Neoproterozoic Roan Group, Central African Copperbelt, Katanga Basin Democratic Republic of the Congo and Zambia

By Michael L. Zientek[1], James D. Bliss[2], David W. Broughton[3], Michael Christie[4], Paul D. Denning[5], Timothy S. Hayes[2], Murray W. Hitzman[6], John D. Horton[5], Susan Frost-Killian[7], Douglas J. Jack[8], Sharad Master[9], Heather L. Parks[1], Cliff D. Taylor[5], Anna B. Wilson[5], Niki E. Wintzer[1], and Jon Woodhead[10]

Abstract

This study estimates the location, quality, and quantity of undiscovered copper in stratabound deposits within the Neoproterozoic Roan Group of the Katanga Basin in the Democratic Republic of the Congo and Zambia. The study area encompasses the Central African Copperbelt, the greatest sediment-hosted copper-cobalt province in the world, containing 152 million metric tons of copper in greater than 80 deposits. This study (1) delineates permissive areas (tracts) where undiscovered sediment-hosted stratabound copper deposits may occur within 2 kilometers of the surface, (2) provides a database of known sediment-hosted stratabound copper deposits and prospects, (3) estimates numbers of undiscovered deposits within these permissive tracts at several levels of confidence, and (4) provides probabilistic estimates of amounts of copper and mineralized rock that could be contained in undiscovered deposits within each tract. The assessment, conducted in January 2010 using a three-part form of mineral resource assessment, indicates that a substantial amount of undiscovered copper resources might occur in sediment-hosted stratabound copper deposits within the Roan Group in the Katanga Basin. Monte Carlo simulation results that combine grade and tonnage models with estimates of undiscovered deposits indicate that the mean estimate of undiscovered copper in the study area is 168 million metric tons, which is slightly greater than the known resources at 152 million metric tons. Furthermore, significant value can be expected from associated metals, particularly cobalt. Tracts in the Democratic Republic of the Congo (DRC) have potential to contain near-surface, undiscovered deposits. Monte Carlo simulation results indicate a mean value of 37 million metric tons of undiscovered copper may be present in significant prospects.

Introduction

In response to growing demand for information on worldwide mineral resources, the U.S. Geological Survey (USGS) conducted a global assessment of undiscovered copper resources (Briskey and others, 2001; Schulz and Briskey, 2003; Zientek and Hammarstrom, 2008; Hammarstrom and others, 2010). Undiscovered resources correspond to mineralized material whose location, grade, quality, and quantity are unknown or incompletely characterized, either in partially delineated sites or completely unknown mineral deposits. The global assessment studies were based primarily on geoscience information including (1) maps of regional geology, metallogeny, tectonics, geochemistry, and geophysics; and (2) databases of known mineral deposits, prospects, and occurrences. This information was used to delineate tracts of land permissive for particular types of undiscovered nonfuel mineral deposits and to make and constrain probabilistic estimates of the quantity of undiscovered resources.

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[10]Private Consultant, Duncraig, Perth, Western Australia.

Copper is found in many types of mineral deposits in diverse geologic settings. However, the USGS assessment effort focused on two deposit types that account for most of the copper that has been discovered and produced—porphyry copper and sediment-hosted stratabound copper (Singer, 1995). The study described in this report assesses undiscovered resources in sediment-hosted stratabound copper deposits in the Neoproterozoic Roan Group in the Katanga Basin, Democratic Republic of the Congo and Zambia (fig. 1).

The Roan Group contains the world's greatest concentration of copper found in sediment-hosted stratabound copper deposits—approximately 150 million metric tons (table 1; Hitzman and others, 2005, 2010). These deposits occur in a 700-kilometer (km)-long arcuate trend, called the Central African Copperbelt, which extends from the southeastern part of the Democratic Republic of the Congo to Zambia. The part of the trend within the Democratic Republic of the Congo is referred to as the Katangan or Shaban Copperbelt; the part in Zambia is called the Zambian Copperbelt. The differentiation of the belt into two parts is based on geopolitics and geology. In 1894, the border between the "Free State of the Congo" and Northern Rhodesia was established at the watershed between the Congo and the Zambezi Rivers. Since that time, geological studies in the Democratic Republic of the Congo were conducted by various mining companies and organizations in Belgium, with results published in French. In Zambia, studies were conducted by mining companies, and later, the geological survey of Zambia, with results published in English. The results of these studies were hard to compare. In the 1980s, working groups discussed geology of the region and the correlation of geologic units. The working groups concluded that broad correlations were possible but the geology of the two parts of the copperbelt was different. Salt tectonics affects the rocks in the Katangan Copperbelt, and many of the copper deposits occur in allochtonous fault sheets or salt structures, whereas the deposits in Zambia are autochtonous and found near the contact between the Katanga Supergroup and underlying basement rocks (fig. 1).

The first written accounts of mineral deposits of this area come from the travel diary of Pedro João Baptisma, who traveled through the region early in the 19th century (Beadle, 1873). Referring to the court of King Cazembe:

> "Ivory comes from the other side the river Luapula, and is brought as tribute by the people; green stones (malachite) are found in the ground, called 'catanga'" Beadle (1873, p. 188).

> "When we started from this farm of Chamuginga Mussenda, we traveled across others with valleys and hills, and saw, on the summit of the hills, stones which appear true (green?), and where they dig the copper; in the midst of this country is where they make the bars[11]" Beadle (1873, p. 222)

The Katangan area was one of three primary sources of copper traded in sub-Saharan Africa up to the late 19th century (Herbert, 1984). Archeological findings suggest that malachite outcrops in the copperbelt were mined as early as the 4th century A.D. (Bisson, 2000). Indigenous peoples may have smelted at least 100 thousand metric tons of copper, requiring the mining of more than 1 million metric tons of ore and waste (Ball, 1922).

Table 1. Principal regions of the world that contain identified copper resources associated within sediment-hosted stratabound copper deposits.

[Information summarized from Zientek, Hayes, and Taylor (2013)]

Area	Number of deposits	Identified copper resources (million metric tons)	Percent of total identified resource
All areas of the world	205	310	100
Katanga Basin	85	150	50
Zechstein Basin	10	79	25
Chu-Sarysu Basin	8	28	9
Kodar-Udokan area	2	20	6

[11]The "bars" refer to "handas," or Katanga crosses that were used as a form of currency (Bisson, 1975).

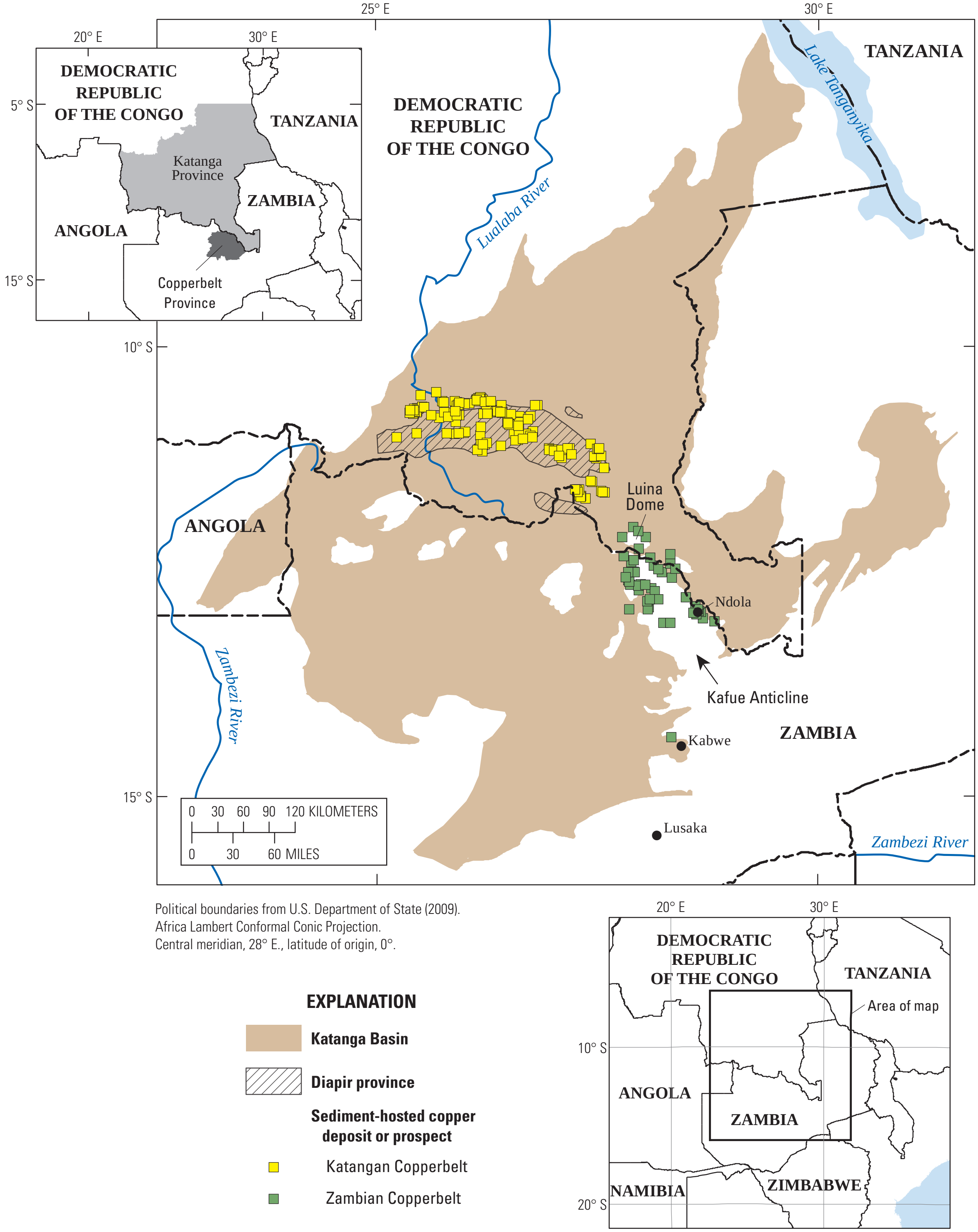

Figure 1. Map showing the location of the Central African Copperbelt and the Katanga Basin, Democratic Republic of the Congo and Zambia. Sediment-hosted stratabound copper deposits and prospects make up the Central African Copperbelt, which is subdivided into the Katangan and Zambian Copperbelts. The Katanga Basin outline is derived and modified from Veselinovic-Williams and Frost-Killian (2003). The diapir province is from Jackson and others (2003).

This report documents the mineral resource assessment process and presents the results of this study. Included are a brief geologic overview of the Katanga Basin and its sediment-hosted stratabound copper deposits, a description of the assessment process, summary of results, and several appendixes. Appendix A is a summary of mineral resource assessment methods and procedures used in USGS global mineral resource assessment reports. Technical terms used throughout the report are defined in this appendix. Appendix B describes the geographic information system (GIS) files that accompany this report; the reader of this report can use these files to compare and integrate the results of this study with their data. Appendix C lists the principal sources of information used in this study. Appendix D is a list of deposits and prospects within the Roan Group; this compilation updates previously published datasets in Taylor and others (2013). Appendixes E, F, and G summarize the following information for each tract: location, geologic feature assessed, rationale for tract delineation, tables and descriptions of known deposits and significant prospects, exploration history, model selection, rationale for estimates, assessment results, and references. Appendix H presents undiscovered deposit estimates made by the assessment panel, together with parallel plots comparing them with the consensus value. This information is provided so that others interested in the assessment process can see the variation in expert opinion that is not reflected in a single consensus estimate used in resource simulation. Appendix I introduces the scientists who participated in the panel that estimated the numbers of undiscovered deposits; most of the panel members are experts in the deposit type being assessed and some were conducting exploration for undiscovered deposits in the study area.

Assessment Terminology and Methodology

Scientific terminology for identified (discovered) mineral resources follows the usage proposed by the Committee for Mineral Reserves and Reporting Standards (2006). “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 exist 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. The term “mineral reserve” is restricted to the economically mineable part of a mineral resource.

The definition of a “known deposit” follows from Singer and Menzie (2010): Known deposits are well explored with resource estimates that (1) indicate pre-mining, in-place mineral endowment; (2) are based on sampling consistent with industry practices for defining mineral resources and reserves; (3) use similar cutoff grades; (4) use consistent rules for defining how ore bodies are spatially grouped into a deposit; and (5) are developed using similar mining and processing methods (Bliss and others, 1987).

This study uses the three-part assessment form described by Singer (1993) and Singer and Menzie (2010) to estimate the location and probable amounts of undiscovered resources. The concept of deposit type underlies geologically based mineral resource assessments; this study estimates the probable amount and location of undiscovered resources associated with sediment-hosted stratabound copper deposits. We use the widely accepted diagenetic model of ore formation when establishing assessment criteria for this deposit type.

Geographic areas are defined where undiscovered mineral resources may be present. These areas, or “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. 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). No areas are removed because of land status. The criteria to select the permissive volume of rock, or assessment unit, are provided by descriptive mineral deposit models and mineral systems models. The assessment depth for this study is 2 km.

Probabilistic distributions of the amount of in-place metal are used to express the amount of undiscovered mineral resource. In order to estimate undiscovered resources, numbers of undiscovered deposits of a given type are estimated at various quantile levels for the permissive tracts. Using Monte Carlo simulations, these undiscovered deposit estimates are combined with tonnage and grade models to derive a probability distribution for the amounts of commodities and rock that could be present in undiscovered deposits. More information about the assessment process is summarized in appendix A.

Sediment-Hosted Stratabound Copper Deposit Types

Sediment-hosted stratabound copper deposits consist of fine-grained, copper- and copper-iron-sulfide minerals that form stratabound to stratiform disseminations in siliciclastic or dolomitic sedimentary rocks. Chalcocite and bornite typically make up the ore zones. Ore minerals occur as cements and replacements and, less commonly, as veinlets.

The concentration of sulfide minerals conforms closely, but not exactly, with stratification of the host rocks. Deposits are characterized by zoning of ore minerals laterally along and across bedding from pyrite to chalcopyrite to bornite to chalcocite to hematite.

Field and laboratory evidence indicates that sediment-hosted stratabound copper deposits formed from late diagenetic fluids generated during the compaction and lithification of sedimentary basins containing successions of red beds and evaporites. Based on ore and gangue mineral zoning and alteration, mineral paragenesis, fluid inclusion studies, and stable isotope geochemistry, the metal-bearing fluids were low temperature (75–220 °C), hematite stable (oxidized), sulfate- and chloride-rich, subsurface sedimentary brines (Hitzman and others, 2005; Zientek, Hayes, and Hammarstrom, 2013). The primary cause of base-metal sulfide precipitation is reduction of sulfate in the brine by organic material.

Stratabound copper deposits are associated with evaporites and red bed deposits (Davidson, 1965; Rose, 1976; Kirkham, 1989). Sediment-hosted stratabound copper mineralization is limited to sedimentary rocks that were deposited after free oxygen first appeared in the Earth's atmosphere at approximately 2,300 Ma, enabling the formation of the earliest red beds (Bekker and others, 2004; Chandler, 1988; Canfield, 2005; Hitzman and others, 2010). Sediment-hosted stratabound copper deposits are found with red beds deposited in an arid climate; these sedimentary depositional environments include aeolian dunes, sabkhas, playas and sand sheets, together with minor alluvial fans, ephemeral rivers, playas, and inland lakes. Evaporite deposits commonly are present within these types of red beds. Sedimentary deposits characteristic of arid environments formed between 20 to 30 degrees of the equator (the horse latitudes) in continental areas; red beds within stratabound sediment-hosted copper deposits are found in rift, transtensional, and intermontane basins (Kirkham, 1989).

Subtypes of sediment-hosted stratabound copper deposits are distinguished by host lithology and the nature of organic material in the sedimentary strata. Host rocks for reduced-facies subtype include black shale, dark-gray to black siltstone, dark-gray dolosiltstone, gray shale, and locally green shale or siltstone, all of which contain varying amounts of solid organic material. Well-sorted, siliciclastic sandstones from a variety of deltaic topset depositional environments are the host rocks for sandstone-type copper deposits. Occurrence of petroleum-bearing fluid inclusions and dead oil[12] that coat detrital grains, stain authigenic minerals, and locally form cements, indicate that the mineralized strata contained petroleum accumulations. For many sandstone copper deposits, these accumulations could have been sour gas (natural gas containing significant amounts of hydrogen sulfide).

Regional Geologic History

The depositional and tectonic development of the Neoproterozoic to Lower Paleozoic Katanga Basin is related to the separation of the Congo Craton from the Rodinian supercontinent[13] (fig. 2) followed by the incorporation of the craton into the Gondwana supercontinent[14]. The Congo Craton is one of about a dozen large cratons that converged in the Late Mesoproterozoic to form the supercontinent, Rodinia (Evans, 2009). Neoproterozoic rifting events tore apart Rodinia, which was followed by reorganization and convergence of the cratons to form the Gondwana Supercontinent from about 650–500 Ma. Since the late Paleoproterozoic, the Congo Craton has endured as a geologic entity with all major Rodinian and Gondwanan events occurring along its margins.

Neoproterozoic Rift Basins

During fragmentation of the Rodinian supercontinent, Neoproterozoic sedimentary basins developed in and around the margin of the Congo Craton in a network of failed rifts (aulacogens) (Cahen, 1954; Lepersonne, 1974, 1977; Alvarez, 1995; Cailteux and others, 2005b; Kadima and others, 2011) (figs. 2 and 3). The basins include (1) rocks of the West Congo Supergroup within the Singha and Mayombe aulacogens; (2) flat-lying rocks of the Lindi Supergroup related to the Northern Zaire Trough (Verbeek, 1970; Thibaut, 1983; Alvarez, 1995); and (3) rocks of the Katanga Supergroup (Robert, 1956; François, 1974; Master and others, 2005; Cailteux and others, 2005b; Batumike and others, 2006). Where rocks in the Neoproterozoic basins are well preserved, typical continental rift assemblages rest unconformably on older basement. The Nchanga Granite is the youngest dated intrusion in the pre-Katangan basement (Garlick, 1973). Petrographic and radiometric studies indicate that pebbles and zircons from the Nchanga Granite are present in the basal Katanga Supergroup, defining a maximum age of about 880 Ma for initiation of deposition (Master and others, 2005).

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[12]Oil at sufficiently low pressure that it contains no dissolved gas or a relatively thick oil or residue that has lost its volatile components (http://www.oilprofessionals.com/glossary/).

[13]Rodinia is the name of a supercontinent that contained most or all of the Earth's landmass between 1.1 and 0.75 billion years ago.

[14]Gondwana is the name of the more southerly of two supercontinents that were part of the Pangea supercontinent that existed between between 510 and 180 million years ago.

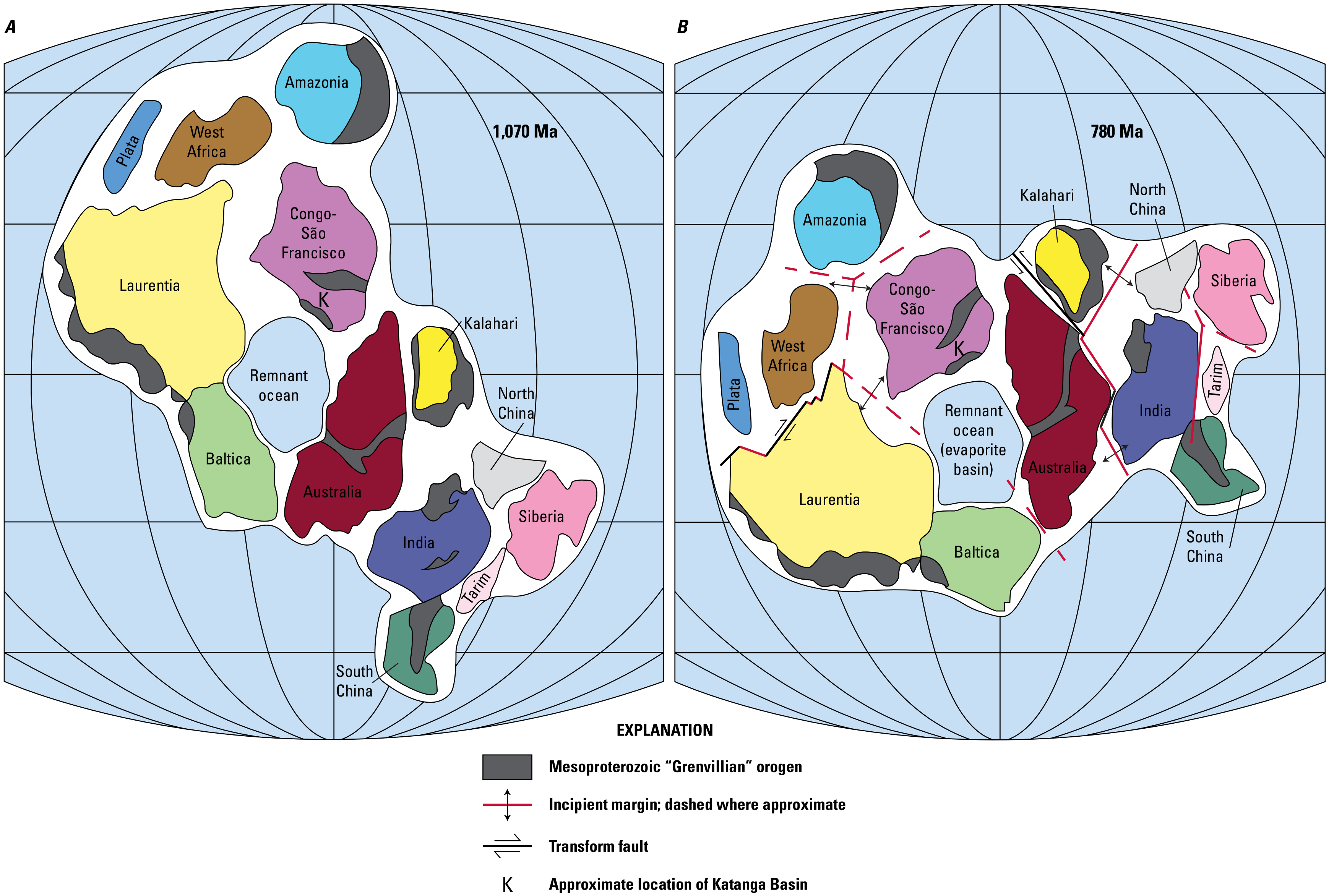

Figure 2. Map showing possible reconstructions of the supercontinent, Rodinia, soon after assembly at 1,070 Ma (*A*) and shortly prior to breakup at 780 Ma (*B*). Cratons are shown in color; Mesoproterozoic "Grenvillian" orogens are shown in gray. The Katanga Basin developed on the Congo-São Francisco craton at the location shown by the letter "K." Modified from Evans (2009).

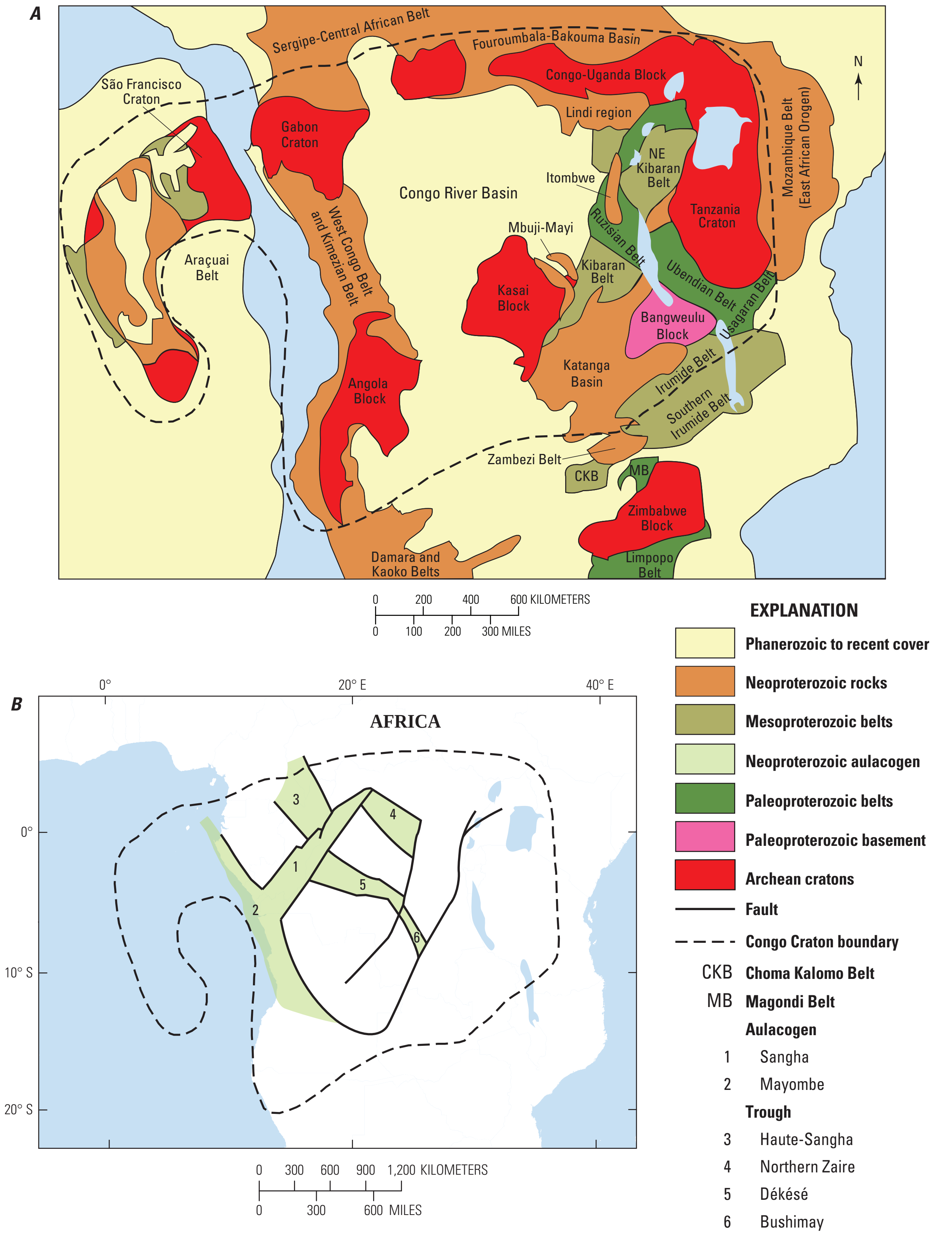

Figure 3. Simplified geologic map of the Congo Craton, showing the distribution of Neoproterozoic rocks, including those of the Katanga Basin, along the margins of the craton (*A*). Modified from Tait and others (2011) and Tack and others (2010). Map showing the location of Neoproterozoic aulacogens developed on the Congo Craton (*B*). Modified from Alvarez (1995).

Pan African Orogeny and the Lufilian Arc

The integration of the Congo Craton into the Gondwana supercontinent formed collisional high-grade terranes along the northern and eastern margins of the Congo Craton and accretionary belts in the west and south (fig. 3; Collins and Pisarevsky, 2005; Tohver and others, 2006; Tack and others, 2010). This tectonic event is referred to as the Pan African Orogeny. The Pan African event that affects Katangan sedimentary rocks is known as the Lufilian Orogeny (Porada and Berhorst, 2000).

The Lufilian Orogeny formed the Lufilian Arc, a belt of curved folds, thrusted terranes, and shear zones that formed during the collision of the Congo and Kalahari Cratons (fig. 4; Cahen and others, 1984; Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999; Porada and Berhorst, 2000; Armstrong and others, 2005; Batumike and others, 2006). The collision resulted in the thrusting of deformed Archean to Proterozoic basement rocks, overlain by Neoproterozoic volcanic and sedimentary rocks, over the edge of the Congo Craton. The Lufilian Arc and its foreland are bordered to the west by the Mesoproterozoic Kibaran Belt and to the east by the Paleoproterozoic Bangweulu block.

The Pan African orogenic events in the Katangan Lufilian Arc took place from approximately 560–530 Ma (Tack and others, 2010). Transpressional deformation in the inner part of the arc is constrained by U-Pb zircon ages of 566±5 and 559±8 Ma for syntectonic granites in the Hook batholith (fig. 4), and by a U-Pb zircon age of 551±19 Ma for hypabyssal rhyolite that was intruded during displacement along the Mwembeshi Shear Zone. Postectonic felsic magmatism in the same area occurred at about 538–533 Ma (Hanson and others, 1993). Late to postectonic hydrothermal mineralization took place in the outer part of the Lufilian Arc at about 514–502 Ma, as shown by U-Pb rutile, monazite, and uraninite ages, and Re-Os molybdenite ages for vein minerals (Richards and others, 1988b; Torrealday and others, 2000).

In the foreland of the West Congo and Lufilian orogens, continental red beds (molasse deposits of the Inkisi Formation in the West Congolian Group and Plateaux/Biano Groups in the Katanga Supergroup) unconformably overlie rift-related sedimentary sequences and record the culmination of the Pan African orogeny (Tack and others, 2008). For both areas, the age of the unconformity is estimated at ~550 Ma from the coincidence of the paleomagnetic poles of the different blocks composing central Gondwana (Tohver and others, 2006). Detrital muscovites from the Plateaux Group yield a maximum Ar-Ar age of 573 Ma (Master and others, 2005), thus supporting the idea that this unit was deposited in the foreland of the Lufilian Orogen. A detrital zircon age of 565 Ma was obtained for the Inkisi Formation of West Congo (Frimmel and others, 2006). These post-Neoproterozoic continental red beds are overlain by upper Carboniferous rocks of the Karoo Supergroup (Cahen and others, 1960; Tack and others, 2010). Proximal to the orogen, the West Congolian and Katangan foreland regions are deformed and the red beds unconformably overlie previously folded sequences of rift-related Neoproterozoic rocks. Distal from the deformed foreland regions and in the Lindi region, layering in the red beds is concordant with that in the underlying Neoproterozoic sequences (Lepersonne, 1974; Tack and others, 2008).

Regional uplift and cooling that affected the whole Katanga Basin is recorded in $^{40}Ar/^{39}Ar$ biotite plateau ages in the range of 496.6±0.6 to 485.2±0.9 Ma, and a muscovite plateau age of 483.6±1.1 Ma from samples taken in the Zambian Copperbelt (Rainaud and others, 2005). Slow cooling of the Lufilian Orogen is indicated by apparent $^{40}Ar/^{39}Ar$ ages obtained from microcline in the Zambian Copperbelt at Musoshi that range from 467.0±2.7 to 405.8±3.8 Ma.

Development of the African Surface

Following the breakup of the Permian-Triassic Gondwana supercontinent, the Afro-Arabian continent was relatively stable. From 130 to 30 Ma, a low-elevation, low-relief land surface largely mantled by deeply weathered rock developed on the continent. This Oligocene land surface is called the “African Surface” by Burke and Gunnell (2008). Continued weathering and development of secondary minerals on the Oligocene land surface continued after parts of central and eastern Africa underwent regional uplift beginning in the Miocene (Lavier and others, 2001). Cobalt- and manganese-residual deposits are found on metal-rich bedrock and iron laterites on barren areas. Secondary manganese ores (west Katanga) and cobalt ores (east Katanga) formed at ~10 Ma and ~3 Ma (Decrée and others, 2010).

During the Quaternary, the climate became arid, resulting in the incision of the surface, formation of valleys, and erosion of residual deposits (Decrée and others, 2010). The African Surface has been partly or completely eroded in some areas, but lateritic or bauxitic cover is found where it has been preserved. Relict silicified inselbergs retain their cobalt caps. Detrital heterogenite (cobalt oxyhydroxide), the main oxidized cobalt mineral derived by weathering of carrollite in sediment-hosted stratabound copper ores, is concentrated in topographic lows (fig. 5). Remnants of the African Surface occur along the drainage divide between the Congo and Zambezi Rivers that define the border between the Democratic Republic of the Congo and Zambia. On the Zambian side of the border, the surface is characterized by monotonously flat terrain with sprawling dambos[15] (Garlick, 1961c). The surface is deeply incised on the Congo drainage, and the terrain is characterized by hills and ridges.

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[15]A term used in central Africa for a small, ill-defined floodplain or channelless drainageway that is extremely flat with broad, grassy clearings, swampy during the wet season but dry for the greater part of the year (AGI Glossary of Geology Online).

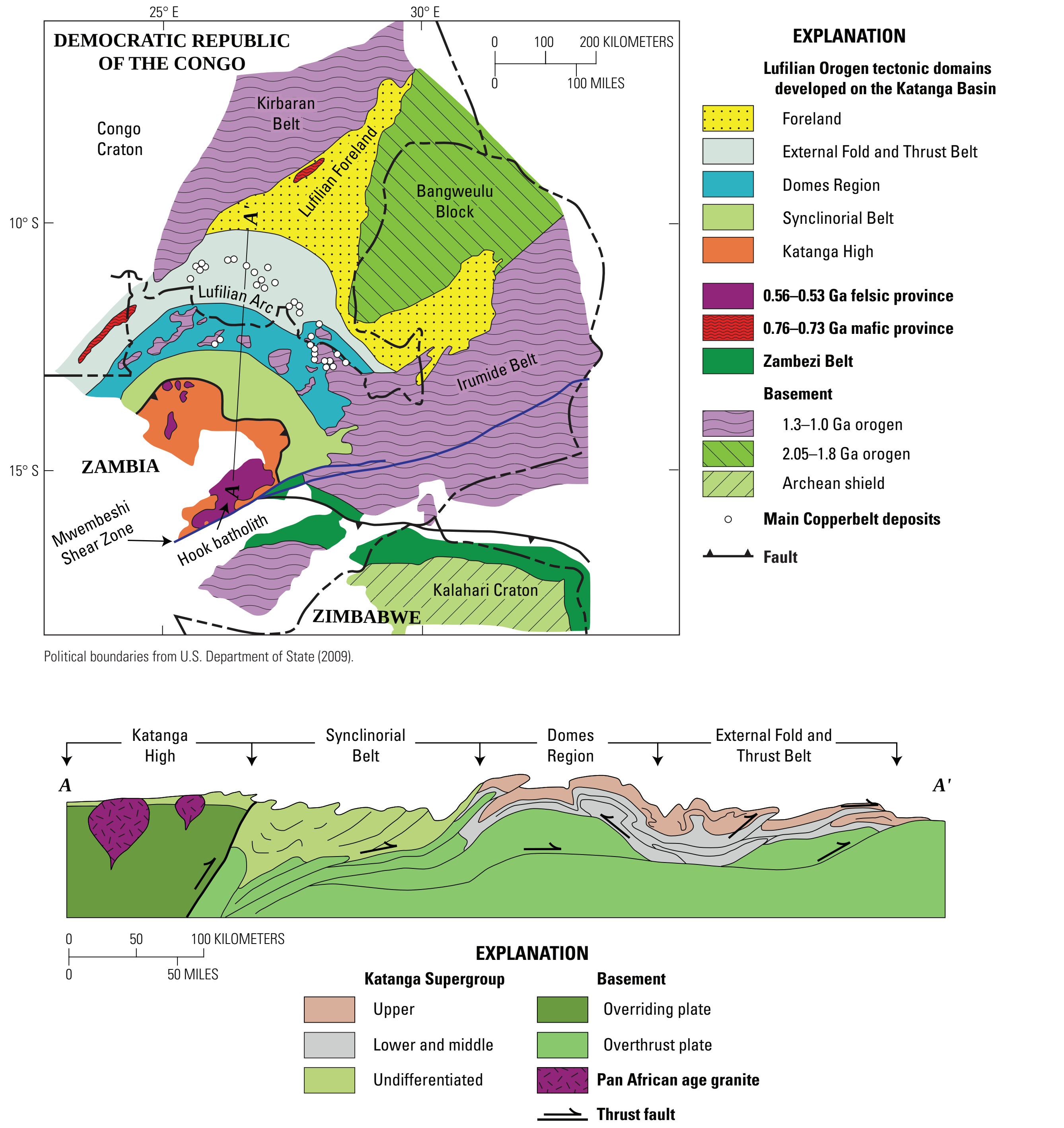


Figure 4. Map and cross section showing the superposition of tectonic features related to the Pan African Lufilian Orogen on the Neoproterozoic Katanga Basin, Democratic Republic of the Congo and Zambia. Modified from Kampunzu and Cailteux (1999), Porada and Berhorst (2000), and Selley and others (2005).

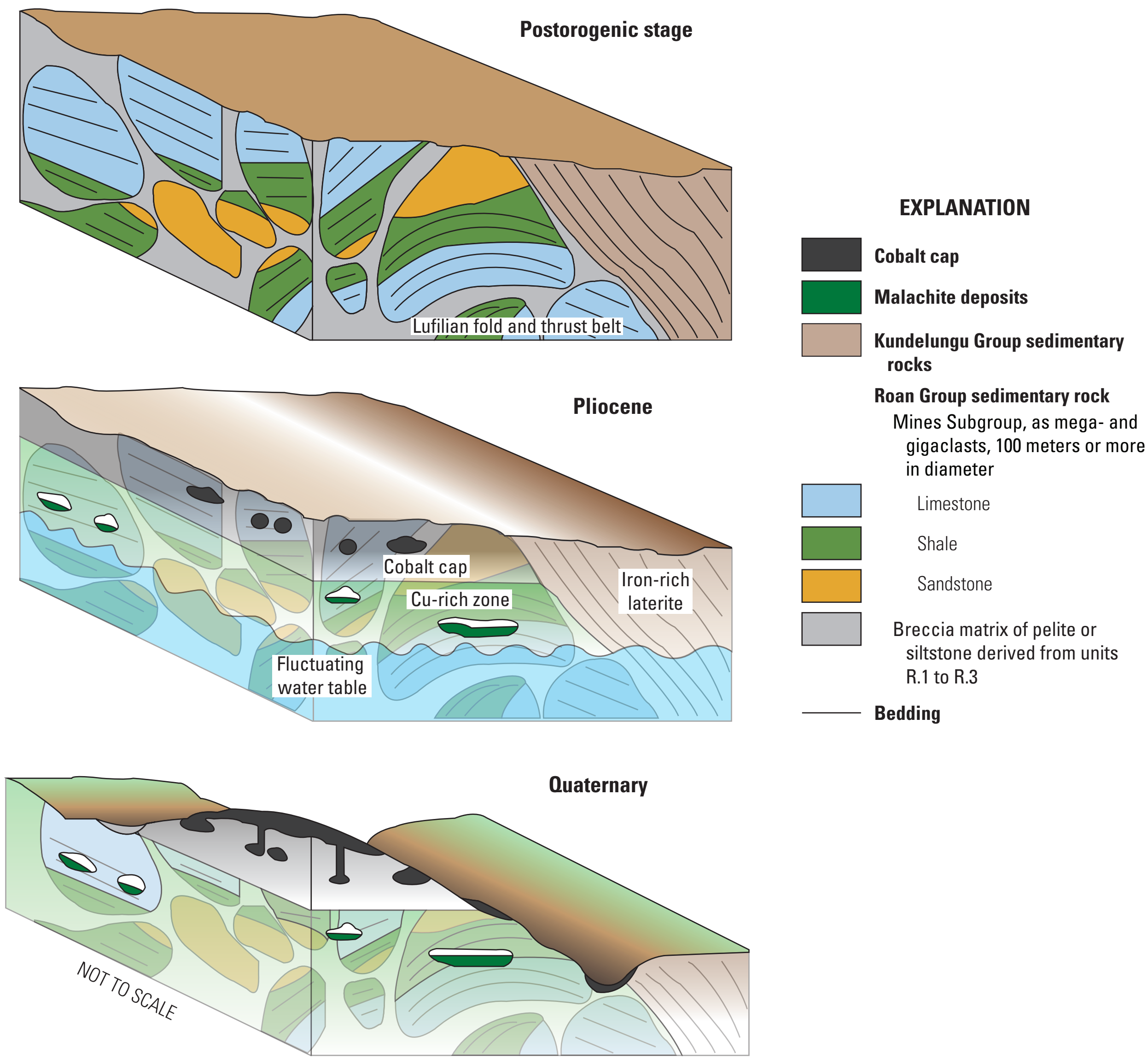


Figure 5. Diagrams illustrating the formation of secondary oxidized copper and cobalt ores in the Katangan Copperbelt. At the end of the Lufilian Orogeny, reduced-facies copper-cobalt mineralization is restricted to Roan Group breccias. By the Pliocene, development of a regional weathering surface results in supergene enrichment of cobalt and copper. In the Quaternary, erosion of the regional lateritic surface forms cobalt caps along the tops of silicified dolomite inselbergs. Modified from Decrée and others (2010).

Stratigraphy and Depositional Environments of the Katanga Supergroup

The Katanga Basin began as a continental rift and evolved into a collision-related foreland basin. The early stage of rift initiation is represented by subaerial fluvial and alluvial strata in several subbasins. These beds are overlain by a major transgression (flooding surface) that begins a depositional sequence characterized by a thick section of shallow-water carbonate rocks overlain by shales. In general, correlations become broader upsection, indicating general widening and coalescence of subbasins (Jackson and others, 2003). Prior to orogenesis, rocks of the basin record a regional facies change from clastic sedimentary rocks (sandstones, siltstones, and shales) in the north to dominantly carbonate rocks (dolomite and limestone) in the south. During the Lufilian Orogeny, the basin was transformed into a foreland basin. Folded sedimentary rocks, originally deposited in a shallow-water foreland basin north of the Lufilian Arc, are overlain by subhorizontal, undeformed, and unmetamorphosed molasse deposits.

Deposits related to two Cyrogenian[16] glacial events are used to divide the thousands of meters of sedimentary rocks in the basin into three lithostratigraphic units: the Roan, Nguba, and Kundelungu Groups (fig. 6; Cailteux and others, 1994, 2005b; Selley and others, 2005). The Grand Conglomérat (approximately 750 Ma), occurs at the base of the Nguba Group, is correlated with the global Sturtian glaciation (750–700 Ma), and predates the Lufilian Orogeny. The Petit Conglomérat, at the base of the Kundelungu Group, is correlated with the global Marinoan-Varangian glaciation (650–635 Ma). These deposits accumulated during the Lufilian Orogeny.

The Lufilian Orogeny caused the extrusion of allochtonous evaporites and shortening of the Lufilian foreland, from about 190 to 85 km (Jackson and others, 2003). Evaporitic rocks deposited during the rift phase of the basin were transformed into regional detachments and diapirs (Jackson and others, 2003). Dissolution of salt is the likely origin for breccias found along the detachments and diapirs.

The stratigraphy of the Katangan sedimentary section is reviewed in the following sections. The Roan Group, the lowest unit, is discussed at length because it hosts important sediment-hosted stratabound deposits and shows regional variation due to deposition in subbasins. The geology of the Nguba and Kundelungu Groups is only briefly mentioned. The section finishes with a description of the Roan breccia, which is thought to have formed by the dissolution of salt structures formed during the Lufilian Orogeny.

Roan Group

Red beds of the Roan Group unconformably overlie pre-Katangan basement rocks, which are in turn overlain by strata deposited in a reducing environment that preserves organic material. The depositional facies in the lower part of the Roan Group differ between the Zambian and Katangan parts of the copperbelt (figs. 7, 8, and 9). The facies differences, the lack of information on depositional ages of the rocks, complex tectonics of the Katangan area, absence of continuous outcrop in the transition area between the two facies, and different traditions of scientific studies between the Democratic Republic of the Congo and Zambia have hindered efforts to correlate rocks in the lower part of the Roan Group (Gray, 1930; Robert, 1956; Mendelsohn, 1961a; François, 1973; Cahen, 1974; Lefebvre and Tshiauka, 1986; Cailteux, 1994; Cailteux and others, 1994, 2005b; Wendorff, 2003).

[16]850–635 Ma.

The Roan Group in the Democratic Republic of the Congo

The Neoproterozoic Roches Argilo-Talqueuses (R.A.T.) Subgroup is composed of red, massive- to irregularly bedded, terrigenous and dolomitic rocks occurring at the base of the Katanga Supergroup in the Democratic Republic of the Congo (figs. 7 and 9; Cailteux, 1994). The red color is related to the presence of hematite in the form of authigenic plates and pigment included in authigenic minerals such as quartz, dolomite, and tourmaline (Cailteux, 1994). Proportions of chloritic-dolomitic cement increase towards the top of the sequence. Detrital quartz is more abundant in the lower part of the sequence; the rocks become more dolomitic in the upper part. Occurrences of desiccation cracks and carbonate-quartz pseudomorphs after anhydrite and gypsum indicate an evaporitic depositional environment. Red R.A.T. is conformably overlain by the Grey R.A.T. member of the Mines Subgroup. Apart from the color difference reflecting distinct redox conditions, lithologic, petrographic, and geochemical features of Red and Grey R.A.T. are similar (Cailteux, 1994).

The Mines Subgroup is a carbonate unit that formed in a reducing environment and is subdivided into three formations (oldest to youngest; figs. 7 and 9): (1) Kamoto Dolomite (R.2.1); (2) dolomitic shales (S.D.="Shales Dolomitiques") (R.2.2); and (3) (C.M.N.="Calcaire à Minerais Noir") or Kambove Dolomite (R.2.3). The Kamoto Dolomite is subdivided into four units. The basal unit is Grey R.A.T., which consists of a 4–8-m-thick chloritic and dolomitic siltstone. It is overlain by three mostly dolomitic units, the "Dolomites stratifiées" or D. Strat. (stratified, fine-grained dolomites), "Roches Siliceuses Feuilletées" or R.S.F. (siliceous, laminated dolomites), and "Roches Siliceuses Cellulaires" or R.S.C. (massive and generally stromatolitic dolomites). The Dolomitic Shales Formation consists mostly of fine clastic material cemented by dolomite. The formation can be further subdivided based on the presence of three carbonaceous marker units. Sedimentary rocks at the base of this formation were deposited in a shallow-water, high-salinity environment (intertidal zone); rocks higher in the formation are interpreted to have formed in a deeper-water environment. The Kambove Dolomite Formation (C.M.N.) is divided into (1) the Lower C.M.N. (mostly dark dolomites, enriched in organic matter), and (2) the Upper C.M.N. (clean dolomites containing interbedded, chloritic dolomitic siltstones).

The Dipeta Subgroup (figs. 7 and 9) is divided into four formations, each characterized by a high proportion of argillaceous and siliciclastic beds at the base and by carbonate beds at the top (Cailteux, 1994; Cailteux and others, 2005b, 2007). The argillaceous-siliciclastic strata include purple-blue, green, or red siltstones, dolomitic shales, and sandstones.

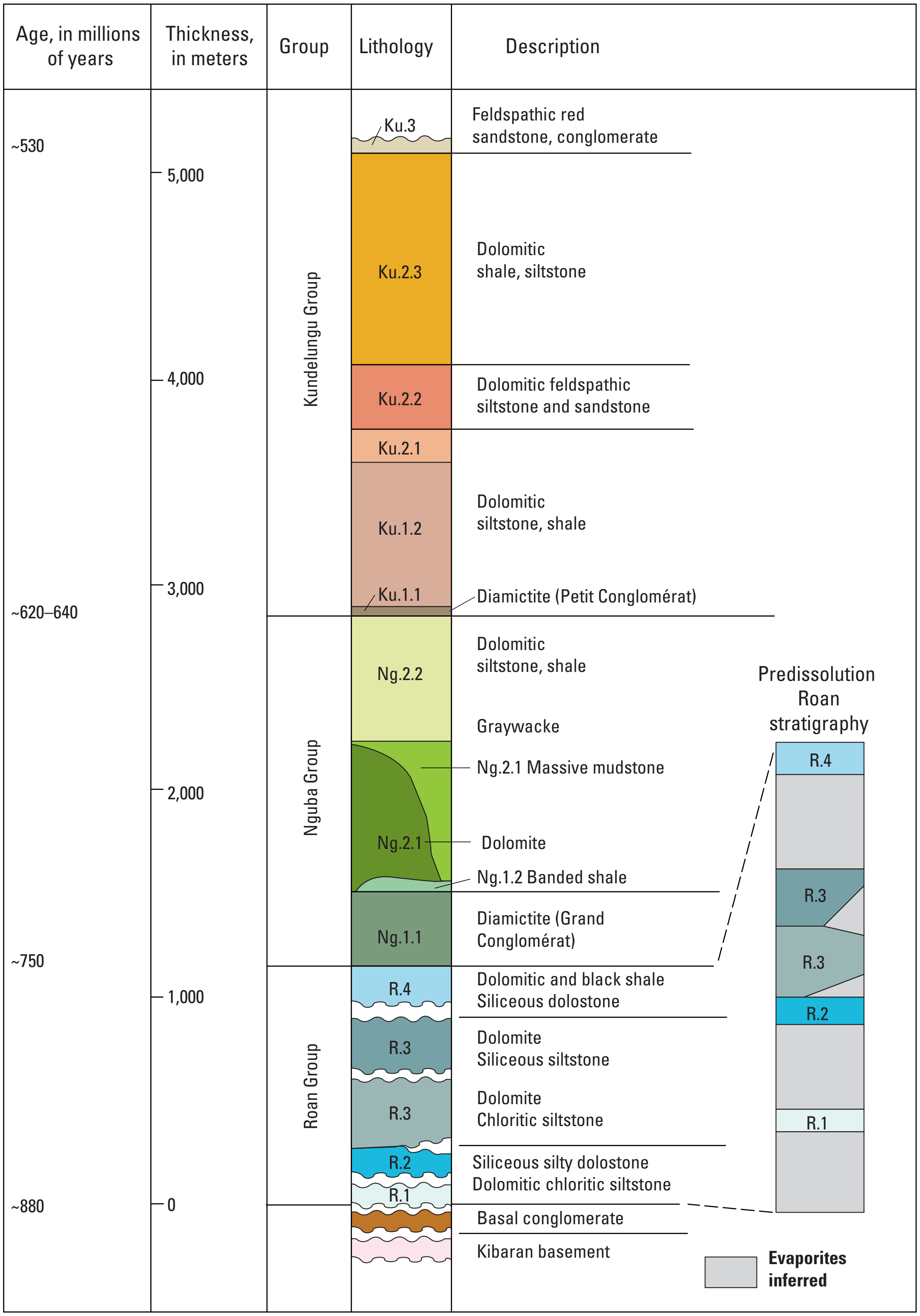


Figure 6. Katangan stratigraphic column showing restored evaporite thicknesses inferred in the original Roan Group. Stratigraphy and symbols after François (1973) and De Magnée and Francois (1988). Basal units below R.1 are unknown in the Democratic Republic of the Congo and are based on the Zambian Copperbelt. Modified from Jackson and others (2003).

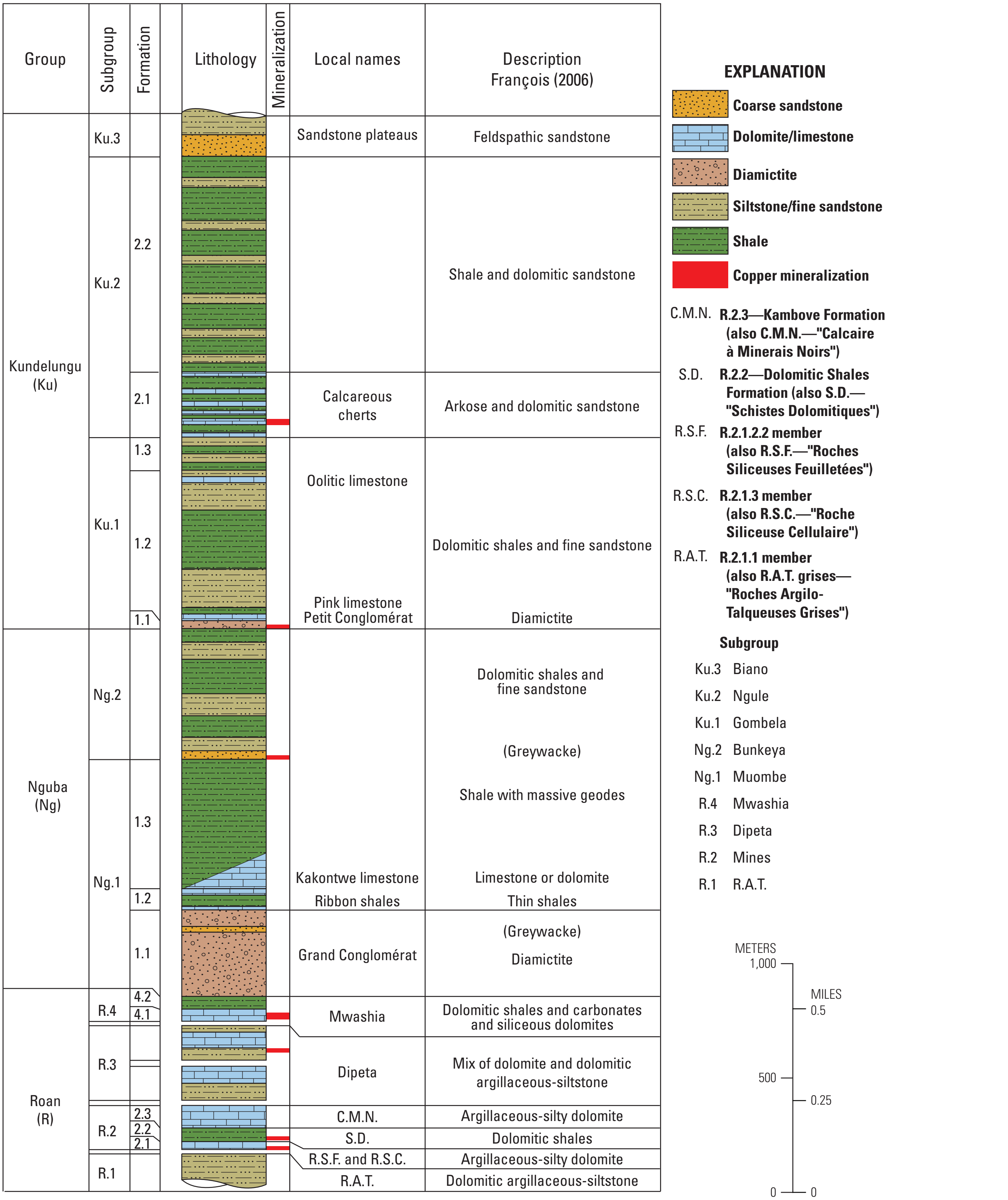
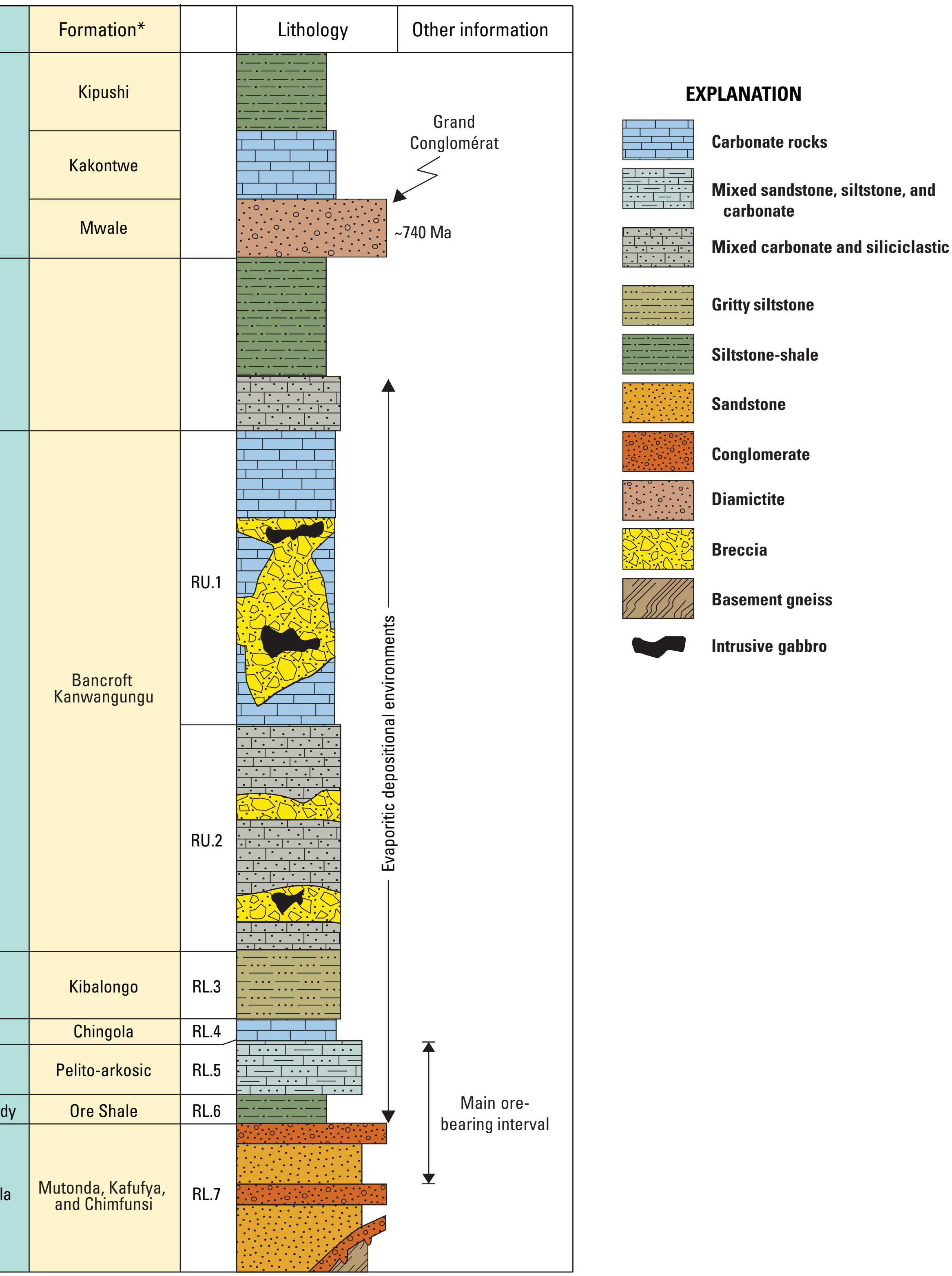


Figure 7. Katangan stratigraphic column showing the position of mineralized strata in the Democratic Republic of the Congo. The reduced-facies—carbonate écaille mineralization assessed in this study is associated with the Mines Group (R2) in the Roan Group. Gaps in the Roan section indicate where evaporites may have been present. Stratigraphic abbreviations: C.M.N.—"Calcaire à Minerais Noirs" (black limestone ore); S.D.—"Schistes Dolomitiques" (dolomitic shales); R.S.F.—"Roches Siliceuses Feuilletées" (laminated siliceous rocks); R.S.C.—"Roches Siliceuses Cellulaires" (cellular siliceous rocks); and R.A.T.—"Roches Argilo-Talqueuses" (clayey talcose rocks). Modified from François (2006).

Group	Subgroup	Formation	Member	Supergroup*	Group*	Group+	Formation+	Subgroup*	Member+
Nguba		Kipushi		Katanga	Nguba	Lower Kundelungu	Kundelungu Shales	Muombe	
		Kakontwe					Kakontwe		
		Mwale					Grand Conglomerate		
Roan	Mwashia				Roan	Mwashia	Upper Middle Lower	Mwashia	
	Upper Roan	Bancroft				Upper Roan	Bancroft	Kirilabombwe	
		Kanwangungu							
	Lower Roan	Kitwe	Kibalongo			Lower Roan	Kitwe		Antelope
			Chingola					Kitwe	Chambishi
			Pelito-arkosic						Nchanga and Rokana
			Ore Shale						Copperbelt Orebo
		Mindola					Mindola Clastics	Mindola	Kafue and Konko

Figure 8. Zambian stratigraphic column showing mineralized interval and nomenclature used in previous studies and this report. Names from Clemmey (1974) and Cailteux and others (2007), indicated with a cross and blue, shaded columns. Names from Selley and others (2005), indicated by an asterisk and beige, shaded columns. Usage in this report shown with gray background.


Formation*
Lithology
Other information
Kipushi
Kakontwe
Mwale
Grand Conglomérat
~740 Ma
Bancroft Kanwangungu
RU.1
RU.2
Evaporitic depositional environments
Kibalongo
RL.3
Chingola
RL.4
Pelito-arkosic
RL.5
dy
Ore Shale
RL.6
Main ore-bearing interval
la
Mutonda, Kafufya, and Chimfunsi
RL.7
EXPLANATION
Carbonate rocks
Mixed sandstone, siltstone, and carbonate
Mixed carbonate and siliciclastic
Gritty siltstone
Siltstone-shale
Sandstone
Conglomerate
Diamictite
Breccia
Basement gneiss
Intrusive gabbro

SUPERGROUP		GROUP	SUBGROUP	FORMATION	FORMER NOMENCLATURE (François, 1987)	LITHOLOGY
		DEMOCRATIC REPUBLIC OF THE CONGO AND ZAMBIA				
Katanga	± 500 Ma	Kundelungu—Ku (formerly Upper Kundelungu—Ks)	Biano—Ku.3		Ks.3	arkoses, conglomerates, argillaceous sandstones
			Ngule—Ku.2	Sampwe—Ku.2.3	Ks.2.2	dolomitic pelites, argillaceous to sandy siltstones
				Kiubo—Ku.2.2	Ks.2.1	dolomitic sandstones, siltstones and pelites
				Mongwe—Ku.2.1	Ks.1.3	dolomitic pelites, siltstones and sandstones
			Gombela—Ku.1	Lubudi—Ku.1.4	Ks.1.2.4	pink oolitic limestone and sandy carbonate beds
				Kanianga—Ku.1.3	Ks.1.2.2 and 1.2.3	carbonate siltstones and shales
				Lusele—Ku.1.2	Ks.1.2.1	pink to gray micritic dolomite
	± 620 Ma			Kyandamu—Ku.1.1	Ks.1.1	Petit Conglomérat (glacial diamictite)
		Nguba—Ng (formerly Lower Kundelungu—Ki)	Bunkeya—Ng.2	Monwezi—Ng.2.2	Ki.2	dolomitic sandstones, siltstones and pelites
				Katete—Ng.2.1	Ki.1.3	dolomitic sandstones, siltstones and shales in northern areas; a shale and dolomite beds ("Série Récurrente") in southern areas
			Muombe—Ng.1	Kipushi—Ng.1.4	Ki.1.2.2	dolomite with dolomitic shale beds in southern areas
				Kakontwe—Ng.1.3		carbonates; Zn-Cu-Pb
				Kaponda—Ng.1.2	Ki.1.2.1	carbonate shales and siltstones; "Dolomie Tigrée" at the base
	± 750 Ma			Mwale—Ng.1.1	Ki.1.1	Grand Conglomérat (glacial diamictite)
		DEMOCRATIC REPUBLIC OF THE CONGO				
		GROUP	SUBGROUP	FORMATION	FORMER NOMENCLATURE (François, 1987)	LITHOLOGY
		Roan—R	Mwashya (formerly Upper Mwashya)—R.4	Kanzadi—R.4.3	R.4.2	sandstones or alternating siltstones and shales
				Kafubu—R.4.2		carbonaceous shales
				Kamoya—R.4.1		dolomitic shales, siltstones, sandstones, including conglomeratic beds and cherts in variable position
			Dipeta—R.3	Kansuki—R.3.4	R.4.1	(formerly Lower Mwashya): dolomites including volcaniclastic beds; Cu-Co
				Mofya—R.3.3		dolomites, arenitic dolomites, dolomitic siltstones
				R.3.2		argillaceous dolomitic siltstones with interbedded sandstone or white dolomite; intrusive gabbros
				R.G.S.—R.3.1		argillaceous dolomitic siltstones ("Roches Greso-Schisteuses")
			Mines—R.2	Kambove—R.2.3		stromatolitic, laminated, shaly or talcose dolomites (2.3.1); locall at the base; interbedded siltstones in the upper part; Cu-Co
				Dolomitic shales—R.2.2		R.2.2.2 and 3: dolomitic shales containing carbonaceous horizons; occasional dolomite or arkose
						R.2.2.1: arenitic dolomite at the top and dolomitic shale at the ba pseudomorphs after evaporite nodules and concretions; Cu-Co
				Kamoto—R.2.1		stromatolitic dolomite (R.S.C. 2.1.3), silicified/arenitic dolomites (R.S.F./D. Strat. 2.1.2), gray argillaceous dolomitic siltstone at the (Grey R.A.T.); pseudomorphs after evaporites at the contact with Cu-Co
			R.A.T.—R.1	red argillaceous dolomitic siltstones, sandstones and pelites ("Roches Argilo-Talqueuses")		
			base of the R.A.T. sequence—unknown			
		< 900 Ma basal pebble and cobble conglomerate				
± 2,050 Ma KIBARAN AND PRE-KIBARAN						

Figure 9. Chart showing the lithostratigraphic correlation of the Katanga Supergroup between the Democratic Republic of the Congo and Zambia. Modified from Cailteux and others (2005b) and Batumike and others (2007).

lternating

	ZAMBIA		
	LITHOLOGY	FORMATION	SUBGROUP
	dolomitic shales, gray to black carbonaceous shales, quartzites		Mwashia
	dolomites to arenitic dolomites interbedded with dolomitic shales; intrusive gabbros (formerly Carbonate Unit or Upper Roan)	Bancroft Kanwangungu RU.1 and RU.2	Kirilabombwe
	shales with grit (Antelope Clastics)	Kibalongo RL.3	
y sandstone	dolomite, argillite beds at top	Chingola RL.4	Kitwe
	arkoses, sandy to dolomitic argillites	Pelito-arkosic RL.5	
se; e base n R.A.T.;	arenites, argillaceous dolomites, argillites, dolomites, evaporites; Cu-Co	Ore Shale RL.6	
	conglomerates, coarse arkoses and argillaceous siltstones	Mutonda	Mindola—RL.7
	quartzites	Kafufya	
	pebble and cobble conglomerate	Chimfunsi	

Carbonate beds are massive or finely layered gray-white, yellow, or red-brown dolomites, with local white talcose dolomites. Evaporitic conditions are indicated by carbonate-quartz pseudomorphs after gypsum and anhydrite, and by collapse breccias in the dolomites. Occurrence of hematite in the siltstones suggests an oxidizing environment. The sequence of oxidized sandy argillaceous facies overlain by lagoonal-type carbonate facies is consistent with a sabkha-type depositional environment. The uppermost formation, the Kansuki (previously called the Lower Mwashia) is made up of carbonate rocks that contain some detrital and volcaniclastic beds.

The clastic-dominant Neoproterozoic Mwashia Subgroup (formerly the Upper Mwashia; figs. 7 and 9) is subdivided into three formations: (1) Kamoya, characterized by dolomitic, silty shales, siltstones, and sandstones, and containing a regional marker unit (the “Conglomerat de Mwashya” bed or complex) at its base; (2) Kafubu, formed by finely bedded and slightly dolomitic shales, with a high carbon content; and (3) Kanzadi, marked by feldspathic sandstones alternating with black shales or siltites (Cailteux and others, 2007). The “Conglomérat de Mwashya” was deposited by subaquatic mass transport by turbidity currents and has characteristics of glacial deposits (Cahen, 1978).

The Roan Group in Zambia

The basal unit of the Lower Roan Subgroup in Zambia, the Mindola Formation, contains texturally immature siliciclastic sedimentary rocks such as conglomerates, quartzite, arkose, and argillaceous- and carbonate-cemented arenites that were deposited in fluvial, alluvial fan, eolian, and fan-delta environments (Binda, 1994; Selley and others, 2005) (fig. 8). The formation is characterized by significant lateral and vertical facies variations. These sedimentary rocks were deposited in several structurally controlled subbasins (Selley and others, 2005); therefore, thickness varies widely and can change abruptly along strike. The Mindola Formation might be absent on the top of paleo-highs but can be up to several hundreds of meters thick in the deepest troughs.

A laterally extensive marine unit, the Ore Shale member, transgresses the basement-bounded subbasins that contain red beds of the Mindola Formation (figs. 8 and 9). The Ore Shale member is 5 to 20 m thick (Greyling and others, 2005) and laterally extensive, having been traced for more than 100 km. The contact between the Mindola Formation and the Ore Shale member represents a major flooding surface. The lower contact of the Ore Shale member is marked by the first appearance of a dolomite bed or argillaceous rock above the red bed deposits (Binda, 1994). The Ore Shale member is a finely laminated dolomitic siltstone, with lesser carbonaceous shale, argillaceous sandstone, and massive to microbially laminated dolomite (Garlick, 1961a; Annels, 1974; Clemmey, 1974; Fleischer, 1984; Selley and others, 2005); these rock types occur as distinct, mappable facies. Three zones are recognized in the member: (1) a basinal carbonaceous argillite facies to the west of the belt, (2) an argillite-siltstone slope facies, and (3) a littoral facies represented by algal bioherms and sabkha deposits to the east (Annels, 1984). Desiccation cracks in siltstones and mudstones of the Ore Shale member provide evidence for periods of subaerial exposure; variably replaced anhydrite nodules indicate evaporitic conditions (Garlick and Fleischer, 1972). The Ore Shale member is overlain by the middle and upper Kitwe Formation, a ~200-m-thick, commonly cyclical sequence of terrestrial conglomerate and subarkose, and marine-evaporitic argillaceous sandstone, dolomitic siltstone, and massive dolomite (Selley and others, 2005).

The Upper Roan Subgroup is a thick succession of dolomites, with subordinate argillites and breccias; predominance of carbonate strata distinguishes the Upper Roan from the Lower Roan Subgroup (figs. 8 and 9; Selley and others, 2005). Meter-scale, upward-fining cycles of sandstone, siltstone, dolomite, algal dolomite, and local anhydrite are characteristic. Nodules and chicken-wire structures composed of dolomite, talc, quartz, and (or) anhydrite, diagnostic of early diagenetic evaporitic processes in a sabkha environment, are found in dolomites and, to a lesser extent, sandstones and siltstones (Selley and others, 2005).

The Mwashia Subgroup[17] is a shale-dominant sequence overlying the dolomite-dominant succession of the Upper Roan Subgroup (figs. 8 and 9; Mendelsohn, 1961a; Marjonen, 2000; Selley and others, 2005). In the northern Zambian Copperbelt, the Mwashia Subgroup consists of a lower dolomite, an intermediate mixed dolomite-siltstone mudstone, and an upper siltstone-mudstone-carbonaceous mudstone sequence; a breccia occurs at the base of the Mwashia Subgroup.

Correlation of the Roan Group

At the formation level, the Roan successions in Zambia and Zaire are lithologically similar (fig. 9). In particular, the Ore Shale member in Zambia corresponds to the Mines Subgroup in the DRC. The similarities become more pronounced in the upper part of the Roan sequence. Both sequences are characterized by a thick section of carbonate rocks (Dipeta in the Democratic Republic of the Congo and Kanwangungu and Kibalongo in Zambia) overlain by shales (Mwashia Subgroup).

[17]In literature, the unit name is spelled Mwashya when referring to rocks in the Democratic Republic of the Congo and Mwashia when discussing rocks in Zambia. In this report, we use the spelling Mwashia.

Nguba Group

The Nguba Group in the Democratic Republic of the Congo and Zambia is subdivided into two major units, the Muombe (formerly Likasi) and Bunkeya Subgroups (Batumike and others, 2007). The base of the Muombe Subgroup (Ng.1) consists of the "Grand Conglomérat", a regional stratigraphic marker unit correlated to the 750 Ma Sturtian glacial event (figs. 7 and 8). The overlying Kaponda, Kakontwe, and Kipushi Formations are interpreted as "cap carbonates"[18] overlying the diamictites of the Grand Conglomérat. Transgressive shallow-water sequences with clasts derived from northern areas overlie the cap carbonate units. Strata of the Muombe Subgroup overlying the Grand Conglomérat display a regional facies change from clastic sedimentary rocks (sandstones, siltstones, and shales) in the north to dominantly carbonate rocks (dolomite and limestone) in the south. The Bunkeya Subgroup is made up of mostly clastic and dolomitic rocks characterized by an abundance of detrital mafic igneous rock grains.

Kundelungu Group

The Kundelungu Group (Ku) in the Democratic Republic of the Congo is subdivided into three subgroups, Gombela (Ku.1), Ngule (Ku.2), and Biano (Ku.3), in ascending order (fig. 9; Batumike and others, 2007). The base of the Gombela Subgroup is the Kyandamu Formation (Petit Conglomérat), consisting of glacial diamictites that are correlated with the 620 Ma Marinoan glacial event. Dolomites of the overlying Lusele Formation are interpreted as cap carbonates. In southern areas, Kyandamu (Petit Conglomérat) rocks contain clasts derived from the underlying Roan Group (Mwashia) and Nguba successions. The occurrence of these clasts record exhumation and erosion of the Roan Group and Nguba rocks during Kyandamu deposition, consistent with northward vergence of thrusting in the Lufilian Arc (Kampunzu and Cailteux, 1999). Therefore, these clasts, within sedimentary deposits that are correlated with the Marinoan glacial event, provide an age constraint for initiation of compressional tectonics in the Katanga Basin.

The Ngule Subgroup is a sequence of pelites, siltstones, and sandstones (Batumike and others, 2007). The lower two formations of this subgroup, Mongwe (Ku.2.1) and Kiubo (Ku.2.2), were deposited in a shallow-water foreland basin that developed north of the Lufilian Arc and are folded (figs. 7 and 9). The Biano Subgroup (Ku.3) is an arenaceous unit composed of conglomerate, arkose, and sandstone. The uppermost formation of the Ngule Subgroup, the Sampwe (Ku.2.3), and overlying rocks of Biano Subgroup consist of subhorizontal, undeformed, and unmetamorphosed rocks that were deposited in the northernmost foreland basin.

Roan Breccias

Breccias derived from specific stratigraphic units in the Roan Group are an important component of Katangan rock exposures in the Lufilian Arc. The Roan breccias occur in four settings in the Democratic Republic of the Congo (Jackson and others, 2003): (1) regional detachments for anticlines, synclines, overthrusted anticline flanks, or klippen (such as the Kamikongwa Thrust in fig. 10; fig.11); (2) local detachments within klippen (for example, the Mongo Sheet in fig. 10); (3) discordant diapiric intrusions (fig. 12); and (4) oblique, strike-slip fault zones (such as the Monwezi Fault in figure 10). In Zambia, most major stratabound breccia bodies occur within white dolomites of the Upper Roan Subgroup (Binda and Porada, 1995).

The Roan breccias in the Democratic Republic of the Congo are spectacular because clasts range from 1 m to 10 km in size (fig. 10; François, 1973; François and Cailteux, 1981; Jackson and others, 2003). Specific terms are used to describe breccias with large clasts. In a "megabreccia," for example, the largest dimension of clasts is 100 to 400 m (American Geosciences Institute, 2013). Jackson and others (2003) coined the term "gigaclast" for fragments 1 km or more in diameter, with gigaclasts constituting gigabreccias. In French geologic literature, large fragments in the Roan breccias are referred to as "écailles." Depending on the size of the clasts in a given location, the Roan breccias can be described as megabreccia or gigabreccia.

The Roan megabreccias and gigabreccias are derived only from specific stratigraphic units. In the DRC, the dolomitic, stratigraphic interval from R.2 to R.3 occurs only in megaclasts or gigaclasts that are set in a finer breccia matrix consisting of dolomitic, chloritic, talcose siltstone (extent of breccia matrix is shown in fig. 13). The breccia matrix is typically gray or lilac and might contain either sulfide minerals or hematite (François, 1973; De Magnée and François, 1988). Continuous sedimentary layers are delicately preserved in these kilometer-scale slabs. Clast margins are controlled by layering, suggesting that Roan rocks parted along weak interlayers to form the clasts. Rocks higher in the stratigraphic section, beginning with the dolomitic R.4 unit and continuing upward into younger rocks, are not found as clasts within the Roan breccia.

[18]Cap carbonates are unusual deposits of dolomites and limestones, often enriched in barite, which sharply overlie Neoproterozoic glacial deposits (Reitner, 2011).

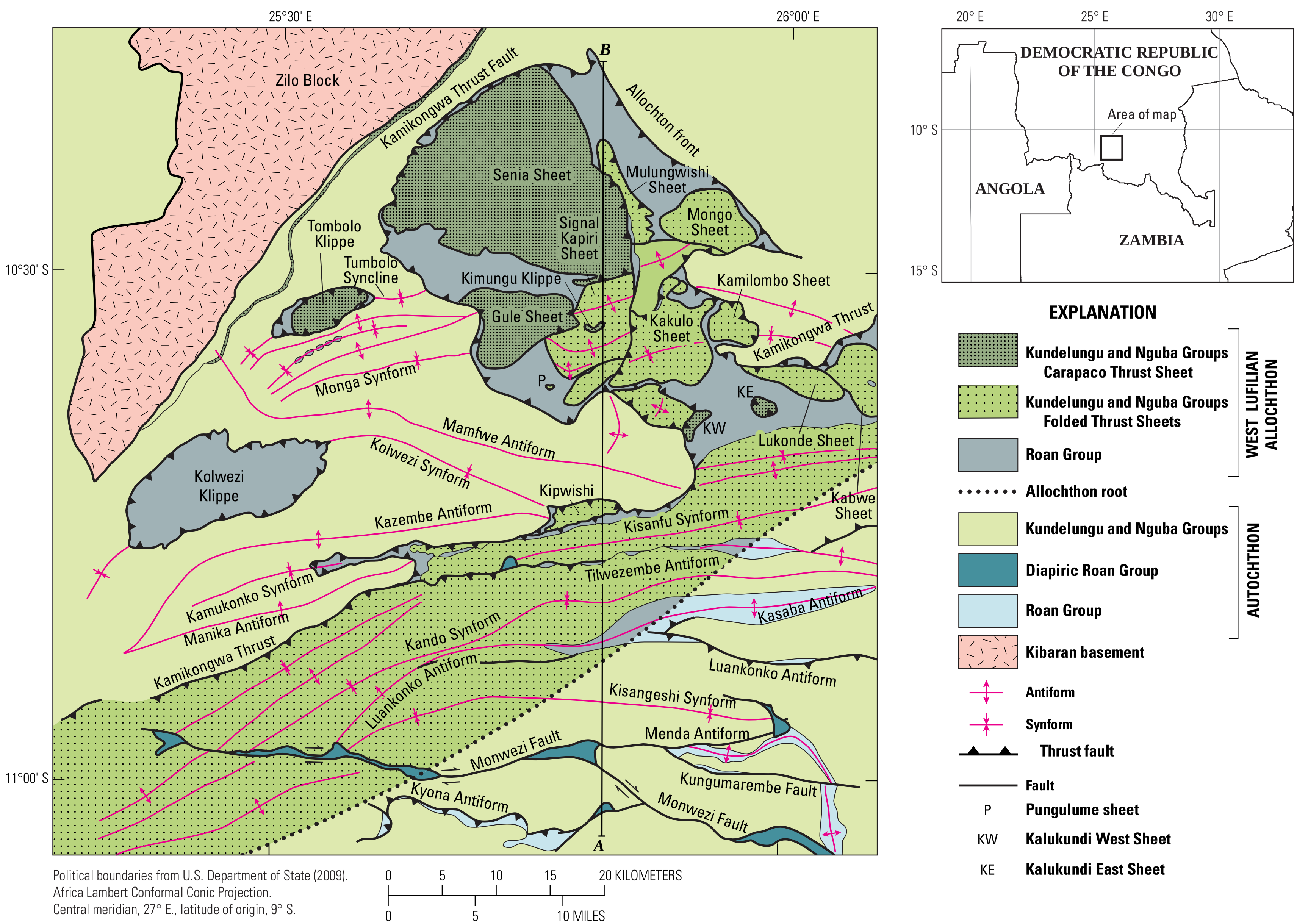


Figure 10. Geologic map of the western end of the External Fold and Thrust Belt, Kolwezi area, Democratic Republic of the Congo. The Roan Group and its associated breccias are associated with allochthons and major regional structures, such as the Monwezi Fault. Modified from Jackson and others (2003). Section A-B shown in figure 19.

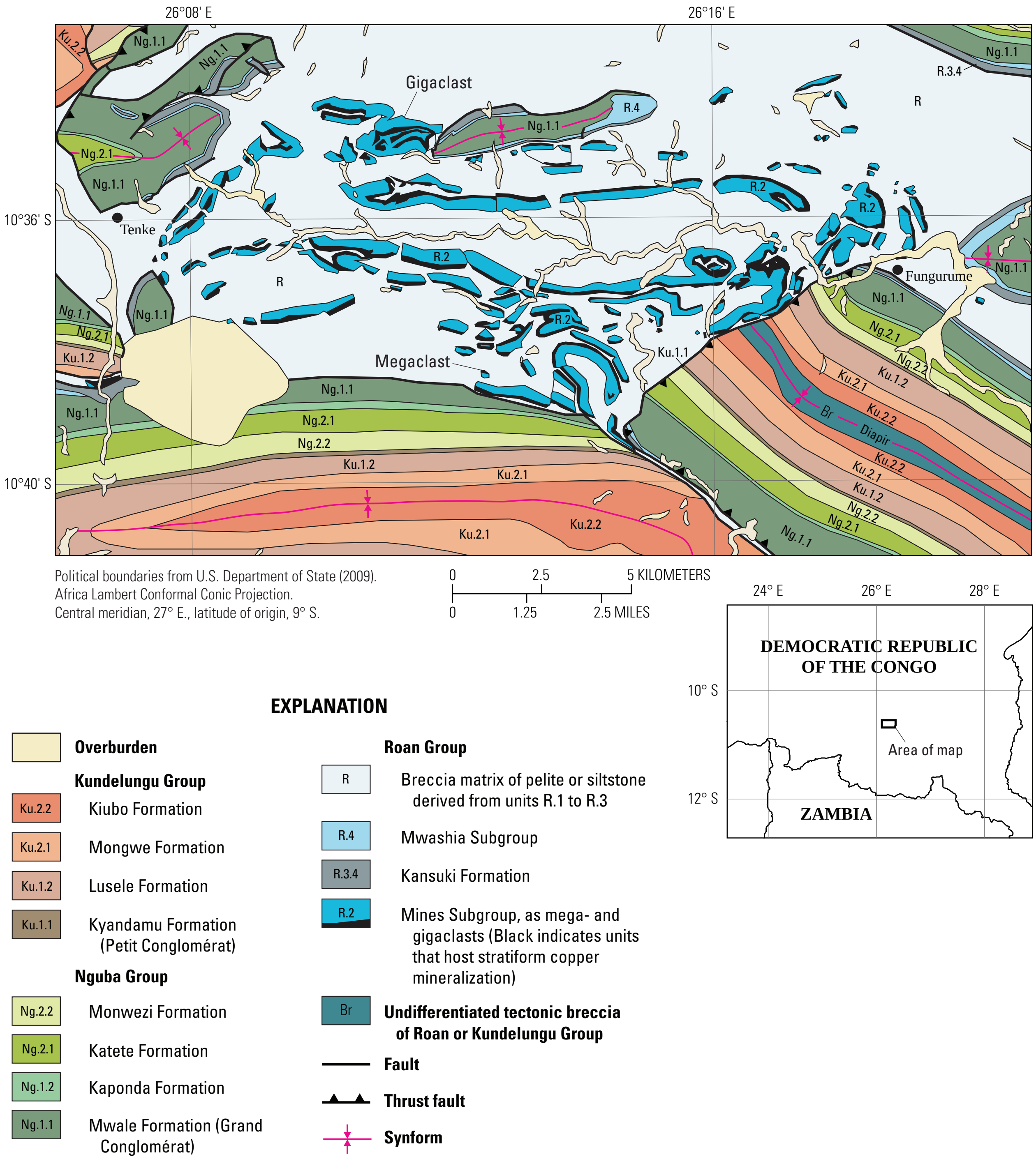


Figure 11. Geologic map of the Tenke-Fungurume area showing exposures of Roan megabreccia and gigabreccia in thrust faults, Democratic Republic of the Congo. The uppermost Roan (R4) is concordant with the overlying Nguba and Kundelungu Groups. In the center of the map, large breccia fragments (megaclasts and gigaclasts) consist of the R2 stratigraphic unit and occur in a breccia matrix of pelite or a dolomitic, chloritic, talcose siltstone (labeled R). Modified from Jackson and others (2003).

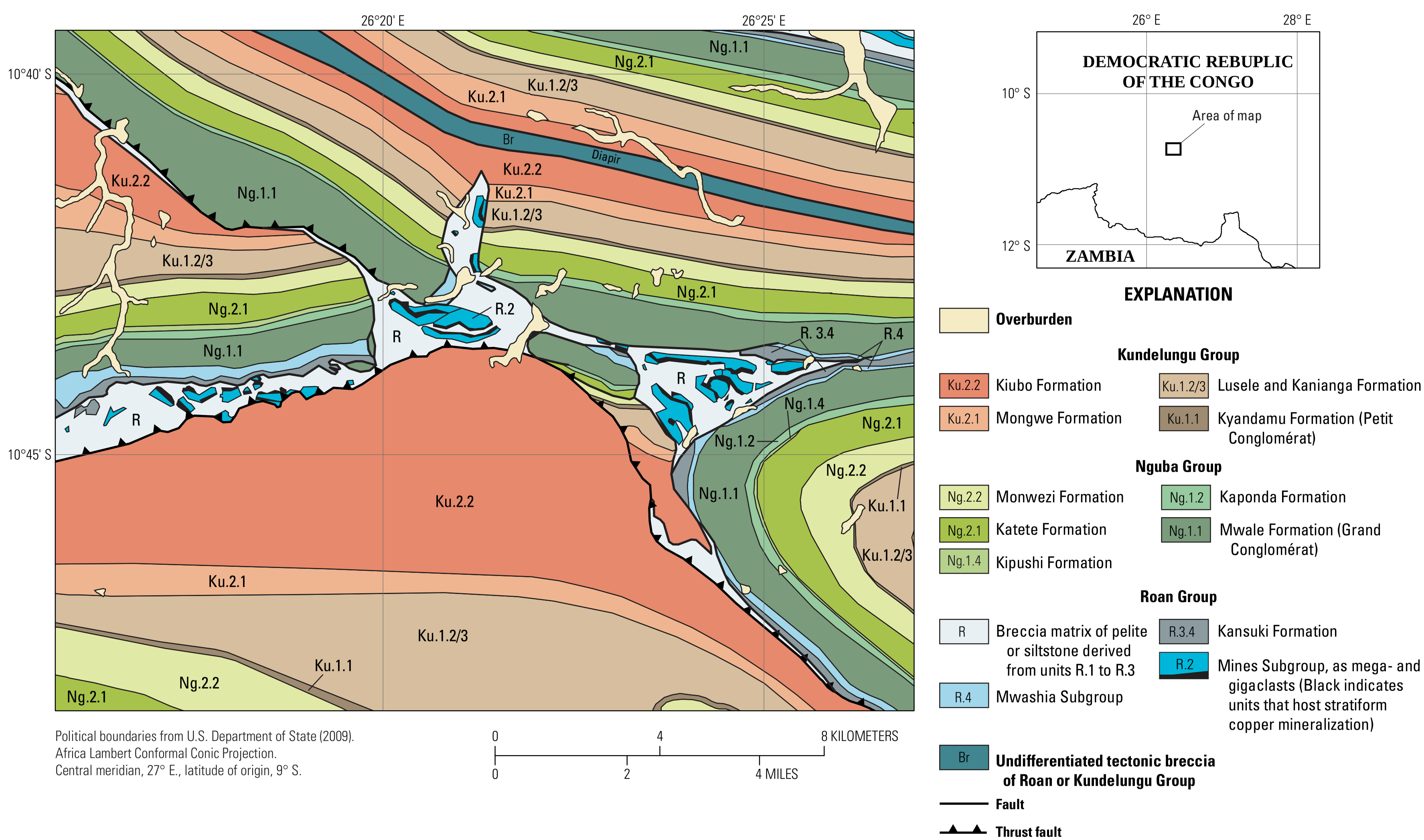
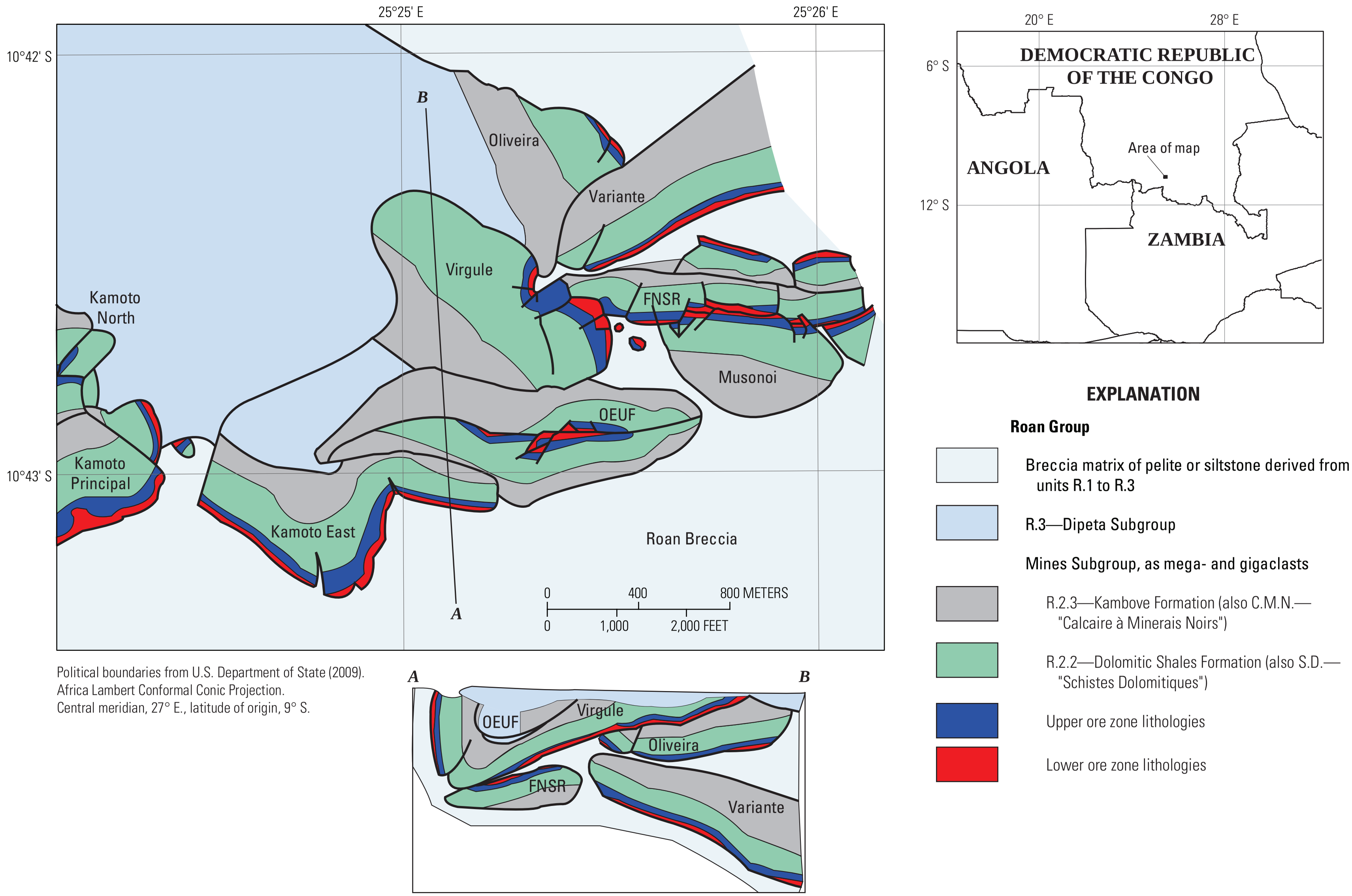


Figure 12. Geologic map of the Mukondo Diapir showing Roan evaporite-related breccia piercing overlying strata of the Nguba and Kundelungu Groups, Democratic Republic of the Congo. Modified from Jackson and others (2003) and Musée royal de l'Afrique centrale (2008).



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 27° E., latitude of origin, 9° S.

Figure 13. Geologic map and cross section of the Kamoto-Oliveira-Virgule (KOV) area, Democratic Republic of the Congo. Sediment-hosted stratabound copper mineralization occurs in large gigabreccia fragments (écaille) of Roan Group strata. On the map and section, each breccia fragment is named (for example, Musonoi or Virgule). Modified from Dixon (2007).

Stratabound and discordant breccias composed of angular to slightly rounded fragments of dolomite and argillite are ubiquitous within the Upper Roan Subgroup in Zambia (Binda, 1994; Binda and Porada, 1995). The breccia matrix consists of carbonate, albite, quartz, anhydrite, and (or) chlorite (Annels, 1984). These breccia units range from centimeters to hundreds of meters in thickness and cut down through lower stratigraphic units to the south and west. The breccia zones have received little study; in drill logs and exploration reports, brecciated intersections are described by a variety of terms, such as breccia, breccio-conglomerate, pseudo-conglomerate, and hybrid rock, suggesting different types of breccia with different origins (intraformational, collapse, and tectonic) (Binda, 1994; Binda and Porada, 1995). In the Mufulira area, two types of breccia are described. One type contains large and small angular fragments of shale or argillite that appear to be disrupted. A second, more abundant type of breccia, consists of heterogeneous, subangular to rounded fragments of shale, dolomite, and chert that are 0.3 to 10 cm in size within a sandy or gritty, argillaceous, dolomitic matrix. Thick bodies of this breccia are either lenticular or transgressive to the bedding or both; adjacent beds are broken and brecciated to some extent (Binda and Porada, 1995). Binda and Porada (1995) suggest that some of the breccias are related to important tectonic dislocations.

The genesis of the Roan breccias could be related to the former presence of salt within the Roan carbonate succession. The R.2 and R.3 units might have been interlayered with significant accumulations of salt beds (De Magnée and François, 1988; Jackson and others, 2003). In the DRC, deformation of the salt layers formed diapirs, salt walls, extrusions, thrust sheets, and fault-cored anticlines above a regional detachment surface produced by thrust faulting during the Lufilian Orogeny (Garlick and Fleischer, 1972; Jackson and others, 2003). The formation of salt diapirs requires a minimum thickness of approximately 500 m of halite (Warren, 1999; Selley and others, 2005). During halokinesis, dolomitic formations or other competent units were broken into fragments and the salt was subsequently dissolved. In Zambia, the generally stratiform geometry of breccia bodies suggests a relatively thin (<500 m) salt accumulation in rocks of the Upper Roan Subgroup (Selley and others, 2005). Derivation of most breccias in the Upper Roan Subgroup in Zambia would have resulted from salt dissolution.

The former existence of evaporites in the Roan Group is supported by paleogeographic reconstructions, the occurrence of rocks normally associated with salt beds, and geophysical surveys. During the Neoproterozoic, several of the basins surrounding and within the Congo Craton formed in an extensional context and developed partly in a restricted coastal plain (Kadima and others, 2011). Plate tectonic reconstructions indicate that the Congo Craton was at latitudes that favored evaporation (Hanson, 2003). Shallow carbonate shelf deposits that include evaporitic strata are found in the West Congolian Group, strata of the Mbuji-Mayi Basin, and the Roan Group (Raucq, 1957; Jackson and others, 2003; Delpomdor and others, 2008; Préat and others, 2010). Well and geophysical evidence suggests the presence of deeply buried evaporites in the Neoproterozoic sedimentary section in the Congo Basin (Kadima and others, 2011).

The earlier existence of evaporites with salt in the Roan Group is supported by sedimentary sequences and textures. The stratigraphic discontinuities marked by breccias in the Roan stratigraphic sequence appear to have formed by dissolution of evaporite intervals (Garlick and Fleischer, 1972; Cailteux, 1983; Cluzel, 1986; De Magnée and François, 1988). The presence of laminates, algal mats, and dolomites are indicative of deposition within coastal sabkhas. In addition, anhydrite and pseudomorphs of gypsum and anhydrite are preserved in some rocks.

Sediment-Hosted Copper Mineralization

Sediment-hosted stratabound copper mineralization occurs throughout the Katangan stratigraphic section but most of the deposits and occurrences are found in the interval between the red beds and overlying reduced rocks of the Roan Group (table 2). Sediment-hosted copper deposits and occurrences are also found within the Grand Conglomérat (Mwale Formation, fig. 14) (Broughton and Rogers, 2010a,b) and some horizons in unit Ks.l.2, at the base of Ki.2, and in Ks.2. (François, 1974). The focus of this assessment report is the potential for undiscovered copper mineral resources within the Mines Subgroup in the Democratic Republic of the Congo and the Lower Roan Subgroup in Zambia; the potential for copper resources in other stratigraphic settings is not assessed herein.

Host beds for reduced-facies copper deposits in many sedimentary basins occur at or just above the flooding surface that marks the transgression between a marine or lacustrine depositional sequences and underlying synrift, nonmarine red beds. In the Katanga Basin, this depositional setting corresponds to the transition between the Mines Subgroup and the underlying lilac R.A.T. in the Democratic Republic of the Congo, and the Kitwe and Mindola Formations in Zambia. The Roan Group in Zambia also has sandstone copper deposits within red beds that underlie the flooding surface. The following information on mineralization in the Roan Group is paraphrased from descriptions in Cailteux (1994), Cailteux and others (2005a), and François (1974, 2006).

In the Democratic Republic of the Congo, most of the known deposits and prospects are within two stratigraphic intervals below and above the R.S.C. member of the Kamoto Formation in the lower part of the Mines Subgroup (fig. 15).

Table 2. Number of deposits and occurrences identified in the Katanga Basin, Democratic Republic of the Congo, in 1974.

[From Francois, 1974. See figure 9 for explanation of stratigraphic unit abbreviations]

Stratigraphic unit	Deposit—certain	Deposit—probable	Deposit—possible	Simple indications	Total
R.1	4	0	0	2	6
R.2	60	7	21	44	132
R.3	4	3	5	17	29
R.4.1	2	2	1	9	14
R.4.2	0	0	1	4	5
Ki.1.1	0	0	0	2	2
Ki.1.2.1	0	0	0	1	1
Ki.1.2.2	2	0	0	1	3
Ki.1.3	0	0	0	3	3
Ki.2	0	0	1	9	10
Ks.1.1	0	0	0	3	3
Ks.1.2.1	0	0	0	2	2
Ks.1.2.2	0	0	0	1	1
Ks.1.3	0	0	0	3	3
Ks.2	0	0	2	10	12
tectonic breccia	0	0	0	7	7
unknown	0	0	0	3	3
Total	72	12	31	121	236

Stratiform copper mineralization is also found higher in the Mines Subgroup, within the Dolomitic Shales (R.2.2) and the Kambove (R.2.3) Formations. Within the Dolomitic Shales Formation, finely disseminated chalcopyrite occurs in three units of black carbonaceous shale. The copper grades are generally low, approximately 0.5 percent. Sparse amounts of disseminated chalcopyrite or carrollite are observed in dolomites of the Kambove Formation.

The richest mineralization is within the first stratigraphic transition in the Katangan section from red or purple strata (anoxidized) upwards into gray strata (oxidized), which in the DRC occurs in the stratigraphic interval between the R.A.T. Subgroup and the Mines Subgroup. These two stratigraphic intervals, each about 10 m thick, can be mineralized, forming a lower and an upper ore body in some areas. At the base of the Mines Subgroup, the lower ore-bearing interval consists of about 2 m of dolomitic sandstone (R.A.T. grises) overlain by about 8 m of gray, finely bedded, siliceous dolomite (D. Strat. + R.S.F.). These rocks are overlain by a massive, light-colored, algal dolomitic biostrome (R.S.C.), 0 to 25 m thick, which is practically devoid of mineralization. The overlying unit (S.D.B.), 5 to 10 m thick, consists of finely stratified gray dolomitic siltstone that is locally mineralized and forms the second ore interval.

In plan view, the stratigraphic intervals on either side of the R.S.C. unit are not uniformly mineralized. Areas with copper-cobalt mineralization are separated by large expanses of pyrite-bearing rocks that might contain some chalcopyrite and carrollite. The areal extent of copper-cobalt mineralization in the lower ore interval is almost always greater than that of the upper one.

The mineralogy of areas having economic concentrations of copper includes fine-grained chalcocite, with some bornite and carrollite; the gangue is dolomitic. These rocks contain approximately 4.5 percent copper and 0.2 percent cobalt. Copper sulfide minerals are typically localized within finely and regularly bedded units. Carrollite can be found in the massive dolomites, between the ore bodies (R.S.C.), or just above the upper mineralized ore unit in an interval called "black ore main zone" or "BOMZ" (François, 2006).

Most ore deposits in the Zambian Copperbelt occur within an approximately 200-m-thick stratigraphic interval of siliciclastic-dominated strata of the Lower Roan Subgroup roughly centered on rocks of the Ore Shale member (fig. 16). Exploration in Zambia traditionally has focused on this interval. The following material is paraphrased from descriptions in Selley and others (2005).

Reduced-facies deposits within the Ore Shale member are laterally extensive, with strike lengths up to 17 km. All deposits occur in a 10- to 20-m-thick interval within the lower part of the Ore Shale member. The host rocks typically are intercalated dolomitic siltstones and thin sandy argillites, but ores are also found in carbonaceous mudstones and siltstones.

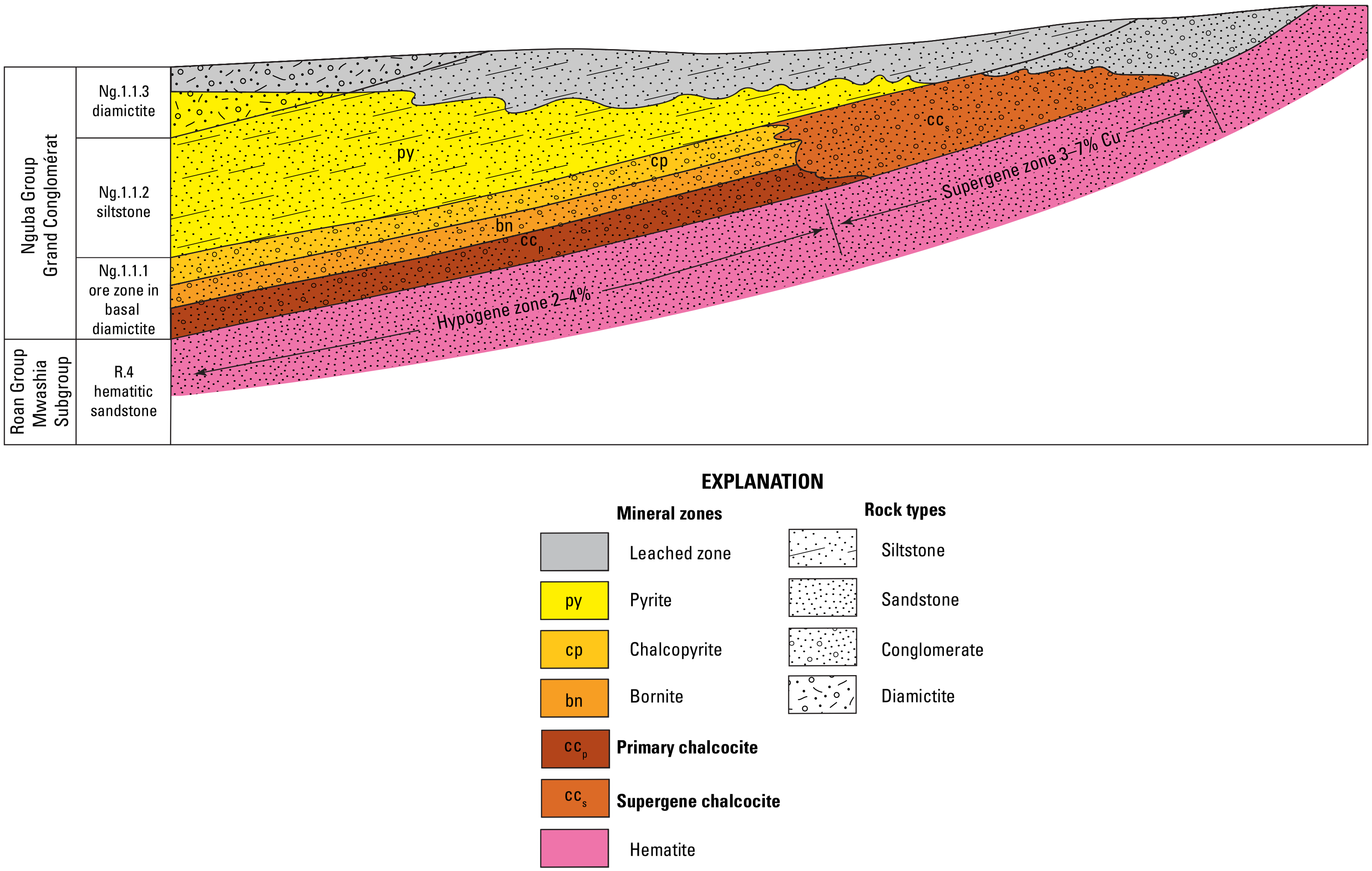


Figure 14. Geologic cross section of the Kamoa deposit, Democratic Republic of the Congo, showing sediment-hosted stratabound copper mineralization associated with the Grand Conglomérat. Modified from Broughton and Rogers (2010a).

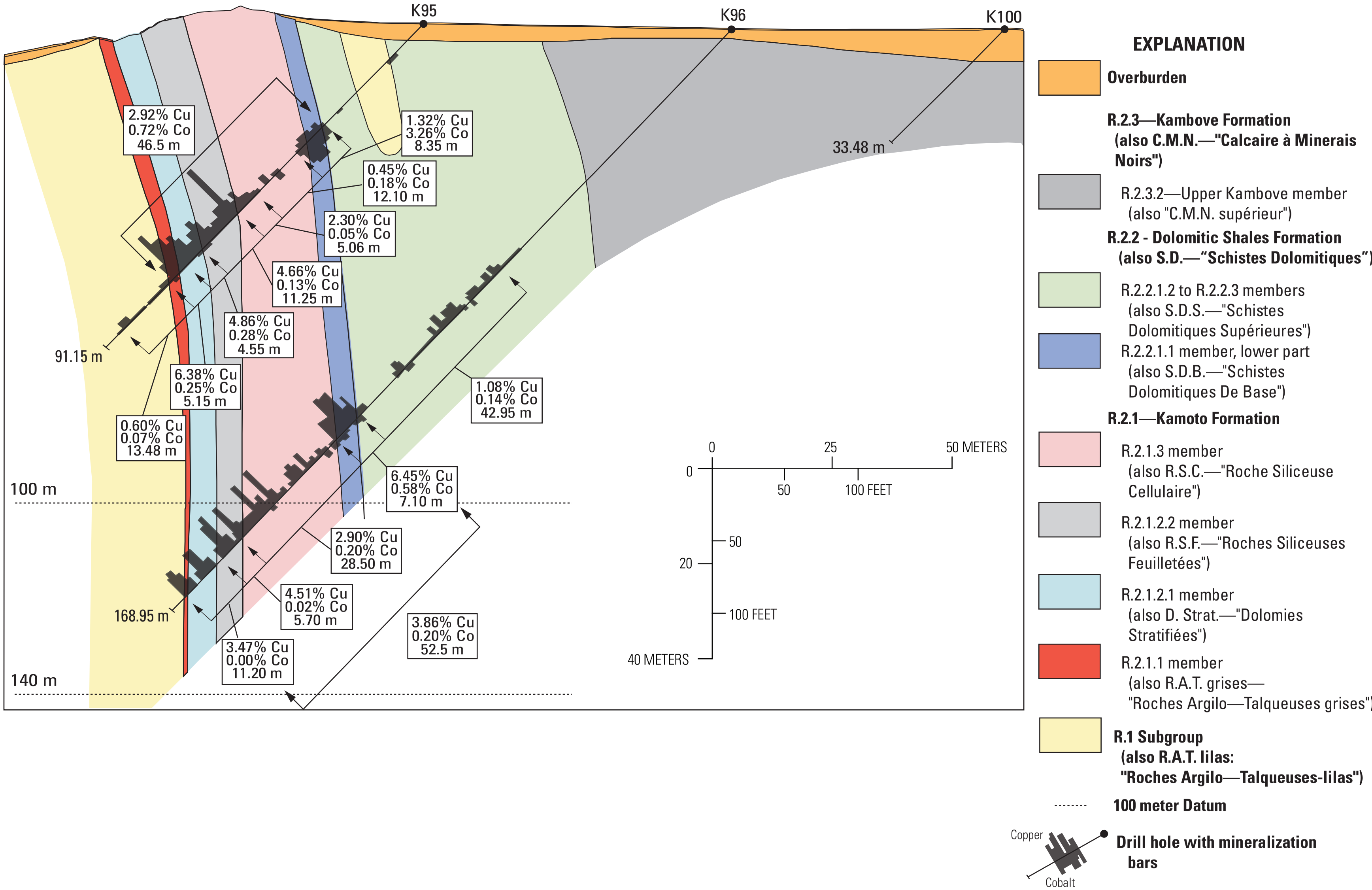


Figure 15. Geologic cross section of the Kalukundi deposit that shows the concentration of copper and cobalt mineralization near the upper and lower contacts of the R.S.C. member of the Kamoto Formation, Democratic Republic of the Congo. High-grade oxide cobalt mineralization is restricted to the near surface. Modified from Africo Resources Ltd. (2008).

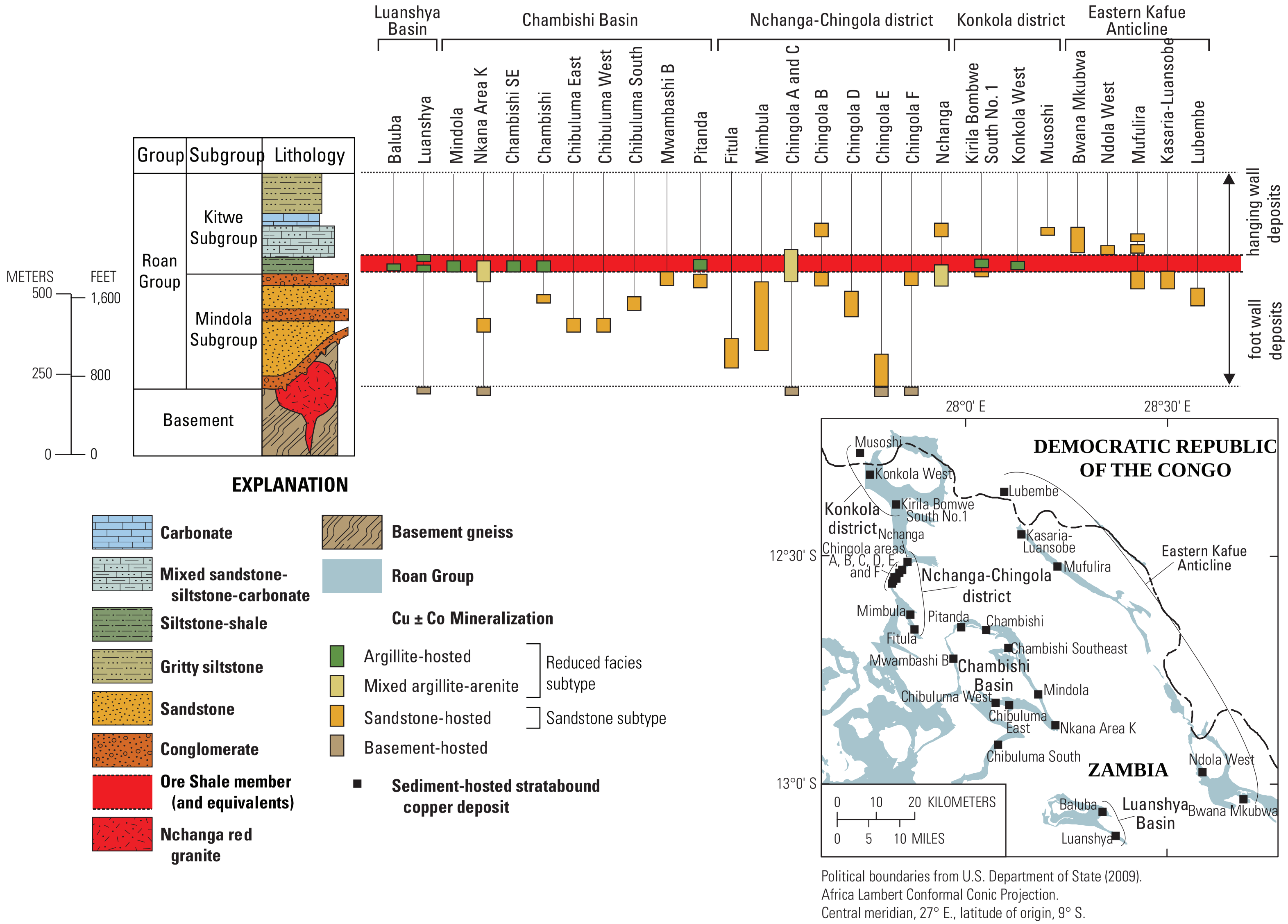


Figure 16. Stratigraphic column of the Roan Group exposed in the Zambian portion of the Central African Copperbelt showing the stratigraphic distribution of reduced-facies (argillite-hosted and mixed argillite-sandstone) and sandstone (arenite-hosted) mineralization. Modified from Selley and others (2005).

Sandstone-type copper deposits with maximum strike lengths of 5 km occur in the footwall and hanging wall of the Ore Shale member. Footwall deposits can either directly underlie rocks of this member or be stratigraphically separated from them by barren sandstones and conglomerates. Hanging-wall ore bodies are less common and are stratigraphically separate from the Ore Shale member. Giant ore deposits, such as Mufulira and Nchanga-Chingola, comprise multiple, vertically stacked ore bodies that occur in both footwall and hanging-wall positions. Interstitial carbonaceous matter in the ore bodies at the Mufulira deposit and the strongly negative carbon isotope values of carbonate gangue at the Mufulira and Mwambashi B deposits provide indirect evidence for the involvement of hydrocarbons in the mineralizing process. Two potential hydrocarbon sources include the Ore Shale member or hydrocarbon source rocks that were located in a different part of the Katanga Basin, outside of the Zambian Copperbelt.

Hypogene ore mineralogy of the Zambian Copperbelt includes chalcocite, bornite, chalcopyrite, pyrite, and carrollite. Lateral and vertical sulfide zoning characterizes many Zambian deposits, particularly the reduced-facies deposits within the Ore Shale member (Mendelsohn, 1961a,b; Fleischer and others, 1976). These deposits generally show an east to west lateral zonation from bornite (±chalcocite), through chalcopyrite (±carrollite), to pyrite (±pyrrhotite, local minor sphalerite). The pyritic zone coincides mostly with the carbonaceous facies of the Ore Shale member (Mendelsohn, 1961a,b, 1989; Fleischer and others, 1976). A vertical zonation is present within the reduced-facies deposits, from bornite (±chalcocite) at the base, through chalcopyrite, to pyrite at the top. Arenite-hosted ore bodies exhibit similar copper-(cobalt) sulfide zoning.

Age of Copper Mineralization

A six-point Re-Os isochron on disseminated chalcopyrite and bornite from Konkola with a slope age of 816±62 Ma is consistent with the deposition of diagenetic mineralization in host rocks deposited after 883±10 Ma (age of basement Nchanga red granite: Armstrong and others, 2005) and before Sturtian glaciation at ~740 Ma (Barra and others, 2004; Selley and others, 2005). A Re-Os age on typical stratiform sulfides at Konkola indicates diagenetic mineral formation at ~800 Ma (Barra and others, 2004). A minimum age of 645±15 Ma was determined for copper-sulfides in disseminated ores from the Musoshi deposit, DRC (Richards and others, 1988a). These samples were free of veinlets and least recrystallized, as well as free from coarse biotite.

Other age dates obtained on mineralized material from Zambia and the DRC span the entire duration of the Lufilian Orogeny and record remobilization of sulfide minerals during metamorphism and deposition. A five point isochron with analyses from the Nkana, Chibuluma, and Nchanga deposits, Zambia yields an age of 583±24 Ma (Barra and others, 2004). This age overlaps ages of earliest biotite and monazite (~590–580 Ma) in the Zambian Copperbelt (Rainaud and others, 2005), as well as the synorogenic Hook batholith in the southern Lufilian Arc (~560 Ma). Vein and veinlet-controlled mineralizing events in the Central African Copperbelt are younger. Barra and others (2004) determined an age of 525.7±3.4 Ma by Re-Os for molybdenite from a chalcopyrite-bearing vein that cuts stratiform mineralization at the Nkana-Mindola deposit. Richards and others (1988b) obtained an age of 514±2 Ma by U-Pb for rutile in quartz-hematite-(microcline-biotite-rutile) veins with late calcite, siderite, anhydrite, and barite that cut stratiform copper ore at Musoshi. Richards and others (1988a) corroborated the late overprinting vein event with a date of 514±3 Ma on uraninite from a crosscutting veinlet at Musoshi. Two pulses of vein-hosted mineralization at the Kansanshi copper deposit, Zambia, have been determined, one at ~512 Ma and another at ~502 Ma (Torrealday and others, 2000). These later dates reflect events that are younger than peak metamorphism and postdate folding.

Weathering of Copper Deposits

Weathering profoundly alters the mineralogy of the copper ores in the Democratic Republic of the Congo and preferentially concentrates copper and cobalt (François, 2006). The weathered upper parts of the copper deposits contain ores having up to 20 percent copper and 5 percent cobalt. The weathering extends to depths of 400 m; sulfide minerals are found just below the water table.

Heterogenite is concentrated near the surface (fig. 15, drill hole K95). Copper is more mobile than cobalt in meteoric surface conditions, moves downward, and precipitates along the water table. Malachite is found in the subsurface in dissolution voids within Neoproterozoic carbonate rocks. From the surface downwards, the following sequence is observed:

- Barren, leached material (up to few meters thick).
- Heterogenite in siliceous clay gangue.
- Malachite and heterogenite in siliceous clay gangue.
- Malachite, heterogenite, copper silicates, cobalt carbonate, and traces of copper sulfide minerals in dolomite gangue. Chalcocite breaks down and copper is re-precipitated in malachite and chrysocolla. Not far from the surface, all dolomite in the gangue is completely removed.
- Copper sulfide minerals, malachite, and heterogenite in dolomitic gangue. Carrollite quickly alters to heterogenite.
- Unweathered copper and cobalt sulfide minerals.

Similar to the deposits in the DRC, secondary supergene and oxide ore minerals are developed from the weathering of hypogene sulfide minerals in the Zambian deposits. The transition from primary sulfide to mixed oxide-sulfide assemblages typically occurs within 30 to 70 m of the surface (Mendelsohn, 1961a,b), although malachite and chalcocite extend to vertical depths of >1 km at the Konkola deposit, and >600 m in the Nchanga Lower ore body (McKinnon and Smit, 1961). Leached caps, where selected metals are removed by weathering processes, reach a thickness of 30 m.

Early Work and Exploration History

The Colonial Period

Precolonial mines in Katanga were first visited by German and Belgian scientific expeditions in the 1880s and 1890s; sites at Djoa, Kalabi, Kamare (current name: Kamwali), Kiola, Lusuichi (current name: Luiswishi), Kimbuie and Inambuloa (current name: Kamdumba and Kamare), Kioabanan, Miambo, Mount Kambobe (current name: Kambove), and Mount Kitulu are specifically mentioned in field records and survey publications (Pirard, 2011). The basic stratigraphy of the Katangan sequence was published by Jules Cornet (Cornet, 1894). A geologic map accompanied by an explanation of the geology, tectonics, and morphology of Katanga, and a description of mineral deposits, was published by Studt and others (1908).

Systematic exploration started soon thereafter and was organized by various groups including the Comite Special du Katanga (CSK) and Tanganyika Concessions Ltd (TCL). By 1906, Tanganyika Concession prospectors located more than 100 old copper workings on the Belgian side of the border, including sites that now are considered major deposits (Gunning, 1961). Ancient mine workings at the site of the Etoile (The Star of the Congo) mine comprised a pit 1,200-m-long, and 183- to 304-m-wide (Walker, 1927; Pirard, 2011). By 1904, resources of 6 to 15 million metric tons of copper were estimated from outcrop data and exploration drilling, respectively (Pirard, 2011). Union Minière du Haut Katanga (UMHK) was formed to operate mines on the deposits that had been discovered in what is now the Democratic Republic of the Congo (Gunning, 1961).

We did not find summaries of exploration methods used by UMHK in the first half of the last century; however, systematic exploration was conducted throughout the Katangan Copperbelt from the 1920s through the 1970s. Some insights on geologic mapping are provided by notes that accompany the 1:100,000-scale map of the Kolwezi-Kalukundi area of the Katangan Copperbelt (François and Lepersonne, 1978). Mining areas were mapped at 1:1,000-scale using information from small pits, trenches, and surveys. Small-scale mapping was conducted from the 1920s to the 1950s. Among mining areas in the Katangan Copperbelt, maps were compiled at a scale of 1:20,000. Outside the arc defined by the copperbelt, maps are based on controlled aerial photo-interpretation at a scale of 1:45,000.

The Kolwezi-Kalukundi map was compiled in the early 1970s and published by the Musée royal de l'Afrique centrale (Royal Museum of Central Africa). This appears to be one of three 1:100,000-scale sheets compiled for the Katangan Copperbelt north of latitude 11º S (fig. 17). The second 1:100,000-scale map, Likasi, was published by the museum in 2004. In 2008, the museum published a 1:500,000-scale map of the copperbelt (Musée royal de l'Afrique centrale, 2008); from the resolution of the linework and information in the attribute table, a third unpublished 1:100,000-scale map (Shaba Northeast) was used in the compilation. Lower resolution sources of information were used for areas south of 11º S latitude.

In 1902, prospectors with the Rhodesian Copper Company were guided to ancient workings that are now the Roan Antelope and Bwana Mkubwa mines in Zambia (Coleman, 1971). Two abandoned workings, parallel to each other, were found on the slope of a kopje (hill) at Bwana Mkubwa. The largest is about 685 m long and varies in width from 1.5 to 7 m. In 1903, prospectors were led to old workings at the site of the Chambishi mine (Gunning, 1961).

In the 1920s, 30s, and 40s, organized, systematic geologic mapping and exploration was conducted throughout the Zambian Copperbelt. Field mapping was done by running systematic traverses; data were recorded on field sheets at a scale of 1 inch to ½ mile (approximately 1:31,680) and were compiled on maps with a scale of 1 inch to 2 miles (1:126,720). Traverses across the strike of the rocks of the Mines Subgroup were spaced at ¼ mile (402 m) intervals. In a 15-year time frame, 156,000 square miles (404,038 square kilometers) were mapped and prospected and 584 occurrences of mineralization were recorded and indicated on geologic maps. Most of the mines and a number of prospects were discovered and partly explored under these programs (Mendelsohn, 1961a, p. 166–167).

Soils are deep in most of the areas underlain by Katangan rocks in Zambia; outcrop represents less than 1 percent of the total surface area. Geochemical methods were applied to residual soils to prospect for mineralization. In their concession area, Chartered Exploration collected and analyzed 250 thousand soil and stream sediment samples over an area of 8,000 square miles (20,720 square kilometers) of subcropping Katangan rocks (Cornwall, 1961). Rhodesian Selection Trust applied geochemical methods to 620 square miles (1,605 square kilometers) on the copperbelt, testing nearly 1,250,000 samples for copper, cobalt, nickel, and zinc (Garlick, 1961b).

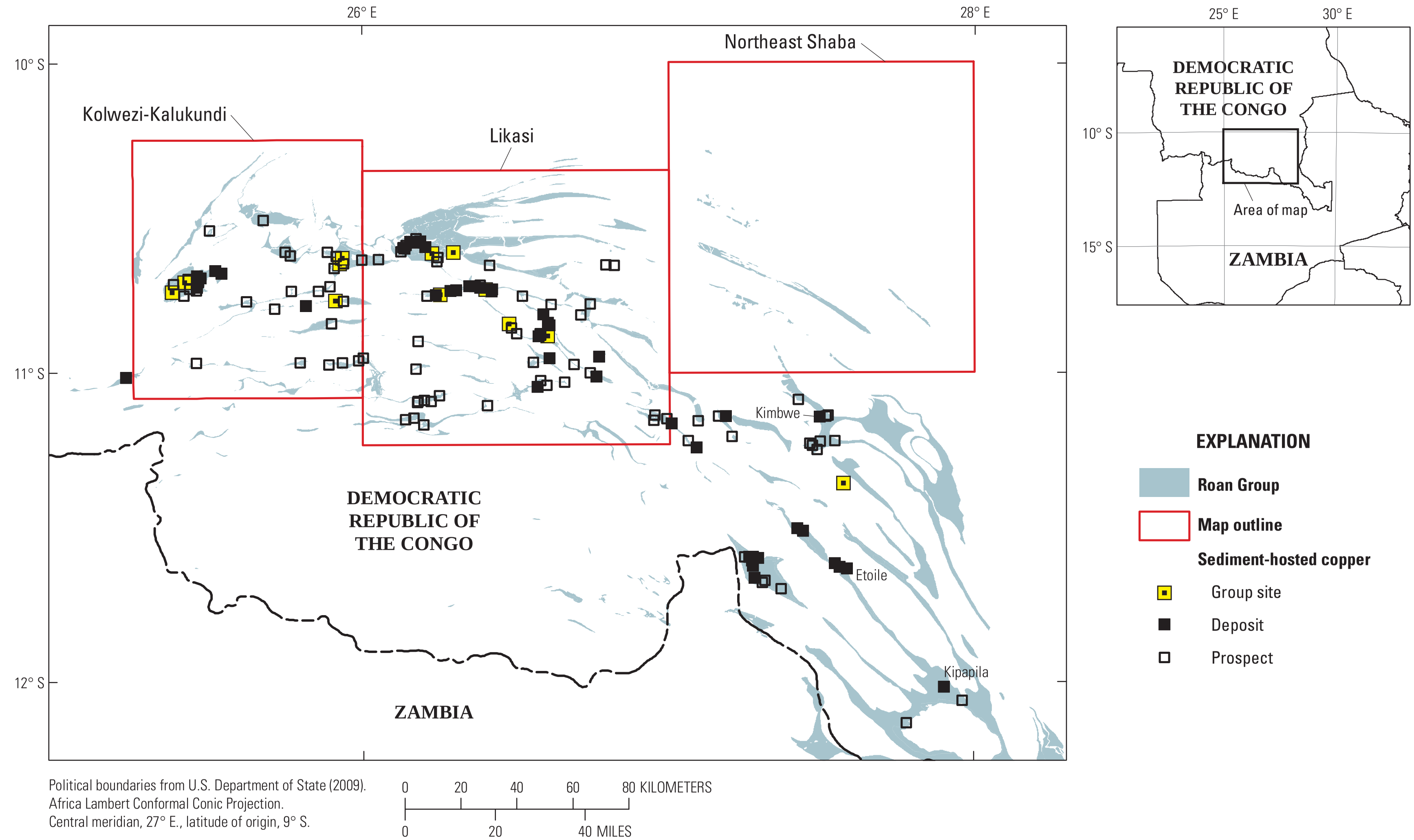


Figure 17. Map showing the location of 1:100,000-scale geologic mapping in relation to exposures of the Roan Group and associated sediment-hosted stratabound copper deposits. Roan outcrops from Musée royal de l'Afrique centrale (2008).

Independence

Belgium granted independence to its former colony in 1960. In 1967, Union Minière du Haut-Katanga was nationalized, leading to the creation of La Générale des Carrières et des Mines (Gécamines), a state-owned metal mining and producing company. In 1991, civil unrest led to the expulsion of many Kasai-originating Baluba tribe members from Katanga and evacuation of some 20 thousand foreigners. Civil war between 1996 and 2001 further disrupted society and the economy. The war ended in 2002 and the transitional government proposed new laws on foreign investment and mining. With the support of the World Bank, Mining Code and Mining Regulations were adopted in 2002 and 2003, respectively (André-Dumont, 2011). Since 2000, Gécamines entered into about 28 partnerships to increase production; the company retains minority interest in each component business (typical 25 to 30 percent; République Democratique du Congo, Ministère des Mines, 2011).

The developments following independence had a tremendous impact on copper production in the DRC. In 1959, the country's copper production was close to 300 thousand metric tons per year. In the 1980s, copper production (all by Gécamines) amounted to approximately 400 thousand metric tons per year, with a peak of about 475 thousand metric tons in 1986. Gécamines produced 200 thousand metric tons in 1991, only 35 thousand metric tons in 1994, and no more than 20 thousand metric tons in 2002. As a result of the partnerships, total copper production increased to about 300 thousand metric tons per year by 2008 and 2009, and reached nearly 500 thousand metric tons in 2010.

Zambian copper production was also affected by events following independence. From the start of industrial mining in Zambia in the 1930s to the early 1960s, copper production increased annually to just over 640 thousand metric tons (Mining Journal, 2008; Limpitlaw, 2011; Keung, 2012). After Zambia gained independence in 1964, copper production continued to increase. In 1969, Zambia's two main copper producing companies were nationalized: Roan Selection Trust became Roan Consolidated Mines Ltd (RCM) and Rhodesian Anglo American Corporation became Nchanga Consolidated Copper Mines. In the year they were nationalized, the mines produced at least 720 thousand metric tons of copper. By the mid-1970s, the mines had poor profitability, which ultimately resulted in a merger of the two companies into Zambia Consolidated Copper Mines (ZCCM) in 1982. In 1984, Zambia's economy went into a depression. Structural reforms of the mining industry took place between 1991 and 2001. Privatization of ZCCM started in 1996; currently, the Government of Zambia retains a minority interest in most of the large projects and mines. Mine production recovered from 249 thousand metric tons in the year 2000 to 686 thousand metric tons in 2010. By the end of the 1990s, most operating mines were privatized and little exploration had been carried out for the previous 25 years. The Mines and Minerals Development Act, enacted in 2008, simplified licensing procedures, placed minimum constraints on prospecting and mining activities, and created a favorable investment environment. Exploration and development activities have since increased.

The stabilization of political and economic conditions in the Democratic Republic of the Congo and Zambia, together with revisions to mining laws in both countries, has led to a resurgence of exploration activity in the copperbelt, particularly in the DRC. Opportunities and risks for mineral investment in the Democratic Republic of the Congo and Zambia are summarized by Mining Journal (2008, 2010), Lydall and Auchterlonie (2011), and Tambwe (2012). At least fifty publicly traded or privately held exploration and mining companies have been active in the Democratic Republic of the Congo and Zambia in the past decade. The majority of the companies are registered in Canada, but firms from Australia, China, South Africa, Switzerland, the United Kingdom, and the United States of America are also active in the region.

Assessment Data

Availability of useful, relevant, and public-domain geologic information is a major factor in being able to properly assess mineral resources (Penney and others, 2007). This assessment is based largely on public domain geologic and mineral occurrence information collected and compiled prior to the mid-1970s. Mineral occurrence data are supplemented by information published after 2000 in technical reports released by publicly traded exploration and mining companies.

The paucity of public domain geologic databases reflects the reality that most geological investigations in the first half of the last century in the Democratic Republic of the Congo and Zambia were conducted by colonial mining companies. Results of this work remain largely unpublished except for summary articles and regional map compilations. The Zambian Geological Survey Department was not established until 1952 and is now publishing 1:100,000-scale geologic maps. Many of the 1:100,000-scale copperbelt maps published by the Zambian Geological Survey in the 1990s and 2000s are based on field mapping and compilation conducted in the 1960s and early 1970s. Licensed geologic maps and minerals information for the Democratic Republic of the Congo are available from the Royal Museum for Central Africa.

For publicly traded companies, scientific or technical information related to recent exploration activities can be found in prospectuses filed with an initial public offering of stocks and, for firms listed on stock exchanges overseen by the Canadian Securities Authority, technical reports required by Canadian National Instrument 43-101 (NI 43-101). The U.S. Securities and Exchange Commission requires similar reports for companies listed on stock exchanges in the United States. A limited number of Competent Persons Reports are available for firms listed on the Johannesburg Stock Exchange. These reports provide useful information on advanced exploration projects and were essential in updating the database of known deposits and their mineral inventory (Taylor and others, 2013). However, companies are not required to release data from geologic mapping or geochemical or geophysical surveys. In addition, there are no requirements for privately owned companies to release any information on their properties.

Geologic Maps

The geologic maps used in this assessment are based on detailed mapping in and near mineralized rocks and reconnaissance mapping based on geologic traverses and airphoto interpretation (appendix C). The scales of the maps range from 1:100,000 to 1:500,000.

Mineral Occurrence Data

The deposits and prospects relevant to the assessment of undiscovered resources in the Roan Group are given in appendix D and in the GIS that accompanies this report (appendix B). Group sites in the database were created by merging records for multiple deposits using a 500-m aggregation distance, measuring either from the edge of an ore body polygon or between points representing deposit locations (Zientek, Hayes, and Taylor, 2013). After applying the spatial aggregation rule, there are 20 sites that represent groups of deposits that occur within the spatial aggregation distance, 65 deposits that fall outside the spatial aggregation distance, and 102 prospects. Significant deposits, defined as those having at least 2 million metric tons of contained copper, are listed in table 3. In addition to the Esri point shapefile of the deposit groups, individual deposits, and prospect locations, a spatial database of ore body polygons was created from information published in the scientific literature and in company technical reports. The outline of open-pit mines was digitized from Google Earth™ imagery to produce another GIS polygon layer that could be used for assessment evaluation. All three Esri files are described by Parks and others (2013) and in appendix B.

Geochemistry and Geophysics

Geochemical and geophysical techniques were used early in the exploration of the copperbelt in Zambia and case studies are presented in Mendelsohn (1961a). Similar exploration techniques were likely used in the Democratic Republic of the Congo. Beginning in the early 2000s, mining and exploration companies used state-of-the-art geochemical and geophysical prospecting methods in both the Democratic Republic of the Congo and Zambia. Results of some of these surveys have been mentioned in case studies of mineral discovery (for example, Broughton and Rogers, 2010a,b) and in NI 43-101 technical reports released by Canadian exploration companies (http://www.sedar.com). Although they are essential parts of the USGS assessment methodology, regional geochemical or geophysical datasets were not available for this assessment.

Table 3. Sediment-hosted stratabound copper deposits containing more than two million metric tons of contained copper (equivalent to giant deposit category of Singer, 1995) in the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.

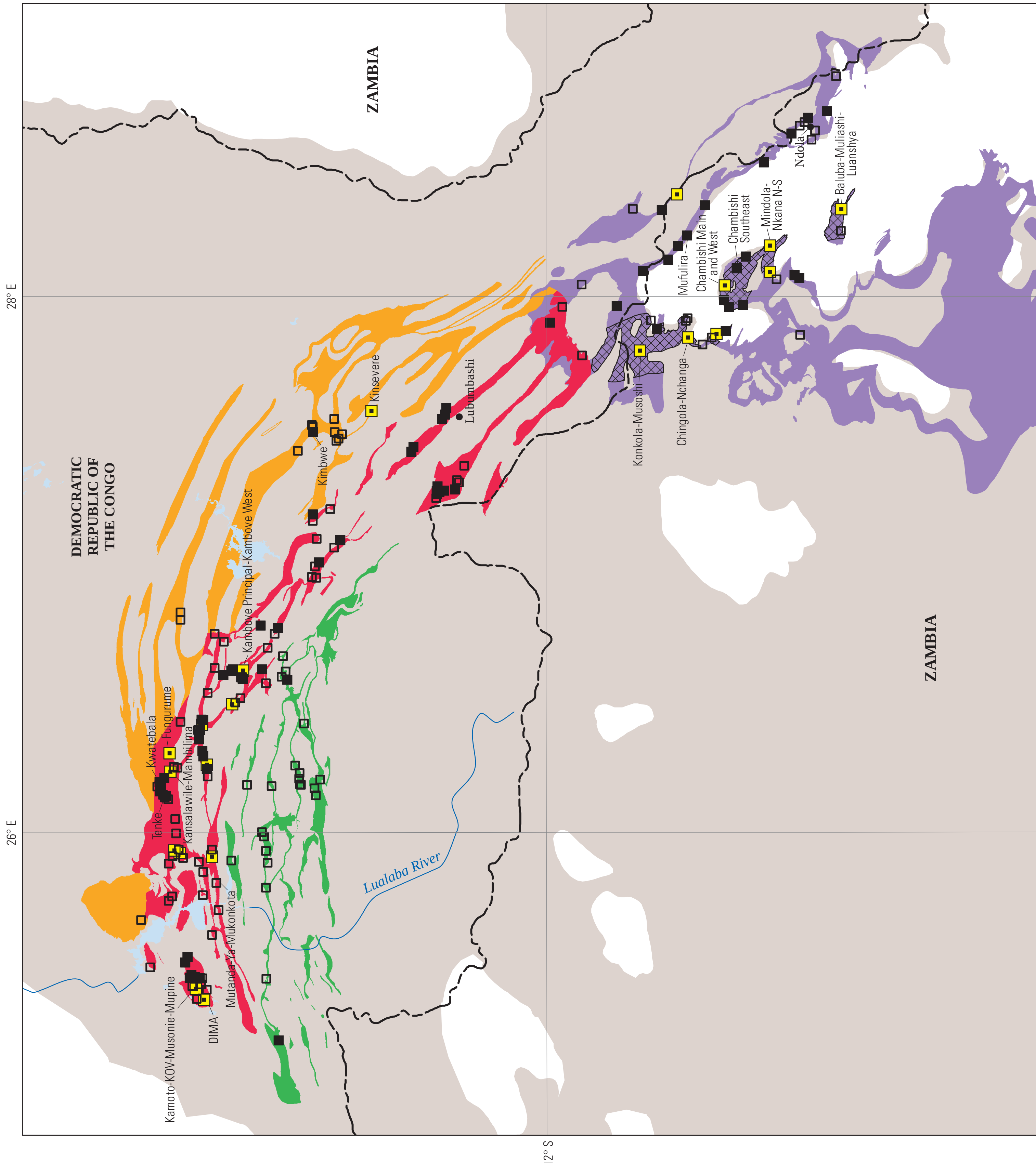
[t, metric tons; DC, Democratic Republic of the Congo; n.b., nonbrecciated; ZM, Zambia]

Name	Basin	Country	Contained copper metal (t)
Reduced-facies—carbonate écaille			
DIMA	Katanga	DC	7,800,000
Fungurume	Katanga	DC	2,800,000
Kambove Principal-Kambove West	Katanga	DC	3,100,000
Kamoto-KOV-Musonie-Mupine	Katanga	DC	19,000,000
Kansalawile-Mambilima	Katanga	DC	2,800,000
Kimbwe	Katanga	DC	2,000,000
Kinsevere	Katanga	DC	2,100,000
Kwatebala	Katanga	DC	2,200,000
Mutanda Ya Mukonkota	Katanga	DC	3,700,000
Tenke	Katanga	DC	2,500,000
Reduced-facies—n.b.			
Baluba-Muliashi-Luanshya	Katanga	ZM	10,000,000
Chambishi Main and West	Katanga	ZM	2,900,000
Chambishi Southeast	Katanga	ZM	3,800,000
Chingola-Nchanga	Katanga	ZM	16,000,000
Kalumbila	Katanga	ZM	2,700,000
Konkola-Musoshi	Katanga	ZM	22,000,000
Mindola-Nkana N-S	Katanga	ZM	15,000,000
Sandstone copper—Roan arenite			
Mufulira	Katanga	ZM	8,900,000

Quantitative Assessment

Permissive Tracts

This assessment focuses on the potential for undiscovered deposits in the Roan Group, particularly in those members of the group that are known to host deposits and represent the potential chemical and physical traps where mineralization is most likely to be localized. For reduced-facies deposits, the assessment unit is the stratigraphic interval where red beds are overlain by marine strata. For sandstone copper deposits, reservoir facies rocks in which mobile reductants might have accumulated comprise the assessment unit. These rock packages form the assessment units used to delineate permissive tracts in the study area (fig. 18).


ZAMBIA
DEMOCRATIC REPUBLIC OF THE CONGO
ZAMBIA
Lualaba River
Lubumbashi
Kinsevere
Kimbwe
Kambove Principal-Kambove West
Kwatebala
Fungurume
Kansalawile-Mambilima
Tenke
Kansalawile
Mutanda-Ya-Mukonkota
Kamoto-KOV-Musonie-Mupine
DIMA
Konkola-Musoshi
Chingola-Nchanga
Mufulira
Chambishi Main and West
Chambishi Southeast
Mindola-Nkana N-S
Ndola
Baluba-Muliashi-Luanshya
28° E
26° E
12° S

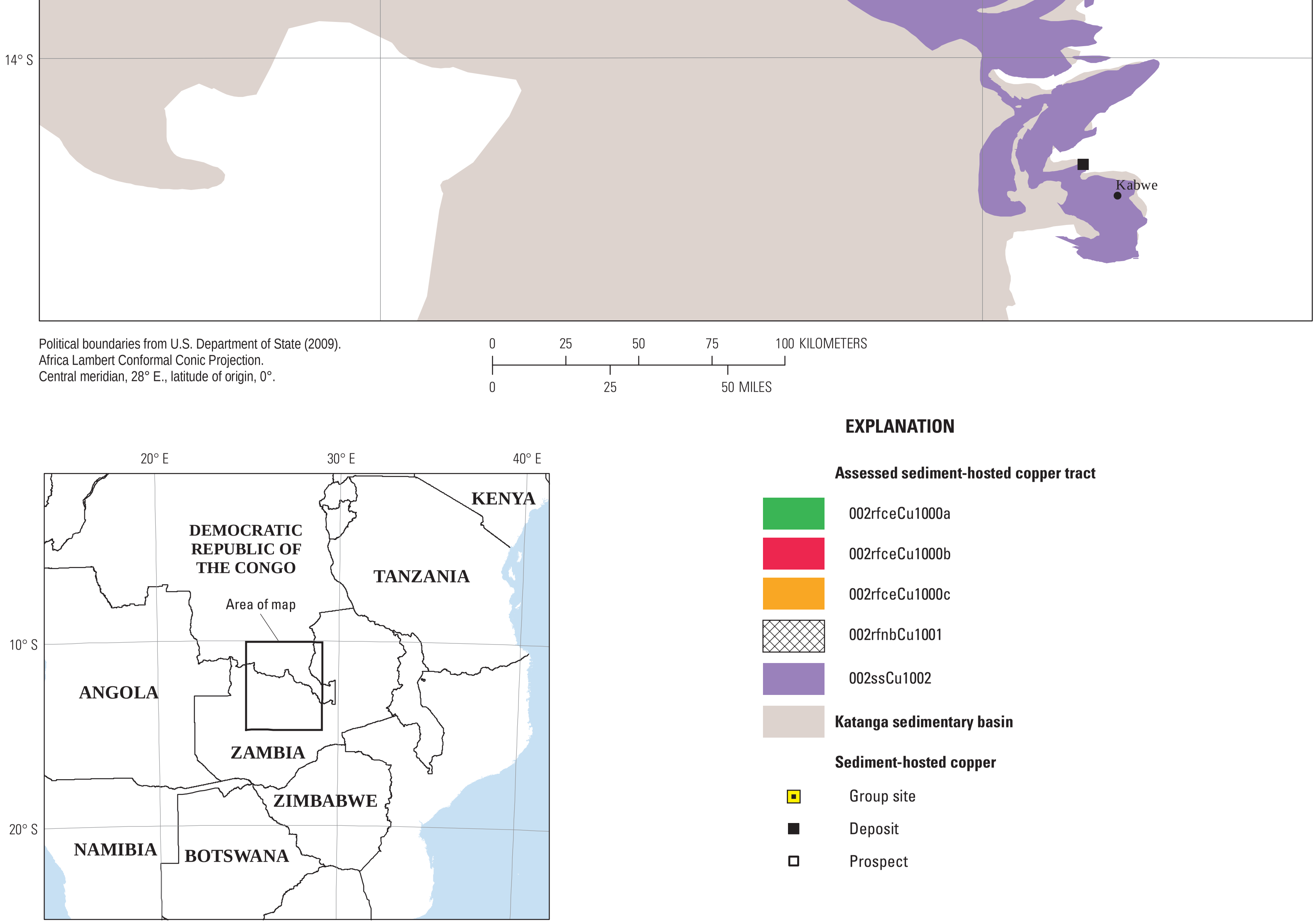


Figure 18. Map showing permissive tracts for sediment-hosted stratabound copper associated with the Roan Group, Central African Copperbelt, Katanga Basin, Democratic Republic of the Congo and Zambia.

Carbonate Écaille Tract

The assessment unit used to delineate the Carbonate écaille tracts (002rfceCu1000a, b, c) is the Mines Subgroup (R.2) of the Roan Group in the Democratic Republic of the Congo (Cailteux and others, 2005b). The permissive tract is delineated by estimating the location of the volume of rock that contains R.2-bearing fragments to a depth of 2 km and projecting it to the surface (fig. 19). The volume of rock containing R.2 fragments was estimated using published geologic maps and cross sections, specifically the digital 1:500,000-scale Arc Cuprifere du Katanga geologic map (Musée royal de l'Afrique centrale, 2008), 12 cross sections (François and Cailteux, 1981; Jackson and others, 2003; François, 2006), and structural data from these sources.

Roan Arenite Tract

The assessment units used to delineate the Roan arenite tract (002ssCu1002) are siliciclastic sedimentary rocks of the Lower Roan Subgroup near the Kafue Anticline and adjacent basement-cored domes that are within about 200 m of the Ore Shale member (fig. 16; Selley and others, 2005). The permissive tract is delineated by estimating the location of the volume of rock containing siliciclastic rocks in the Lower Roan Subgroup to a depth of 2 km and projecting it to the surface; the cross section in figure 20 illustrates this concept for permissive rocks in the Mufulira Syncline.

Ore Shale Tract

The assessment unit used to delineate the Ore shale tract (002rfnbCu1001) is the Ore Shale member of the Kitwe Formation of the Roan Group (fig. 16; Selley and others, 2005) because it is the host for large, laterally continuous, reduced-facies, stratiform copper-cobalt deposits in Zambia. The permissive tract is delineated by estimating the location of the volume of rock containing the Ore Shale member to a depth of 2 km and projecting it to the surface.

Grade and Tonnage Models

Data from about 170 well-explored deposits were used to construct grade and tonnage models for several sediment-hosted stratabound copper deposits (Zientek, Hayes, and Taylor, 2013). Analysis of variance tests show that sediment-hosted stratabound copper deposits in the Central African Copperbelt have significantly higher copper grades than deposits found elsewhere. The cause for the higher grades could be higher hypogene copper grades or copper enrichment by supergene processes. Supergene enrichment has taken place but the possibility of high hypogene copper grades cannot be excluded. Regardless, to reduce bias in the assessment process, the following regional models were constructed to use with this assessment:

1. **Reduced-facies deposits that are not in salt solution breccias.** The grade and tonnage model used for the assessment of reduced-facies deposits that occur in the Ore Shale member in the Zambian part of the Central African Copperbelt is based on global data for 50 reduced-facies deposits. Mean and median values for ore tonnage are 180 and 34 million metric tons, respectively; mean and median copper grades are 1.6 and 1.5 percent copper, respectively.

2. **Reduced-facies deposits that occur in salt dissolution breccias.** Reduced-facies deposits hosted by the Mines Subgroup of the Roan Group occur within favorable stratigraphic intervals preserved in gigabreccia fragments in the Roan breccias. A regional reduced-facies grade and tonnage model, based on data for 50 reduced-facies—carbonate écaille deposits, was created for this mineral resource assessment. Mean and median values for ore tonnage are 42 and 10 million metric tons, respectively; mean and median copper grades are 3.3 and 2.9 percent copper, respectively.

3. **Sandstone copper deposits in the Roan Group, Zambia**. In the Central African Copperbelt, sandstone-hosted copper deposits are found in coarser-grained siliciclastic rocks above and below the Ore Shale member of the Kitwe Subgroup, and in dolomitic siltstone, which is a lateral facies equivalent to the Ore Shale Formation. A regional variant of the sandstone copper grade and tonnage model, sandstone copper—Roan arenite, was created for use in the mineral resource assessment of undiscovered deposits in the Roan Group in Zambia. The grade and tonnage model is based on data for 20 sandstone-hosted copper deposits in the Zambian Copperbelt. Mean and median values for ore tonnage are 34 and 11 million metric tons, respectively; mean and median copper grades are 2.4 and 1.7 percent copper, respectively.

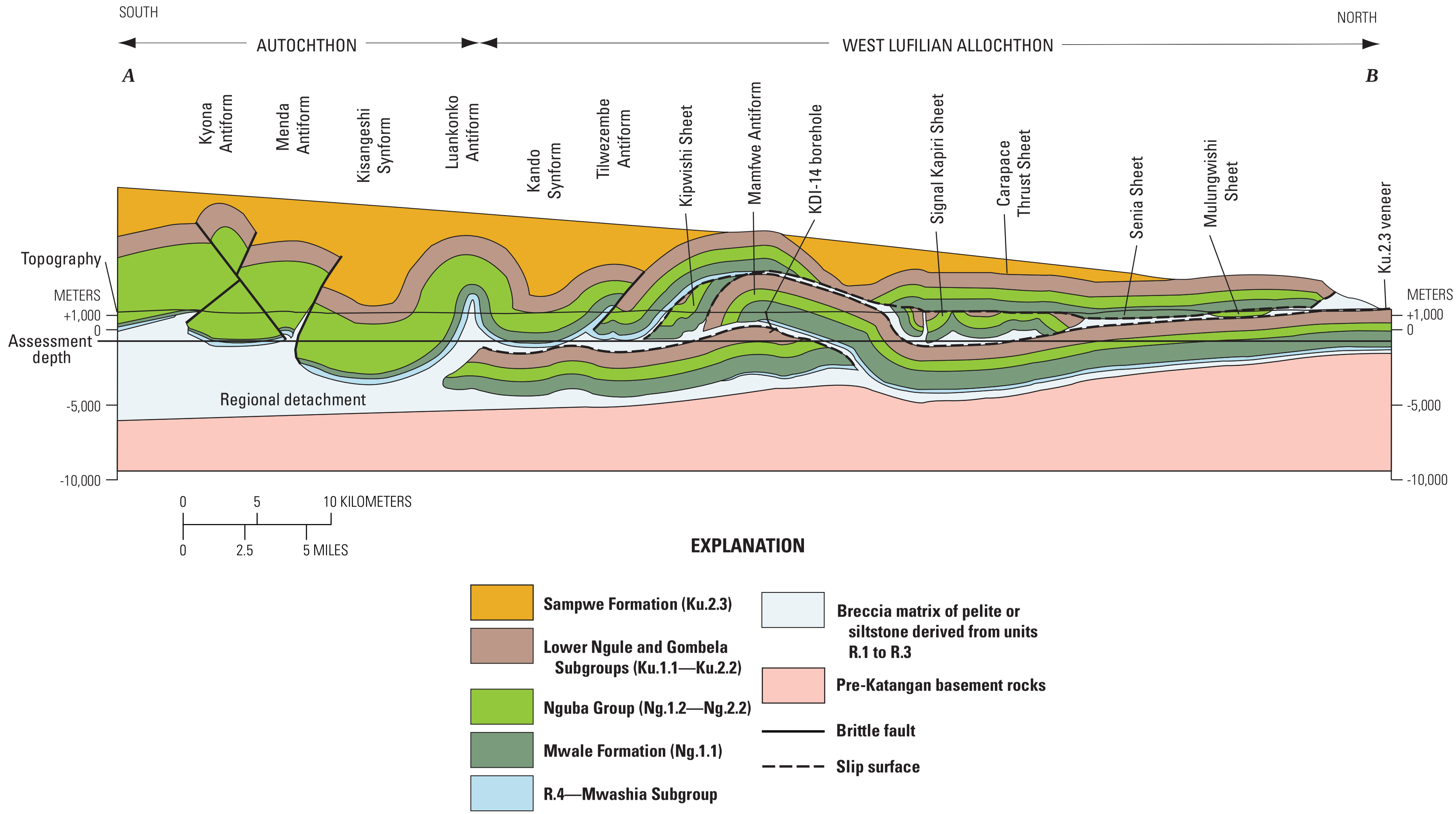


Figure 19. Balanced geologic cross section through the western end of the External Fold and Thrust Belt, Kolwezi area, Democratic Republic of the Congo, with assessment depth of 2 km shown. Section location is shown in figure 10. Modified from Jackson and others (2003).

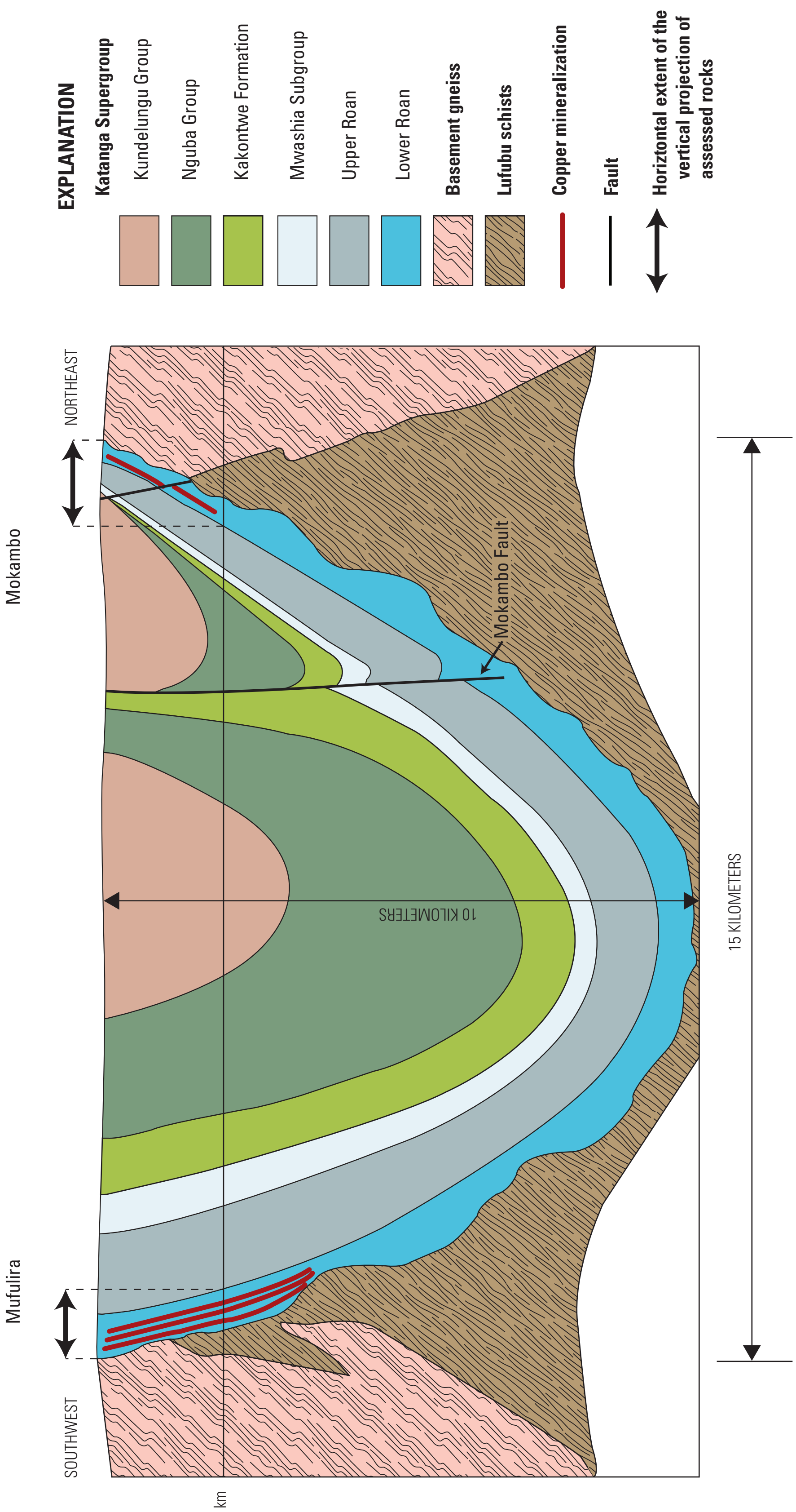


Figure 20. Geologic cross section through the Mufulira Syncline, Zambia, with assessment depth of 2 km shown. Modified from African Eagle Resources plc (2009).

Estimate of the Number of Undiscovered Deposits

In January 2010, numbers of undiscovered deposits were estimated by an expert panel (appendix I). After discussion of area geology and deposit models, assessment team members made separate, subjective estimates of the numbers of undiscovered deposits. Estimators were asked for the least number of deposits of a given type that they believed could be present at three specified levels of certainty (90 percent, 50 percent, and 10 percent). For example, on the basis of all available data, a team member might estimate that there is a 90-percent chance of 1 or more, a 50-percent chance of 5 or more, and a 10-percent chance of 10 or more undiscovered deposits occurring in a given permissive tract. Each person made initial estimates without sharing their results until everyone was finished; then, the results were compiled and discussed. This discussion is crucial because it almost always reveals information or insight not held by all of the panelists. Next, individual scores (appendix H) were adjusted and a single estimate was selected for the simulation process for each tract. The final estimate of undiscovered deposits reflects both uncertainty in what may exist and favorability of the tract (Singer, 1993). Preliminary assessment results were presented to an internal USGS review panel. In addition to hearing presentations, this review panel had access to all available data and could address technical questions to the assessment team. The panel evaluated the assessment and provided written comments that were addressed during the preparation of this report.

Final team estimates of the numbers of undiscovered deposits in each assessed tract are summarized in table 4, together with statistics that describe mean expected numbers of undiscovered deposits, the standard deviation and coefficient of variation within the estimate, and the number of known deposits. Within the Carbonate écaille tracts (002rfceCu1000a, b, c), with 56 known deposits, a mean of 121 undiscovered deposits is predicted to a depth of 2 km. Within the Ore shale tract, having 9 known deposits, a mean of 1.5 undiscovered deposits is estimated. A mean of 10 undiscovered deposits is predicted in the Roan arenite tract (002ssCu1002), which contains 20 known deposits.

Table 4. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for Roan Group permissive tracts, Central African Copperbelt, Democratic Republic of the Congo and Zambia.

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

Tract	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
Southern carbonate écaille	3	8	18	35	35	11	8.8	83	2	13	1,334	0.0097
Central carbonate écaille	50	85	180	180	180	100	49	49	52	152	3,538	0.043
Northern carbonate écaille	3	8	20	20	20	9.9	6.2	63	2	12	4,311	0.0028
Ore shale	1	1	3	3	3	1.5	0.93	61	9	11	890	0.012
Roan arenite	5	8	20	20	20	10	5.8	56	20	30	13,060	0.0023

Probabilistic Assessment Simulation Results

Probable amounts of undiscovered resources for the tracts were estimated by combining consensus estimates for numbers of undiscovered deposits with sediment-hosted stratabound copper models (Zientek, Hayes, and Taylor, 2013) using the Economic Mineral Resource Simulator (EMINERS) program (Root and others, 1992; Duval, 2012; Bawiec and Spanski, 2012). Simulation results are reported at selected 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. Results of the Monte Carlo simulation are shown on a histogram (fig. 21) and summarized in table 5.

All of the assessed tracts contain known mineral deposits with identified resources. Furthermore, all assessed tracts, with the exception of the Ore shale tract (002rfnbCu1001), have more estimated undiscovered deposits than known deposits. As would be expected, the mean and median estimates for undiscovered amounts of copper exceed the amount of known copper in each tract, again, except for the Ore shale tract (002rfnbCu1001).

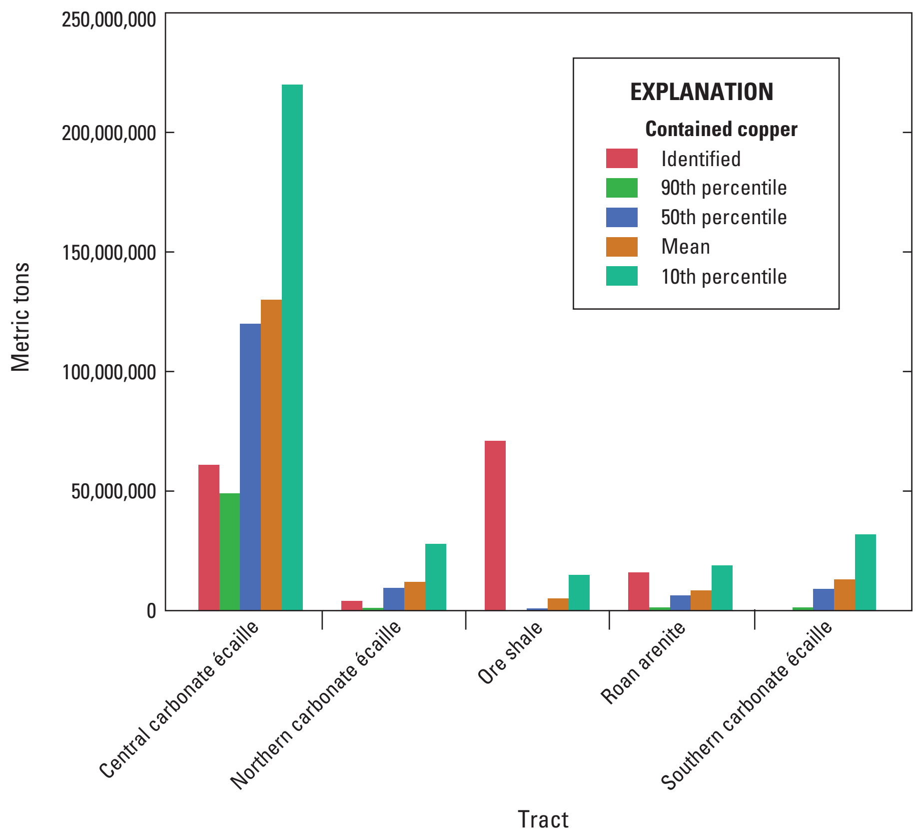


Figure 21. Histogram comparing identified and undiscovered copper resources associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.

Table 5. Results of Monte Carlo simulations of undiscovered resources for Roan Group permissive tracts, Central African Copperbelt, Democratic Republic of the Congo and Zambia.

[t , metric tons; Mt, million metric tons]

Tract name	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Undiscovered resources of silver, (t)								
Ore shale	0	0	0	5,500	21,000	7,100	0.09	0.52
Undiscovered resources of cobalt, metric tons								
Central carbonate écaille	3,100,000	5,700,000	14,000,000	28,000,000	30,000,000	16,000,000	0.44	0.00
Southern carbonate écaille	22,000	100,000	1,100,000	4,000,000	5,300,000	1,600,000	0.35	0.04
Northern carbonate écaille	6,400	95,000	1,100,000	3,400,000	4,300,000	1,500,000	0.40	0.05
Undiscovered resources of copper, (t)								
Central carbonate écaille	25,000,000	49,000,000	120,000,000	220,000,000	240,000,000	130,000,000	0.45	0.00
Southern carbonate écaille	310,000	1,300,000	9,100,000	32,000,000	42,000,000	13,000,000	0.37	0.03
Northern carbonate écaille	250,000	1,100,000	9,600,000	28,000,000	34,000,000	12,000,000	0.42	0.03
Roan arenite	770,000	1,400,000	6,400,000	19,000,000	23,000,000	8,400,000	0.39	0.02
Ore shale	0	16,000	880,000	15,000,000	24,000,000	5,100,000	0.23	0.07
Rock in undiscovered deposits, (Mt)								
Central carbonate écaille	870	1,700	3,900	7,500	8,100	4,300	0.45	0.00
Southern carbonate écaille	9	44	320	1,100	1,400	450	0.38	0.03
Northern carbonate écaille	8	38	340	930	1,100	420	0.43	0.03
Roan arenite	39	68	320	820	990	390	0.42	0.02
Ore shale	0	1	55	740	1,200	280	0.24	0.07

Near-Surface Assessment of the Carbonate Écaille Tracts

The Carbonate écaille tracts (002rfceCu1000a, b, c) have the potential for near-surface, undiscovered deposits. As part of this study, 44 of the 87 prospects in these tracts were identified as significant (appendix D). Significance was determined by evaluating the intensity of surface disturbance related to exploration activity as seen on satellite images. Sites with more disturbances are assumed to have more indications of mineralization. Therefore, significant prospects had pits or quarries, trenches, drill roads or drill pads, and (or) areas of artisanal workings.

Significant prospects were ranked and assigned probabilities to estimate the amount of undiscovered metal that might be present at or near the surface (table 6). Simulation results indicate a mean value of 37 million metric tons of undiscovered copper may be present within these significant prospects (table 7). Sites similar to these are most likely to be developed in the near future. The locations of the sites are known and some historical exploration results should be in company archives.

Mutanda-Ya-Mukonkota is an example of a prospect whose status has been upgraded from prospect to giant deposit. In 2009, when we started compiling information, Mutanda-Ya-Mukonkota in the Central carbonate écaille tract (002rfceCu1000b) was identified as a prospect within a small (300 m by 2,500 m) body of the Roan Group exposed along the Tilwezembe Antiform (fig. 10). Google Earth™ images, taken as late as July 6, 2009, showed limited surface disturbance at this site. However, images from August 8, 2010, reveal the construction of a mining complex; the following year, Glencore International plc announced resources of 299.6 million metric tons of ore containing 1.23 percent copper and 0.588 percent cobalt (Wimberly and others, 2011). The amount of contained copper at Mutanda-Ya-Mukonkota meets the criterion of a giant copper deposit as defined by Singer (1995). Similar development of other known prospects in the Carbonate écaille tracts (002rfceCu1000a, b, c) is expected.

Table 6. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for significant prospects in the Carbonate écaille tracts, Democratic Republic of the Congo.

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

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
20	29	44	44	44	29	9.4	32	44	73	9,180	0.0080

Table 7. Results of Monte Carlo simulations of undiscovered resources associated with significant prospects in the Carbonate écaille tracts, Democratic Republic of the Congo.

[t, metric tons; Mt, million metric tons; Co, cobalt; Cu, copper]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	9,900,000	15,000,000	36,000,000	62,000,000	71,000,000	37,000,000	0.46	0.00
Co (t)	1,100,000	1,700,000	4,300,000	7,900,000	9,200,000	4,600,000	0.45	0.01
Rock (Mt)	340	520	1,200	2,100	2,400	1,300	0.46	0.00

Discussion

This probabilistic assessment indicates that a substantial amount of undiscovered copper is contained within sediment-hosted stratabound copper deposits in the Roan Group in the Katanga Basin (tables 8 and 9). The mean estimate of undiscovered copper in the study area, 168 million metric tons, is slightly greater than the known resources of 152 million metric tons. Significant value can be expected from associated metals, particularly cobalt. By comparison, the Chu-Sarysu Basin in Kazakhstan has identified copper resources of 27.6 million metric tons with a mean estimate of 60.5 million metric tons of undiscovered copper contained within sandstone-type sediment-hosted stratabound copper deposits (Box and others, 2012).

About 30 percent of the known copper resources in the Central African Copperbelt have been produced, with no real difference in the proportion of production between the Democratic Republic of the Congo and Zambia (table 9). However, the greatest proportion of undiscovered resource is likely to be contained within the Central carbonate écaille tract (002rfceCu1000b) of the Democratic Republic of the Congo (fig. 22). This tract contains about 40 percent of the known endowment but 77 percent of the mean undiscovered resource. The change in proportion reflects evidence that relatively little undiscovered resource remains in the Ore shale tract (002rfnbCu1001), which has the largest known endowment of copper within the assessed tracts.

The Southern and Central carbonate écaille tracts (002rfceCu1000a, b) have large estimates for the number of undiscovered deposits as well as high deposit density. In this tract, most of the known deposits are hosted in gigaclasts in Roan Breccia. The grade and tonnage model was developed using deposits that occur in this tract; their size is ultimately related to the size of the mineralized breccia fragments. The assessment panel made the assumption that the size distribution and proportion of mineralized megaclasts and gigaclasts in the subsurface are likely to be similar to what is seen on the surface. The proportion of megabreccia and gigabreccia fragments that are mineralized was analyzed using geologic maps, deposit and occurrence databases, and satellite images. Our colleagues from the mining industry reported that historical exploration in the tract was limited to the upper 300 m of the surface. The deposit density seen at the surface was projected to the assessment depth of 2 km. A detailed discussion of the rationale for the large estimate for this tract is given in appendix H.

Table 8. Selected simulation results of undiscovered copper resources compared with known resources in Roan Group permissive tracts, Central African Copperbelt, Democratic Republic of the Congo and Zambia.

[t, metric tons]

Tract coded ID	Tract name	Number of known deposits	Mean number of undiscovered deposits	Contained copper in known deposits (t)	90th percentile estimate of undiscovered copper resources (t)	Median estimate of undiscovered copper resources (t)	Mean estimate of undiscovered copper resources (t)	10th percentile estimate of undiscovered copper resources (t)
002rfceCu1000a	Southern carbonate écaille	2	11	150,000	1,300,000	9,100,000	13,000,000	32,000,000
002rfceCu1000b	Central carbonate écaille	52	100	61,000,000	49,000,000	120,000,000	130,000,000	220,000,000
002rfceCu1000c	Northern carbonate écaille	2	9.9	4,100,000	1,100,000	9,600,000	12,000,000	28,000,000
002rfnbCu1001	Ore shale	9	1.5	71,000,000	16,000	880,000	5,100,000	15,000,000
002ssCu1002	Roan arenite	20	10	16,000,000	1,400,000	6,400,000	8,400,000	19,000,000

Table 9. Comparison of known copper resources, estimates of copper production, and mean estimates of undiscovered copper in the Central African Copperbelt, Democratic Republic of the Congo and Zambia.

[Estimates of number of known deposits, their contained resources, and production to 2009 from Taylor and others (2013). Previous estimates of copper production in Zambian Copperbelt to 1988 is from Freeman (1988); production estimate for the Katangan Copperbelt to 1996 is from Fortin (2006)]

Region	Number of known deposits	Total contained copper in known deposits (metric tons)	Previous estimates of copper production (metric tons)	Estimated production to 2009 (metric tons)	Mean undiscovered copper estimate (metric tons)
Katangan Copperbelt	56	64,700,000	18,600,000	13,700,000	155,000,000
Zambian Copperbelt	29	87,000,000	29,200,000	36,500,000	13,500,000
Central African Copperbelt	85	152,250,000	47,800,000	50,200,000	168,500,000

The likelihood for occurrence of near-surface undiscovered deposits is not the same for the permissive tracts delineated for this study. Simulation results indicate a mean value of 37 million metric tons of undiscovered copper may be present within significant prospects in the Southern and Central carbonate écaille tracts (002rfceCu1000a, b). For the Ore shale tract (002rfnbCu1001), the assessment panel concluded that undiscovered deposits are not likely to occur near the surface; any undiscovered deposits would be at depth. For the well-explored northern part of the Roan arenite tract (002ssCu1002), any undiscovered deposits also would likely be at depth. The southern part of this tract, however, has more sedimentary cover rocks and hence more potential for undiscovered deposits near the surface. The possibility that undiscovered deposits will be found and developed is partly determined by natural conditions that affect our ability to apply modern exploration techniques. Little or no rock exposure because of deep soil cover or dense vegetation makes it difficult to apply mapping techniques. This limitation applies to the Northern carbonate écaille tract (002rfceCu1000c), which is covered largely by lakebed deposits and a Tertiary weathering surface.

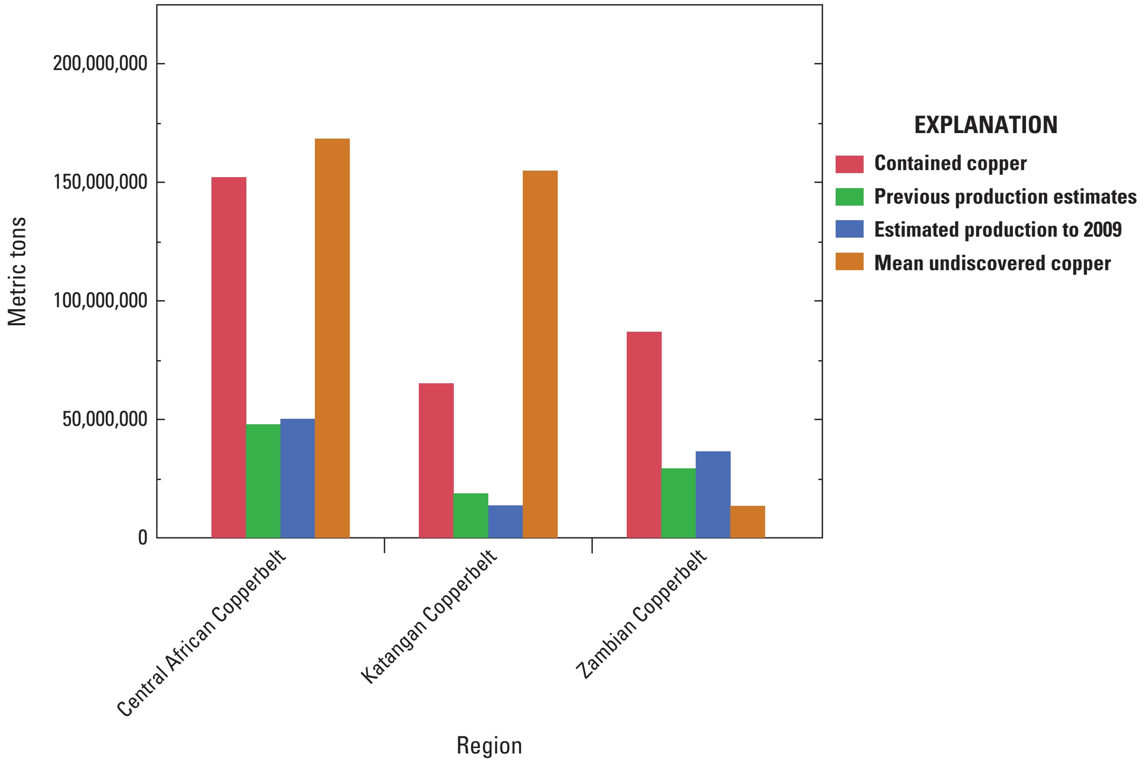


Figure 22. Histogram comparing identified resources, production, and mean undiscovered copper associated with the Roan Group in the Katangan and Zambian portions of the Central African Copperbelt, Democratic Republic of the Congo and Zambia.

Policy-related criteria contribute to the ability of nations, states, and provinces to attract exploration investment (Penney and others, 2007; McMahon and Cervantes, 2012). Ninety-three jurisdictions have been scored in an industry survey and are rated[19] using a composite index that measures the effects on exploration of government policies including uncertainty concerning the administration, interpretation and enforcement of existing regulations, environmental regulations, regulatory duplication and inconsistencies, taxation, uncertainty concerning native land claims and protected areas, infrastructure, socioeconomic agreements, political stability, labor issues, geological database, physical security (for example, threat of attack by terrorists, criminals, and so on), the reliability of legal systems, and trade barriers (McMahon and Cervantes, 2012). In the 2011–2012 survey, Zambia is ranked 50th out of 93 jurisdictions; the Democratic Republic of the Congo is ranked 67th. The survey also scores jurisdictions by policy and mineral potential assuming no land-use restrictions exist in place and assuming industry “best practices.” On that basis, the Democratic Republic of the Congo is in the top 10 jurisdictions, ranked at number 4. Zambia is ranked number 62 out of the 79 jurisdictions.

In conclusion, the potential for undiscovered mineral deposits in the Roan Group is significant, particularly for the Carbonate écaille tracts (002rfceCu1000a, b, c). Additionally, historical evaluation of prospects within the Roan Group likely used higher cutoff grades than what are used today. Many significant prospects in the Carbonate écaille tracts are near the surface and amenable to low-cost, open-pit mining if an economically feasible mineral inventory can be identified. Undiscovered deposits at depth, in any of the tracts, will be difficult to find and more expensive to mine. Finally, the significant resource potential of the various tracts is offset by substantial risks of conducting business in this part of the world (Mining Journal, 2008, 2010; Lydall and Auchterlonie, 2011; and Tambwe, 2012).

[19] In the rankings, lower numbers indicate better.

Considerations for Users of this Assessment

Assessment results should be interpreted with due caution. This mineral resource assessment provides maps that show where undiscovered deposits may exist and gives estimates of how much resource might be present in these areas; however, it does not specifically address the likelihood of future development. This study does not evaluate how much of the undiscovered resource is likely to be found, how much it would cost to find, and if found, what part would be economic under various conditions. Economic filters can estimate the proportion of the total undiscovered resource that may be economic (Robinson and Menzie, 2012) but this technique has not been applied to results of this study.

Permissive tracts are based on geology, irrespective of current land-use conditions. Therefore, tracts include lands already developed for other uses, or protected areas withdrawn from mineral development. Tracts are compiled to be displayed at a scale of 1:1,000,000, and even though higher resolution information is used in the compilations, this information is not intended for use at larger scales.

USGS Global Mineral Resource Assessment products represent a synthesis of current, readily available information. This assessment is based on the deposit models, maps, and data represented in this report. Different datasets would result in a different assessment.

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Appendixes A–I

Appendix A. Mineral Resource Assessment Methods and Procedures Used in Global Mineral Resource Assessment Reports

By Michael L. Zientek[1] and Jane M. Hammarstrom[2]

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 a volume of rock is present that might be economic. If a 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 segregate 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[3] 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[4], 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

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

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

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

[4]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).

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 of volumes of mineralized rock that are above cutoff grade[5] (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”:

1. “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).
2. “natural concentrations of useful minerals or rocks, which can be economically exploited” (Pohl, 2011).
3. “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).
4. “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).
5. “an accumulation of associated mineralized bodies that constitute a single mineralizing event, including subsequent processes (for example, 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[6] 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

[5]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).

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

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 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

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 the 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 the deposition of ore minerals will not occur unless all the 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 tonnage and grade 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 tonnage and grades), (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, tonnages and grades are approximated by piecewise linear distributions to avoid unrealistically large values.

Simulation results are reported at selected 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[7] and stratiform[8] deposit types by estimating the number of undiscovered deposits is problematic. Examples of stratabound

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

[8] 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.

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, in press). 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:

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

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/m^3.

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 Assessment Results

Permissive tracts are polygons that are represented with 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) used this approach to perform an economic analysis of undiscovered resources estimated in porphyry copper deposits in six tracts located in North America.

Operational Procedures

The 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 occurrences (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 tonnage and grade) are well explored and should be classified as known deposits

Select appropriate grade and tonnage model

- Select published tonnage and grade 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 tonnage and grade 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 technical reviews, in addition to co-author and project managers reviews

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Appendix B. Spatial Databases for Sediment-Hosted Stratabound Copper Deposits and Prospects, Central African Copperbelt, Democratic Republic of the Congo and Zambia

By Heather L. Parks[1], J. Douglas Causey[1], Paul D. Denning[2], Timothy S. Hayes[3], John D. Horton[2], Michael J. Kirschbaum[2], Cliff D. Taylor[2], Anna B. Wilson[2], Niki E. Wintzer[1], and Michael L. Zientek[1]

Introduction

Databases and maps of the location, size, and geologic type of known mineral deposits and occurrences are essential components of mineral resource assessment studies. Four spatial databases provide data for use in an assessment of undiscovered sediment-hosted copper resources in the Central African Copperbelt (CACB) in the Democratic Republic of the Congo (DRC) and Zambia. The spatial databases are presented as Esri shapefiles, which contain spatial and descriptive data for deposits and prospects, ore bodies, open pits, and permissive tracts. These databases can be queried in a geographic information system (GIS) to portray the distribution, geologic setting, and resource potential of copper deposits and to model grade and resource tonnage in the region. The files are an updated version of those published by Parks and others (2013).

Overview of Spatial Databases

The spatial databases are briefly described in table B1. They are provided in vector format as Esri shapefiles and packaged with a lookup table for unit descriptions, a metadata file, a list of references cited, and a brief descriptive ASCII text file in the compressed archive file *sir2010-5090T_GIS.zip*, which is available on the Internet at http://pubs.usgs.gov/sir/2010/5090/t/.

Deposits and Prospects

The spatial database for deposits and prospects in the Central Africa Copperbelt (CACB), *CACB_deposits_prospects*, is an Esri point shapefile that contains spatial and descriptive data for 167 deposits and prospects and 20 group sites that represent sediment-hosted copper deposits and prospects in the CACB. It provides locations of deposits and prospects, in addition to descriptive information for use in a GIS and for estimating undiscovered mineral resource endowments.

The dataset was created, in part, from preexisting compilations, reports, and maps of copper deposits and prospects. Descriptive data from digital files were combined into a coherent, single shapefile. Data for deposit and prospect sites having multiple records were then combined to provide a single record for each site. Tonnage and grade information was derived from Taylor and others (2013). Group sites were created to represent multiple sites that were grouped using a 500-m aggregation distance for purposes of grade and tonnage modeling. These sites can be identified using the "SiteStatus" field in the attribute table.

The positional accuracy of the location for each site was checked against mineral occurrence maps and figures in reports. Locations of many sites were derived from coordinates provided in reports and databases; some were manually digitized from maps in reports. Deposit and prospect locations were defined on the basis of the highest resolution data available. For example, a 1:100,000-scale map took precedence over a 1:1,000,000-scale map for the site location. Some locations of developed sites were compared against mines visible on satellite imagery from Google Earth™[4] and were adjusted accordingly. Because the maps and satellite images used different datums, we converted all reference material to the same datum (WGS 1984) when locations were corrected.

We investigated a variety of data—published and unpublished, open access and licensed, and public and proprietary. Sites that could not be verified using publicly available data were excluded from the compilation. Examples of the types of information used are summarized in table B2; a complete list of sources can be found in the references file provided with the databases.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]http://www.google.com/earth/index.html.

Table B1. Description of digital data files for spatial databases (GIS).

File name	File description
Compressed archive file containing spatial databases, associated metadata files, references, and readme.txt	
sir2010-5090T_GIS.zip	GIS and associated files: Esri shapefiles, metadata (*.xml), references (*.xlsx), and readme.txt (ASCII text)
Esri shapefiles	
CACB_deposits_prospects.shp	Sediment-hosted copper deposits and prospects
CACB_open_pits.shp	Sediment-hosted copper deposit open pits
CACB_orebodies.shp	Sediment-hosted copper deposit ore bodies
CACB_permissive_tracts.shp	Sediment-hosted copper permissive tracts
Relational table	
Unit_look_up_table.xlsx	Table with unit names and descriptions that can be joined to the Unit field in the shapefile CACB_deposits_prospects.shp
Metadata –extensible markup language (XML) format (*.xml) files	
CACB_deposits_prospects_metadata.xml	Metadata for shapefile of deposits and prospects
CACB_open_pits_metadata.xml	Metadata for shapefile of open pits
CACB_orebodies_metadata.xml	Metadata for shapefile of ore bodies
CACB_permissive_tracts_metadata.xml	Metadata for shapefile of permissive tracts
List of full references	
GIS references.xlsx	Table listing short references used in shapefiles and complete references

Table B2. Examples of the types of sources used to compile the CACB_deposits_prospects shapefile.

Data type	Citation
Information in the public domain	
Report	Guernsey (1952)
Report with map	François (1974)
Report with spatial database	Kirkham and others (1994)
Spatial databases	Cox and others (2003); Kirkham and others (2003); Huderek (2008a,b, 2010)
Licensed and proprietary information	
Proprietary minerals database	Infomine[1], Intierra[2], Metals Economic Group[3]
Spatial databases	GeoPubs (1998); Veselinovic-Williams and Frost-Killian (2003); Chartry and Franceschi (2004); Zambia Geological Survey Department, written comm., 2006; Musée royal de l'Afrique centrale (2008)
Unpublished minerals reports	Freeman (1988); Armand François, written comm., 1996

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

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

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

Table B3 lists the fields in the deposits and prospects shapefile and a short definition of each field. The site name (listed in the field "Name") is based on the most frequent usage in publicly available sources. Codes in the field "Unit" are based on the correlation of units in Zambia and the Democratic Republic of the Congo by Cailteux and others (2007). A lookup table has been included and can be joined with the "Unit" field in a GIS to obtain definitions of the unit codes. Table B4 shows the lithologic descriptions of stratigraphic units and correlations between Zambian and DRC units.

Table B3. Definitions of user-defined fields in the attribute table for the shapefile CACB_deposits_prospects.

Field name	Description
Tract_ID	Coded ID for permissive tract in which site is located
Tract_name	Name of permissive tract in which site is located
Group_name	Name for cluster of deposits which are grouped together (and for which resource data are aggregated) in order to describe and model grade and tonnage. See use of the 500 m spatial aggregation rule in this report
Name	Name of site
Name_other	Other names used for the site
Includes	Names of deposits that were grouped based on proximity (see use of the 500 m spatial aggregation rule in this report); list may overflow into the field "Includes2"
Includes2	Continuation of list of names of deposits that were grouped based on proximity
Type	Mineral deposit type
Subtype	Sediment-hosted copper subtype
SiteStatus	Status of site; prospect—grade and tonnage values are not provided, deposit—grade and tonnage values are provided, and group—represents multiple deposits within 500 m of each other that have been grouped together due to 500 m aggregation rule
Latitude	Latitude in decimal degrees. −90.00000 to 90.00000. Negative south of the equator
Longitude	Longitude in decimal degrees. −180.00000 to 180.00000. Negative west of the Greenwich meridian
Country	Country in which the site is located
State_Prov	State or province in which the site is located
Age_range	Age of host rock, in standard divisions of geologic time
Comm_major	Major commodities in decreasing order of economic importance
Tonnage_Mt	Ore tonnage, in millions of metric tons, zero indicates no data
Cu_pct	Average copper grade, in weight percent, zero indicates no data
Co_pct	Average cobalt grade, in weight percent, zero indicates no data
Con_Cu_t	Contained copper, in million metric tons, zero indicates no data
Comments	Miscellaneous comments
HostRocks	Simplified lithologic description of host rocks
Unit	Geologic map unit label in which site is located; see table 3 for detailed information relating label to rock unit description
Footwall	Lithology of footwall rocks
Hangwall	Lithology of hangingwall rocks
Mineralogy	Ore and gangue minerals in approximate order of abundance
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying "GIS references.xlsx" file
Tctnic_set	Tectonic setting; entry describes the type of associated structural feature
Complex	Tectonic complex; name of the associated structural feature

Table B4. Description of Katangan lithologies used in the “Unit” field (modified from Cailteux and others, 2007).

[–, no data]

<table>
<tr><th colspan="4">CONGO</th><th colspan="3">ZAMBIA</th></tr>
<tr><th>GROUP</th><th>SUBGROUP</th><th>FORMATION</th><th>LITHOLOGY</th><th>LITHOLOGY</th><th>FORMATION</th><th>SUBGROUP</th></tr>
<tr><td rowspan="13">Roan (R)</td><td rowspan="3">Mwashya (formerly Upper Mwashya) (R.4)</td><td>Kanzadi (R.4.3)</td><td>sandstones or alternating siltstones and shales</td><td rowspan="3">dolomitic shales, gray to black carbonaceous shales, quartzites</td><td rowspan="3">–</td><td rowspan="3">Mwashia (Mw.1.1)</td></tr>
<tr><td>Kafubu (R.4.2)</td><td>carbonaceous shales</td></tr>
<tr><td>Kamoya (R.4.1)</td><td>dolomitic shales, siltstones, sandstones, including conglomeratic beds and cherts in variable positions</td></tr>
<tr><td rowspan="4">Dipeta (R.3)</td><td>Kansuki (R.3.4)</td><td>(formerly Lower Mwashya): dolomites including volcaniclastic beds; Cu-Co</td><td rowspan="3">dolomites to arenitic dolomites interbedded with dolomitic shales; intrusive gabbros (formerly Carbonate Unit or Upper Roan)</td><td rowspan="3">Bancroft Kanwangungu (RU.1 and RU.2)</td><td rowspan="4">Kirilabombwe</td></tr>
<tr><td>Mofya (R.3.3)</td><td>dolomites, arenitic dolomites, dolomitic siltstones</td></tr>
<tr><td>R.3.2</td><td>argillaceous dolomitic siltstones with interbedded sandstone or white dolomite; intrusive gabbros</td></tr>
<tr><td>R.G.S. (R.3.1)</td><td>argillaceous dolomitic siltstones (“Roches Greso Schisteuses”)</td><td>shales with grit (Antelope Clastics)</td><td>Kibalongo (RL.3)</td></tr>
<tr><td rowspan="4">Mines (R.2)</td><td>Kambove (R.2.3)</td><td>stromatolitic, laminated, shaly or talcose dolomites; locally sandstone at the base; interbedded siltstones in the upper part; Cu-Co</td><td>dolomite, argillite beds at top</td><td>Chingola (RL.4)</td><td rowspan="4">Kitwe</td></tr>
<tr><td rowspan="2">Dolomitic shales (R.2.2)</td><td>R 2.2.2 and 3: dolomitic shales containing carbonaceous horizons; occasional dolomite or arkose</td><td>arkoses, sandy to dolomitic argillites</td><td>Pelito-arkosic (RL.5)</td></tr>
<tr><td>R 2.2.1: arenitic dolomite at the top and dolomitic shale at the base; pseudomorphs after evaporite nodules and concretions; Cu-Co</td><td rowspan="2">arenites, argillaceous dolomites, argillites, dolomites, evaporites; Cu-Co</td><td rowspan="2">Ore Shale (RL.6)</td></tr>
<tr><td>Kamoto (R.2.1)</td><td>stromatolitic dolomite (R.S.C.), silicified/arenitic dolomites (R.S.F./D. Strat.), gray argillaceous dolomitic siltstone at the base (Grey R.A.T.); pseudomorphs after evaporites at the contact with R.A.T.; Cu-Co</td></tr>
<tr><td>R.A.T. (R.1)</td><td colspan="2">red argillaceous dolomitic siltstones, sandstones and pelites (“Roches Argilo-Talqueuses”)</td><td>conglomerates, coarse arkoses and argillaceous siltstones</td><td>Mutonda</td><td rowspan="2">Mindola (RL.7)</td></tr>
<tr><td colspan="3">base of the R.A.T. sequence—unknown</td><td>quartzites</td><td>Kafufya</td></tr>
</table>

Permissive Tracts

The spatial database for permissive tracts, *CACB_permissive_tracts*, is an Esri polygon shapefile that contains spatial and descriptive information for five sediment-hosted copper permissive tracts in the CACB. These tracts delineate areas where undiscovered deposits of sediment-hosted copper may occur within the upper 2 km of the Earth's crust.

Processing steps for tract delineation are detailed in appendixes E, F, and G of this report. Table B5 lists fields in the database and a short description of each field.

Table B5. Definitions of user-defined attribute fields in the shapefile CACB_permissive_tracts.shp.

Field name	Description
Tract_ID	User-defined, unique identifier assigned to permissive tract
Coded_ID	Coded, unique identifier assigned to permissive tract
Tract_name	Informal name of permissive tract
Unregcode	Three digit UN code for the region that underlies most of the permissive tract
Country	Country(ies) in which the permissive tract is located
Commodity	Primary commodity being assessed
Dep_type	Name of the deposit type assessed
GT_model	Grade-tonnage model used for the undiscovered deposit estimate
Geology	Geologic feature assessed
Age	Age of the assessed geologic feature
Asmt_date	Year assessment was conducted
Asmt_depth	Maximum depth beneath the Earth's surface used for the assessment, in kilometers
Est_levels	The set of percentile (probability) levels at which undiscovered deposit estimates were made
N90	Estimated number of deposits associated with the 90th percentile (90 percent chance of at least the indicated number of deposits)
N50	Estimated number of deposits associated with the 50th percentile (50 percent chance of at least the indicated number of deposits)
N10	Estimated number of deposits associated with the 10th percentile (10 percent chance of at least the indicated number of deposits)
N05	Estimated number of deposits associated with the 5th percentile (5 percent chance of at least the indicated number of deposits)
N01	Estimated number of deposits associated with the 1st percentile (1 percent chance of at least the indicated number of deposits)
N_expected	Expected (mean) number of deposits. N_Expected=(0.233×N90)+(0.4×N50)+(0.225×N10)+(0.045×N05)+(0.03×N01)
s	Standard deviation. s=0.121−(0.237×N90)−(0.093×N50)+(0.183×N10)+(0.073×N05)+(0.123×N01)
Cv_percent	Coefficient of variance, in percent. Cv=(s/N_Expected)×100
N_known	Number of known deposits in the tract
N_total	Total number of deposits. N_total=N_Expected+N_Known
Area_km^2	Area of permissive tract, in square kilometers
DepDensity	Deposit density (total number of deposits per square kilometer). DepDensity=N_total/Area_km2
DepDen10E5	Deposit density per 100,000 square kilometers. DepDen10E5=DepDensity×100,000
Estimators	Names of people on the estimation team
Notes	Miscellaneous notes

Ore Bodies

The spatial database for copper ore bodies, *CACB_orebodies*, is an Esri polygon shapefile that contains spatial and descriptive information for 79 polygons representing copper deposits hosted in sedimentary rocks that have been defined by exploration. Its purpose is to document the areal extent (as projected to the surface) of known ore bodies in the Central African Copperbelt and to constrain estimates of mineral resource endowment for the region.

Areal extents of ore bodies were manually digitized from plan maps that were georeferenced for use in a GIS. The shape of an ore body can reflect geologic contacts, economic cutoff limits, and (or) property boundaries. Table B6 lists fields in the database and a short description of each field. Ore bodies were given the name of the deposit to which it belongs.

Open-Pit Mines

The spatial database for open pits, *CACB_open_pits*, is an Esri polygon shapefile that contains spatial and descriptive information for 87 polygons representing open-pit mines of sediment-hosted copper deposits in the CACB. It provides the areal extent of open pit mining and was designed for use in mineral assessments to define previously mined areas for consideration in the resource assessment process.

Surface extents of open pits were manually digitized from Google Earth™ satellite imagery and the data were then imported into an Esri shapefile. The open pits were given the same name as that of the corresponding mine seen in Google Earth™ or corresponding deposit or prospect. Table B7 lists fields in the database and a short description of each field.

Table B6. Definitions of user-defined attribute fields in the shapefile CACB_orebodies.shp.

Field name	Description
Group_name	Name of group to which ore body belongs. Groups represent clusters of deposits which are grouped together (and for which resource data are aggregated) in order to describe and model grade and tonnage; correlates to Group_name in CACB_deposits_prospects.shp.
Name	Name of deposit to which ore body belongs; correlates to Name in the shapefile CACB_deposits_prospects.shp and to Name in the shapefile CACB_open_pits. (Multiple ore bodies can exist for one deposit)
Area_km^2	Area of the areal extent (as projected to the surface) of the ore body, in square kilometers
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying “GIS references.xlsx” file

Table B7. Definitions of user-defined attribute fields in the shapefile CACB_open_pits.shp.

Field name	Description
Group_name	Name of group to which open pit belongs. Groups represent clusters of deposits which are grouped together (and for which resource data are aggregated) in order to describe and model grade and tonnage
Name	Name of deposit to which open pit belongs; correlates to Name in the shapefile CACB_deposits_prospects and to Name in the shapefile CACB_orebodies
Area_km^2	Area of open pit, in square kilometers
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying “GIS references.xlsx” file

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Appendix C. Principal Sources of Information Used in the Assessment

By Michael L. Zientek[1], James D. Bliss[2], David W. Broughton[3], Michael Christie[4], Paul D. Denning[5], Timothy S. Hayes[2], Murray W. Hitzman[6], John D. Horton[5], Susan Frost-Killian[7], Douglas J. Jack[8], Sharad Master[9], Heather L. Parks[1], Cliff D. Taylor[5], Anna B. Wilson[5], Niki E. Wintzer[1], and Jon Woodhead[10]in

The principal geologic maps used in the assessment are published by the Royal Museum of Central Africa and the Zambia Geological Survey. The Royal Museum of Central Africa publishes material for the Democratic Republic of the Congo, both in hard copy and as geographic information system (GIS) files. Map scales vary from 1:500,000 to 1:100,000. The Zambia Geological Survey published geologic maps at 1:100,000-scale. Where no other information is available for Zambia, we used an older 1:500,000-scale map (table C1).

Mineral occurrence data are essential for conducting mineral resource assessments. In the Democratic Republic of the Congo, compilations and reports published by Armand François summarize the state of knowledge of the state-owned mining company as of the early 1970s. The reports provide information on the type of mineralization (stratiform, vein, and so on), the geologic map unit hosting the site, and some indication of the size or importance of the site. In 1974, there were 72 known deposits, 12 probable deposits, 31 possible deposits, and 121 mineral indications in the Katangan Copperbelt (table 2; François, 1974). Mineral occurrence information for the rest of the Katanga Basin in the Democratic Republic of the Congo is based on a 1:2,000,000-scale mineral occurrence map (Service Géologique de la République du Zaïre, 1976). The publications by Mendelsohn (1961), Fleischer and others (1976), and the 1:100,000-scale geologic maps and 1:1,500,000-scale minerals maps (Legg, 1973) are the chief sources of information for Zambia. The information in global mineral occurrence compilations (Kirkham and others, 1994; Cox and others, 2003) is based largely on these primary sources; however, Kirkham and colleagues were able to add production and resource information using data from mining companies. Significant updates of mineral inventory information were published by Kirkham and Broughton (2005) and Goossens (2007, 2008). Another important source of information was Google Earth™ files created by Richard Huderek, of Antwerp, Belgium (Katangan Copperbelt.kml and Zambian Copperbelt.kml; Huderek, 2008a,b, 2010). These kml databases were conceived as due-diligence for investment but are updated to meet the needs of various non-governmental organizations (NGOs).

Table C1 summarizes the principal sources of information used in this assessment study. Figure C1 is an index map showing the extent of the geologic maps.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

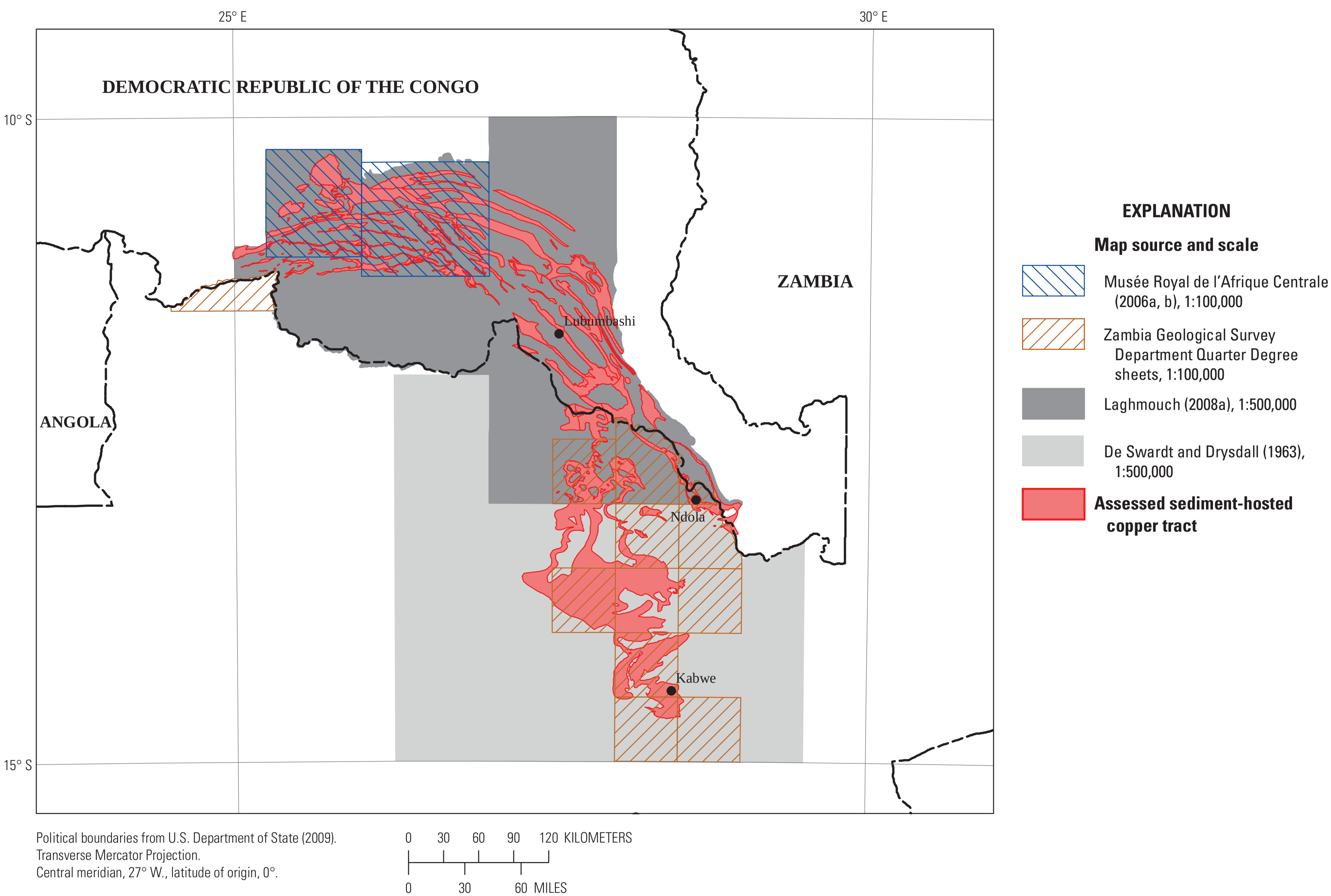
[10]Private Consultant, Duncraig, Perth, Western Australia.

Table C1. Sources of geologic maps and mineral occurrence information.

Name or title	Scale	Citation
Geology		
Carte géologique de la région de Kolwezi-Kalukundi (Shaba) République du Zaïre [Geological map of the Kolwezi-Kalukundi area (Shaba) Republic of Zaire]	1:100,000	François and Lepersonne (1978)
Carte géologique de la République Démocratique du Congo, Region de Kolwezi-Kalukundi, Partie ouest de l'arc cuprifère du Katanga [Geological map of the Democratic Republic of the Congo, Kolwezi-Kalukundi region Western Katanga Copper Arc] [GIS and raster]	1:100,000	Musée royal de l'Afrique centrale (2006a)
Carte géologique de la République Démocratique du Congo, Region de Likasi, Partie centrale de l'arc cuprifère du Katanga [Geologic map of the Democratic Republic of Congo, Likasi Region, central part of the Katangan Copperbelt] [GIS and raster]	1:100,000	Musée royal de l'Afrique centrale (2006b)
Geological map covering Map Sheet 1228C2 (Mufulira-East)	1:100,000	Czech Geological Survey (2007)
Geological map of Chief Kanyama's area	1:100,000	Key and Banda (2000)
Geological map of the Bwana Mkubwa area	1:100,000	Moore (1968a)
Geological map of the Chingola area	1:100,000	Garrard (1994)
Geological map of the Chipembi area	1:100,000	Arthurs and others (1995)
Geological map of the Chisamba area	1:100,000	Moore (1964)
Geological map of the Kabwe area	1:100,000	Cairney and Kerr (1997)
Geological map of the Kapiri Mposhi area	1:100,000	Smith (1965)
Geological map of the Kitwe-Mufulira area	1:100,000	Marjonen (2000)
Geological map of the Luanshya area	1:100,000	Hickman (1992)
Geological map of the Mukubwe area	1:100,000	Keppie (1994)
Geological map of the Ndola area	1:100,000	Moore (1968b)
Carte géologique et miniere de la République Démocratique du Congo, L'arc cuprifère du Katanga, etat des connaissances 2008 [Geologic and mineralization map of the Democratic Republic of the Congo, Katanga copper arc, state of knowledge in 2008] [GIS and raster]	1:500,000	Musée royal de l'Afrique centrale (2008)
Provisional geological map of part of the western, north-western, central, and southern provinces of Northern Rhodesia	1:500,000	De Swardt and Drysdall (1963)
Geological map of the Republic of Zambia, second edition	1:1,000,000	Thieme and Johnson (1981)
Carte géologique du Zaïre [Geologic map of Zaire]	1:2,000,000	Lepersonne (1974)
Mineral occurrences database and GIS map of the Democratic Republic of Congo	1:2,000,000	Chartry and Franceschi (2004)

Table C1. Sources of geologic maps and mineral occurrence information.—Continued

Name or title	Scale	Citation
Mineral deposits and occurrence		
Carte géologique et miniere de la République Démocratique du Congo, L'arc cuprifère du Katanga, etat des connaissances 2008 [Geologic and mineralization map of the Democratic Republic of the Congo, Katanga copper arc, state of knowledge 2008] [GIS and raster]	1:500,000	Musée royal de l'Afrique centrale (2008)
Geological dataset of the Central African Copperbelt	1:500,000	GeoPubs (1998)
Stratigraphie, tectonique et minéralisations dans l'arc cuprifère du Shaba (République du Zaïre) [Stratigraphy, tectonics and mineralizations in the Shaba copper-bearing arc (Republic of Zaire)]	1:500,000	François (1974)
Carte des gîtes minéraux du Zaïre [Map of mineral deposits of Zaire] (1st edition)	1:2,000,000	Service Géologique de la République du Zaïre (1976)
A prospector's guide to mineral occurrences in Northern Rhodesia	1:1,000,000	Guernsey (1952)
Provisional mineral map of the Republic of Zambia	1:1,500,000	Legg (1973)
Mineral occurrences database and GIS map of the Democratic Republic of Congo	1:2,000,000	Chartry and Franceschi (2004)
Digital international metallogenic map of Africa	1:5,000,000	Veselinovic-Williams and Frost-Killian (2003)
Sediment-hosted copper deposits of the world: Deposit models and database		Cox and others (2003)
La partie centrale de l'Arc cuprifère du Katanga; étude géologique [The central part of the Katanga Copperbelt; geologic study]	Varies	François (2006)
Description of mineral deposits on the Copperbelt (and Kabwe, Nampundwe)	Varies	Freeman (1988)
Katangan_copperbelt.kml	Varies	Huderek (2008a)
Zambian_copperbelt.kml	Varies	Huderek (2008b)
Katangan_copperbelt.kml	Varies	Huderek (2010)
Global distribution of sediment-hosted stratiform copper deposits and occurrences	Varies	Kirkham and others (1994)
World distribution of sediment-hosted, stratiform copper deposits and occurrences	Varies	Kirkham and others (2003)
Supplement to the sediment-hosted stratiform copper ore system	Varies	Kirkham and Broughton (2005)
Phoenix rising in an uncertain world—New mining activities in Katanga	Varies	Goossens (2007)
Annex 2—Evaluation of DRC mineral resources—Report prepared for the World Bank, November-December, 2006	Varies	Goossens (2008)



Political boundaries from U.S. Department of State (2009).
Transverse Mercator Projection.
Central meridian, 27° W., latitude of origin, 0°.

Figure C1. Index map showing sources of geologic mapping in relation to the Roan Group permissive tracts, Democratic Republic of the Congo and Zambia.

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Appendix D. Deposits and Prospects Within the Roan Group, Democratic Republic of the Congo and Zambia

By Michael L. Zientek[1], James D. Bliss[2], David W. Broughton[3], Michael Christie[4], Paul D. Denning[5], Timothy S. Hayes[2], Murray W. Hitzman[6], John D. Horton[5], Susan Frost-Killian[7], Douglas J. Jack[8], Sharad Master[9], Heather L. Parks[1], Cliff D. Taylor[5], Anna B. Wilson[5], Niki E. Wintzer[1], and Jon Woodhead[10]

This appendix consists of a table and an Excel file that contain detailed information about the sediment-hosted stratabound copper deposits and prospects in the study area. Table D1 is a summary of information included in the Excel file, sorted by tract, site status, and site name. The workbook *AppendixD_RoanDepositsProspects.xlsx* has one worksheet that contains more information about the sites listed in table D1 and a second worksheet of references cited. Both worksheets are also available as tab-delimited text files, AppendixD_RoanDepositsProspects.txt and AppendixD_RoanDepositsProspectsRefs.txt.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

[10]Private Consultant, Duncraig, Perth, Western Australia.

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.

[Mt, million metric tons. Country code; DC, Democratic Republic of the Congo; ZM, Zambia. Deposit subtype; rfCuCE, reduced-facies copper-carbonate écaille; rfCuNB, reduced-facies copper, non-brecciated; ssCuRA, sandstone copper-Roan arenite. Significant and giant deposits have more than 50,000 and 2,000,000 metric tons contained copper, respectively. Criteria used to rank prospects described in appendix E; –, no data]

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille									
Bangwe	10.7289	26.3839	DC	rfCuCE	Deposit	–	0.24	4.30	0.300
Dilala East	10.695	25.47	DC	rfCuCE	Deposit	Significant deposit	38.2	2.92	0.868
Etoile	11.6354	27.5841	DC	rfCuCE	Deposit	Significant deposit	29.7	4.32	0.312
Etoile Extension	11.6301	27.5597	DC	rfCuCE	Deposit	–	3.13	0.30	0.610
Fwalu	10.5807	26.155	DC	rfCuCE	Deposit	Significant deposit	40.3	2.46	0.173
Kababankola	10.7333	26.4227	DC	rfCuCE	Deposit	–	1.89	1.62	1.120
Kamatanda	10.951	26.7727	DC	rfCuCE	Deposit	–	0.40	4.90	0.000
Kamfundwa	10.8152	26.58916	DC	rfCuCE	Deposit	Significant deposit	26.8	2.72	0.200
Kamoya	10.8859	26.57362	DC	rfCuCE	Deposit	Significant deposit	10.0	2.70	0.450
Kamwale	11.1431	27.1871	DC	rfCuCE	Deposit	Significant deposit	1.56	4.92	1.960
Kananga	10.6892	25.4588	DC	rfCuCE	Deposit	Significant deposit	8.1	1.80	0.884
Karavia	11.6667	27.281	DC	rfCuCE	Deposit	–	0.55	3.92	0.000
Karu East	11.6277	27.2764	DC	rfCuCE	Deposit	Significant deposit	5.5	1.80	0.000
Kasonta	11.5996	27.2749	DC	rfCuCE	Deposit	Significant deposit	1.5	5.18	0.000
Kasonta South	11.6101	27.2718	DC	rfCuCE	Deposit	Significant deposit	4.4	1.64	0.000
Kazibizi	10.8428	26.6045	DC	rfCuCE	Deposit	–	1.0	3.20	0.600
Kipapila	12.0173	27.9023	DC	rfCuCE	Deposit	Significant deposit	2.6	4.40	0.540
Kipoi North	11.2448	27.092	DC	rfCuCE	Deposit	Significant deposit	5.27	1.36	0.050
Kiwana II	10.737	26.3055	DC	rfCuCE	Deposit	–	0.082	2.70	0.350

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Kolwezi	10.7259	25.4581	DC	rfCuCE	Deposit	Significant deposit	20.0	6.00	0.010
Kwatebala	10.5793	26.18883	DC	rfCuCE	Deposit	Giant deposit	115.0	1.95	0.362
Lufomboshi	10.7521	26.2381	DC	rfCuCE	Deposit	–	0.225	1.98	0.060
Luishia	11.1668	27.0087	DC	rfCuCE	Deposit	Significant deposit	49.4	3.16	0.401
Luiswishi	11.5151	27.4391	DC	rfCuCE	Deposit	Significant deposit	8.0	2.50	1.100
Luita	10.7394	26.286	DC	rfCuCE	Deposit	–	0.438	2.90	0.600
Lukuni	11.506	27.4207	DC	rfCuCE	Deposit	Significant deposit	2.70	4.30	0.100
Lupoto	11.5993	27.2631	DC	rfCuCE	Deposit	Significant deposit	37.1	2.63	0.088
M'Sesa	10.8503	26.6099	DC	rfCuCE	Deposit	Significant deposit	8.0	5.90	0.213
Mukondo	10.7244	26.3487	DC	rfCuCE	Deposit	Significant deposit	36.3	2.00	1.400
Mutanda-Ya-Mukonkota	10.786	25.8135	DC	rfCuCE	Deposit	Giant deposit	300	1.23	0.588
Mutoshi	10.6817	25.5386	DC	rfCuCE	Deposit	Significant deposit	10.8	4.20	0.304
Mutoshi (breche)	10.6816	25.53846	DC	rfCuCE	Deposit	Significant deposit	45.5	1.75	0.000
Mutoshi Northwest	10.6726	25.5174	DC	rfCuCE	Deposit	Significant deposit	10.0	4.00	0.000
Mwandinkomba	10.5963	26.2049	DC	rfCuCE	Deposit	Significant deposit	35.4	3.16	0.138
Niamumenda	11.6024	27.2922	DC	rfCuCE	Deposit	Significant deposit	2.60	2.25	2.308
Ruashi	11.619	27.5444	DC	rfCuCE	Deposit	Significant deposit	45.8	2.81	0.246
Saafi	10.7401	26.4204	DC	rfCuCE	Deposit	–	0.181	2.70	0.300
Shamitumba	10.9571	26.60978	DC	rfCuCE	Deposit	–	0.175	3.30	0.700
Shituru	11.0157	26.76382	DC	rfCuCE	Deposit	Significant deposit	7.86	4.39	0.680

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Taratara	10.7245	26.3667	DC	rfCuCE	Deposit	–	0.165	1.83	0.920
Tenke	10.6015	26.1372	DC	rfCuCE	Deposit	Giant deposit	122	2.06	0.276
DIMA	10.7423	25.3785	DC	rfCuCE	Group	Giant deposit	280	2.79	0.189
Disele/Kankeru	10.7525	26.2544	DC	rfCuCE	Group	Significant deposit	4.05	2.69	0.068
Fungurume	10.6153	26.2966	DC	rfCuCE	Group	Giant deposit	64.3	4.33	0.362
Kabolela North and South	10.8463	26.4788	DC	rfCuCE	Group	Significant deposit	11.7	2.31	0.501
Kakanda East-Kakanda North-Kakanda South	10.7351	26.4026	DC	rfCuCE	Group	Significant deposit	32.4	2.90	0.180
Kalukundi-Kii	10.6326	25.9347	DC	rfCuCE	Group	Significant deposit	12.8	2.43	0.458
Kalumbwe-Myunga	10.7724	25.91098	DC	rfCuCE	Group	Significant deposit	1.45	3.74	0.540
Kambove Principal-Kambove West	10.8862	26.6044	DC	rfCuCE	Group	Giant deposit	46.9	6.59	0.213
Kamoto-KOV-Musonie-Mupine	10.7108	25.4194	DC	rfCuCE	Group	Giant deposit	416	4.49	0.387
Kansalawile-Mambilima	10.6183	26.2278	DC	rfCuCE	Group	Giant deposit	113	2.48	0.164
Principal-Anticline	10.6523	25.9252	DC	rfCuCE	Group	Significant deposit	14.5	2.62	0.716
Bumen	11.5989	27.2484	DC	rfCuCE	Prospect	–	–	–	–
Chabara	10.7402	25.8548	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Deziwa	10.7959	25.71277	DC	–	Prospect	–	–	–	–
Judeira	11.2235	27.06448	DC	rfCuCE?	Prospect	Significant prospect, rank 3	–	–	–
Kabolela East	10.8585	26.48542	DC	rfCuCE	Prospect	–	–	–	–
Kabunda North	10.5432	25.4995	DC	–	Prospect	Significant prospect, rank 3	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Kabwelunono	10.5978	26.1322	DC	rfCuCE	Prospect	–	–	–	–
Kabwimia	10.7386	25.7674	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Kakavilondo	10.6113	26.12492	DC	rfCuCE	Prospect	–	–	–	–
Kakontolwa	10.724	25.89286	DC		Prospect	–	–	–	–
Kalabi	10.7815	26.74261	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Kalukundi West	10.6262	25.9139	DC	–	Prospect	Significant prospect, rank 3	–	–	–
Kamoya East	10.883	26.58109	DC	rfCuCE	Prospect	–	–	–	–
Kamoya West	10.8782	26.57916	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Kampase	10.7523	25.4153	DC	rfCuCE	Prospect	–	–	–	–
Kampesimpesi	11.209	27.20774	DC	rfCuCE	Prospect	–	–	–	–
Kampina	10.7823	26.61506	DC	–	Prospect	Significant prospect, rank 2	–	–	–
Kanshishi	11.14	26.95464	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Kansongwe	11.1517	26.9932	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Kanunka	10.7719	25.62007	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Karajipopo	10.9774	26.69007	DC	rfCuCE	Prospect	–	–	–	–
Karoano	11.1571	26.95188	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Karoanzo	10.7206	26.3833	DC	rfCuCE	Prospect	–	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Kasombo I	11.6743	27.3151	DC	rfCuCE	Prospect	–	–	–	–
Kasombo II	11.6817	27.30696	DC	rfCuCE	Prospect	–	–	–	–
Kebumba	11.1433	27.16266	DC	rfCuCE	Prospect	–	–	–	–
Kesho	10.6496	25.9372	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Kilamusembe	10.715	25.38095	DC	rfCuCE	Prospect	–	–	–	–
Kingamyambo	10.6988	25.42938	DC	rfCuCE	Prospect	–	–	–	–
Kinsankata	10.6123	25.8851	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Kisanfu	10.772	25.93753	DC	–	Prospect	Significant prospect, rank 1	–	–	–
Likasi	11.0032	26.74284	DC	rfCuCE	Prospect	–	–	–	–
Ludjiba	10.9702	26.55717	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Mabaya	12.1331	27.7797	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Manda	10.6569	26.41474	DC	rfCuCE	Prospect	–	–	–	–
Mashitu	10.6656	25.90741	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Mukandila	10.6311	26.24657	DC	rfCuCE	Prospect	–	–	–	–
Mupapala	10.7553	26.2102	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Musonie East	10.7096	25.46306	DC	rfCuCE	Prospect	significant prospect, rank 1	–	–	–
Mutaka North	10.7567	26.52203	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Mwati	12.0614	27.9623	DC	rfCuCE	Prospect	–	–	–	–
Nimura	10.8169	26.7132	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Nioka East	10.7365	25.45735	DC	rfCuCE	Prospect	–	–	–	–
Nioka West	10.7314	25.43476	DC	rfCuCE	Prospect	–	–	–	–
Pumpi	10.6372	26.05222	DC	rfCuCE	Prospect	–	–	–	–
Pumpi South	10.6395	25.99792	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Pungulume	10.6126	25.747	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Pungulume Southeast	10.6242	25.76376	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Sefu	10.5704	26.17374	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Shandwe	11.1583	27.0963	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Shimbidi	10.5911	26.1427	DC	rfCuCE	Prospect	–	–	–	–
Shinkusu	10.5842	26.1721	DC	rfCuCE	Prospect	–		–	–
Siniaparara	10.8769	26.5029	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Unnamed	11.7014	27.3684	DC	–	Prospect	–	–	–	–
Zaka	10.6446	26.24279	DC	rfCuCE	Prospect	–	–	–	–
Northern carbonate écaille									
Kimbwe	11.1454	27.4943	DC	rfCuCE	Deposit	Giant deposit	50.0	4.00	0.000
Kinsevere	11.3604	27.5733	DC	rfCuCE	Group	Giant deposit	50.2	4.09	0.000
Kakonge East	10.6572	26.8221	DC	rfCuCE?	Prospect	–	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Central carbonate écaille—Continued									
Kakonge West	10.6559	26.7947	DC	rfCuCE?	Prospect	Significant prospect, rank 3	–	–	–
Kapota Central	11.2251	27.4955	DC	rfCuCE	Prospect	–	–	–	–
Kapota South	11.2515	27.486	DC	rfCuCE	Prospect	–	–	–	–
Kapota Southwest	11.2385	27.4699	DC	rfCuCE	Prospect	–	–	–	–
Kapota West	11.2306	27.4615	DC	rfCuCE	Prospect	–	–	–	–
Kasala	11.0898	27.4241	DC	rfCuCE?	Prospect	Significant prospect, rank 1	–	–	–
Mapandwe	11.2233	27.5438	DC	rfCuCE	Prospect		–	–	–
Nambulwa	11.1402	27.52031	DC	rfCuCE?	Prospect	Significant prospect, rank 3	–	–	–
Tondo	10.51	25.67505	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Wusumbu	11.1441	27.5141	DC	rfCuCE?	Prospect	–	–	–	–
Ore shale									
Chambishi Southeast	12.7	28.1061	ZM	rfCuNB	Deposit	Giant deposit	178	2.13	0.069
Fitwaola	12.4085	27.8806	ZM	rfCuNB	Deposit	Significant deposit	3.45	2.94	0.090
Ichimpe	12.7351	28.1493	ZM	rfCuNB	Deposit	Significant deposit	3.1	1.78	0.000
Pitanda	12.6539	27.9886	ZM	rfCuNB	Deposit	Significant deposit	15.0	1.70	0.000
Baluba-Muliashi-Luanshya	13.0831	28.3267	ZM	rfCuNB	Group	Giant deposit	405	2.55	0.039
Chambishi Main and West	12.658	28.0426	ZM	rfCuNB	Group	Giant deposit	116	2.53	0.240
Chingola-Nchanga	12.523	27.8467	ZM	rfCuNB	Group	Giant deposit	567	2.80	0.023
Konkola-Musoshi	12.3453	27.7985	ZM	rfCuNB	Group	Giant deposit	774	2.90	0.065
Mindola-Nkana N-S	12.8233	28.1908	ZM	rfCuNB	Group	Giant deposit	702	2.17	0.061
Luano	12.5139	27.9087	ZM	rfCuNB	Prospect	–	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Roan arenite									
Bwana Mkubwa	13.0315	28.6923	ZM	ssCuRA	Deposit	Significant deposit	8.6	3.34	0.000
Chibuluma South	12.9125	28.0809	ZM	ssCuRA	Deposit	Significant deposit	7.37	3.70	0.017
Chifupu	12.9307	28.0703	ZM	ssCuRA	Deposit	Significant deposit	1.94	3.05	0.000
Fitula	12.6599	27.8717	ZM	ssCuRA	Deposit	Significant deposit	4.5	5.00	0.000
Itawa	12.9617	28.668	ZM	ssCuRA	Deposit	Significant deposit	40.0	0.76	0.000
Kasaria-Luansobe	12.4497	28.1386	ZM	ssCuRA	Deposit	Significant deposit	21.5	2.31	0.000
Kinsenda	12.2614	27.9655	DC	ssCuRA	Deposit	Significant deposit	35.0	5.50	0.000
Lubembe	12.3571	28.0949	DC	ssCuRA	Deposit	Significant deposit	47.5	2.20	0.000
Mokambo North	12.4262	28.3221	ZM	ssCuRA	Deposit	Significant deposit	3.85	1.70	0.000
Mufulira	12.5198	28.2285	ZM	ssCuRA	Deposit	Giant deposit	332	2.66	0.040
Mutundu North	12.5845	28.3409	ZM	ssCuRA	Deposit	Significant deposit	4.3	1.44	0.000
Mwambashi B	12.7232	27.9687	ZM	ssCuRA	Deposit	Significant deposit	14.2	1.78	0.000
Mwerkera	12.7998	28.5007	ZM	ssCuRA	Deposit	Significant deposit	7.1	1.53	0.000
Ndola East	12.9012	28.6094	ZM	ssCuRA	Deposit	Significant deposit	40	0.76	0.000
Nsato	12.4849	28.188	ZM	ssCuRA	Deposit	Significant deposit	8.4	1.61	0.000
Pitanda South	12.6738	27.9612	ZM	ssCuRA	Deposit	Significant deposit	7.06	1.58	0.000
Sebembere	14.3479	28.3347	ZM	ssCuRA	Deposit	Significant deposit	5.7	1.70	0.000
Chibuluma-Chibuluma West	12.8232	28.0933	ZM	ssCuRA	Group	Significant deposit	19.9	3.69	0.186

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Roan arenite—Continued									
Mimbula	12.6266	27.8611	ZM	ssCuRA	Group	Significant deposit	46.9	1.20	0.000
Mokambo Project - Mokambo South	12.4828	28.3811	ZM	ssCuRA	Group	Significant deposit	20.9	1.64	0.000
Chabwanyama	12.6091	27.8478	ZM	ssCuRA	Prospect	–	–	–	–
Chiwempala	12.5754	27.8214	ZM	ssCuRA	Prospect	–	–	–	–
Kabula	12.9325	27.8574	ZM	ssCuRA	Prospect	–	–	–	–
Kalulushi	12.8459	28.0654	ZM	ssCuRA	Prospect	–	–	–	–
Kasabi	12.3197	28.327	DC	–	Prospect	–	–	–	–
Katchili	12.1321	28.0452	DC	–	Prospect	–	–	–	–
Kawiri South	12.3858	27.9113	ZM	ssCuRA	Prospect	–	–	–	–
Lufubu South	13.0825	28.2455	ZM	ssCuRA	Prospect	–	–	–	–
Manner's Farm	12.9488	28.6509	ZM	ssCuRA	Prospect	–	–	–	–
Nchanga Nose	12.5213	27.9194	ZM	ssCuRA	Prospect	–	–	–	–
Ndola	12.9877	28.6201	ZM	ssCuRA	Prospect	–	–	–	–
Ndola South	13.0649	28.8221	ZM	ssCuRA	Prospect	–	–	–	–
Ndola West	12.9744	28.58569	ZM	ssCuRA	Prospect	–	–	–	–
Rymar	12.9312	28.6376	ZM	ssCuRA	Prospect	–	–	–	–
Southern carbonate écaille									
Kalongwe	11.0171	25.2259	DC	rfCuCE	Deposit	significant deposit	3.0	5.00	0.000
Shinkolobwe Signal	11.0494	26.5706	DC	rfCuCE	Deposit	–	0.125	3.17	1.697
Djambelwa	11.044	26.6015	DC	rfCuCE	Prospect	–	–	–	–
Guluwe	11.0283	26.5815	DC	rfCuCE	Prospect	–	–	–	–
Kafumbaswambo	11.0928	26.20139	DC	rfCuCE	Prospect	–	–	–	–
Kamonga West	10.992	26.1742	DC	rfCuCE	Prospect	–	–	–	–
Kampamba	10.8435	25.89723	DC	rfCuCE	Prospect	–	–	–	–
Kanaronga	10.971	25.4556	DC	rfCuCE	Prospect	–	–	–	–
Kasompi West	10.9765	25.8882	DC	–	Prospect	Significant prospect, rank 1	–	–	–

Table D1. Deposits and prospects associated with the Roan Group, Katanga Basin, Democratic Republic of the Congo and Zambia.—Continued

Site name	Latitude (degrees south)	Longitude (degrees east)	Country code	Deposit subtype	Site status	Rank	Tonnage (Mt)	Copper (%)	Cobalt (%)
Kavundi Northwest	10.9641	25.9859	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Kavungo	10.9555	26.00218	DC	rfCuCE	Prospect	–	–	–	–
Kawesitu North	11.0782	26.25083	DC	rfCuCE	Prospect	–	–	–	–
Kiamoto	11.1497	26.1664	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Kiamoto West	11.1541	26.1392	DC	rfCuCE	Prospect	–	–	–	–
Kibolwe	11.1713	26.19907	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Lufungu	10.9703	25.795	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Menda	10.9712	25.9324	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Milebi	10.9018	26.18	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Mindigi	11.0994	26.1784	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Mirungwe	11.0957	26.18068	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–
Mwombe	11.1106	26.40692	DC	rfCuCE	Prospect	Significant prospect, rank 1	–	–	–
Shomberwa	11.0346	26.65895	DC	rfCuCE	Prospect	Significant prospect, rank 2	–	–	–
Swambo	11.0951	26.22347	DC	rfCuCE	Prospect	Significant prospect, rank 3	–	–	–

Appendix E. Sediment-Hosted Stratabound Copper Assessment for Tract 002rfceCu1000a–c, Southern, Central, and Northern Carbonate Écaille, Democratic Republic of the Congo

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Deposit Type Assessed

Deposit type: Sediment-hosted stratabound copper

Descriptive model: Sediment-hosted stratabound copper—reduced-facies, carbonate écaille subtype (Cox, 2003; Hayes and others, in press; Zientek, Hayes, and Hammarstrom, 2013)

Grade and tonnage model: Sediment-hosted stratabound copper—reduced-facies, carbonate écaille subtype (Zientek, Hayes, and Taylor, 2013; appendix E)

Table E1 summarizes selected assessment results.

Table E1. Summary of selected resource assessment results for the Carbonate écaille tracts (002rfceCu1000a, b, c), Democratic Republic of the Congo.

[km^2, square kilometers]

Tract coded ID and name	Date of assessment	Assessment depth (kilometers)	Tract area (km^2)	Known copper resources (metric tons)	Mean estimate of undiscovered copper resources (metric tons)	Median estimate of undiscovered copper resources (metric tons)
002rfceCu1000a–Southern carbonate écaille	January 2010	2	1,330	150,000	13,000,000	9,100,000
002rfceCu1000b–Central carbonate écaille	January 2010	2	3,540	61,000,000	130,000,000	120,000,000
002rfceCu1000c–Northern carbonate écaille	January 2010	2	4,310	4,100,000	12,000,000	9,600,000

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

[10]Private Consultant, Duncraig, Perth, Western Australia.

Location

This tract forms an arcuate belt in the Democratic Republic of the Congo (DRC) that extends from Kolwezi in the west, through Kambove and Likasi, to Lubumbashi in the southeast.

Geologic Feature Assessed

Neoproterozoic Mines Subgroup of the Roan Group in the Katanga Basin.

Delineation of the Permissive Tract

Geologic Criteria

The assessment unit used to delineate permissive tracts is the Mines Subgroup (R.2) of the Roan Group in the DRC (fig. E1; Cailteux, 1994; Cailteux and others, 2005; François, 2006). The stratigraphic interval contains reduced, organic-bearing strata and overlies the oxidized red beds of the R.A.T. Formation. These reduced strata served as the site of mineral deposition from oxidized, copper-bearing ore-fluids that were derived from, and were in equilibrium with, the red beds. Mineralized Mines Subgroup strata can be mapped and correlated from the Kolwezi (Kamoto) and Tenke Fungurume areas to the Etoile deposit (figs. E2 and E3). Southeast of Etoile, there is a 50-km-gap in exposure to the Kipapila deposit, on the northwest side of the Luina Dome, where a condensed Mines Subgroup section is recognized. Variations in the thickness and facies of the Mines Subgroup are parallel to the structural trends (folds and faults) of the rocks (fig. E4). Outcrop trends are controlled by postdepositional structural features.

The Mines Subgroup occurs only in gigabreccia fragments within Roan breccia. The Roan breccias in the DRC occur in (1) regional detachments for anticlines, overthrusted flanks of anticlines, or klippen; (2) local detachments within klippen; (3) discordant diapiric intrusions; and (4) late-formed, oblique, strike-slip fault zones. The nature of the breccia exposure varies systematically within the tract. In the southwest, most exposures are in diapiric intrusions and the strike-slip fault zones; away from the area of diapirs, the breccia is spatially within regional detachments and is found in the cores of folds or along thrust welds[11]. The size of the breccia fragments is smaller within the diapirs and fault zones than in the folds and thrust welds.

One of the first geologists to study the Belgian Congo, Jules Cornet, noted that the mineralized beds in the Katangan Copperbelt are rather easy to locate because they are within denuded hills in the landscape (Pirard, 2011). This observation was insightful because strata in the Mines Subgroup are resistant to weathering, and vegetation plays an important role in effectively mapping areas with copper mineralization. Early in the exploration of the copperbelt, prospectors and geologists observed that clearings, or dambos[12], over the Roan Group were underlain by copper-bearing strata. The clearings, referred to as “copper clearings” or “copper dambos,” lack trees but support a distinct flora that is tolerant of high concentrations of copper (fig. E5; Horscroft, 1961; Faucon and others, 2010).

The distribution of gigabreccia fragments within the Mines Subgroup is shown on 1:100,000-scale maps for Kolwezi and Likasi (Musée royal de l’Afrique centrale, 2006a,b). Rocks of the Mines Subgroup are resistant to erosion and can be recognized on topographic maps and digital elevation models. High relief areas can be seen in the northern portion of figure E6. The topographic expression is particularly pronounced in the Congo River watershed, where the Tertiary erosion surface has been dissected. Individual gigabreccia fragments are not shown on the 1:500,000-scale maps, but the digital elevation model (DEM) and maps in technical reports released by mining companies show that they crop out as far south as the Etoile deposit, about 40 km to the southeast of the drainage divide between the Congo and the Zambezi Rivers. Following the gap in exposure, gigabreccia fragments are mapped also in the Kipapila area.

The permissive areas for the Roan sub-tracts (002rfceCu1000a, b, c) in the Democratic Republic of the Congo are delineated by estimating the location of the volume of rock within the Mines Subgroup that contains gigabreccia fragments to a depth of 2 km and projecting it to the surface (fig. E7). The volume of rock containing Mines Subgroup fragments was estimated using published geologic maps and cross sections, specifically the digital 1:500,000 Arc Cuprifère du Katanga geologic map (Musée royal de l’Afrique centrale, 2008b), 12 cross sections (François and Cailteux, 1981; Jackson and others, 2003; François, 2006), and structural data from these sources.

[11]Fault weld is a fault surface or fault zone joining strata originally separated by autochtonous or allochtonous salt; equivalent to a salt weld along which there has been significant fault slip or shear (Jackson and Talbot, 1991).

[12]A term used in central Africa for a small, ill-defined floodplain or channelless drainageway that is extremely flat with broad, grassy clearings, swampy during the wet season but dry for the greater part of the year (AGI Glossary of Geology Online).

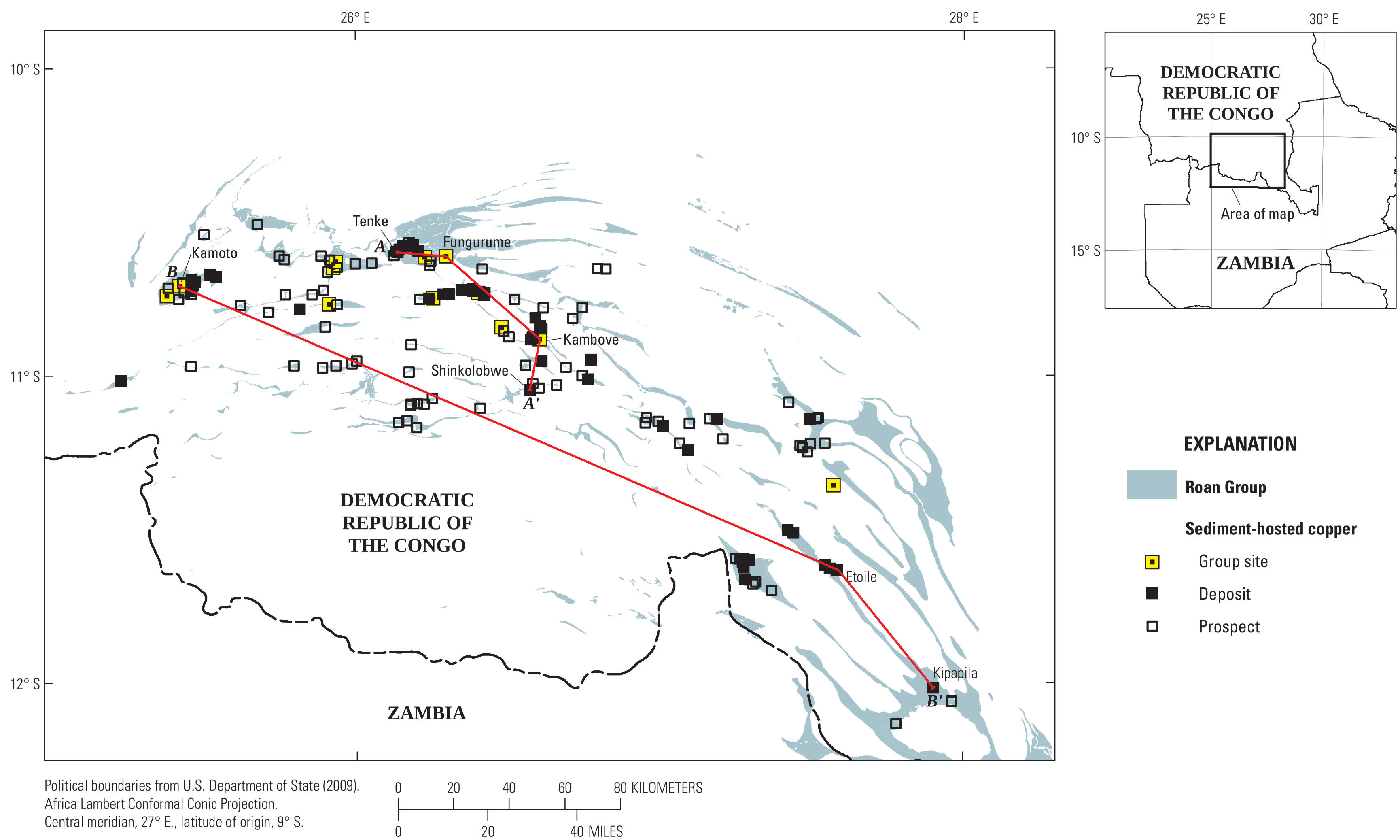


Figure E1. Map showing distribution of rocks of the Roan Group in the Democratic Republic of the Congo, the location of sediment-hosted stratabound copper deposits and prospects, and section lines for figures E2 and E3. Roan outcrops from Musée royal de l’Afrique centrale (2008a).

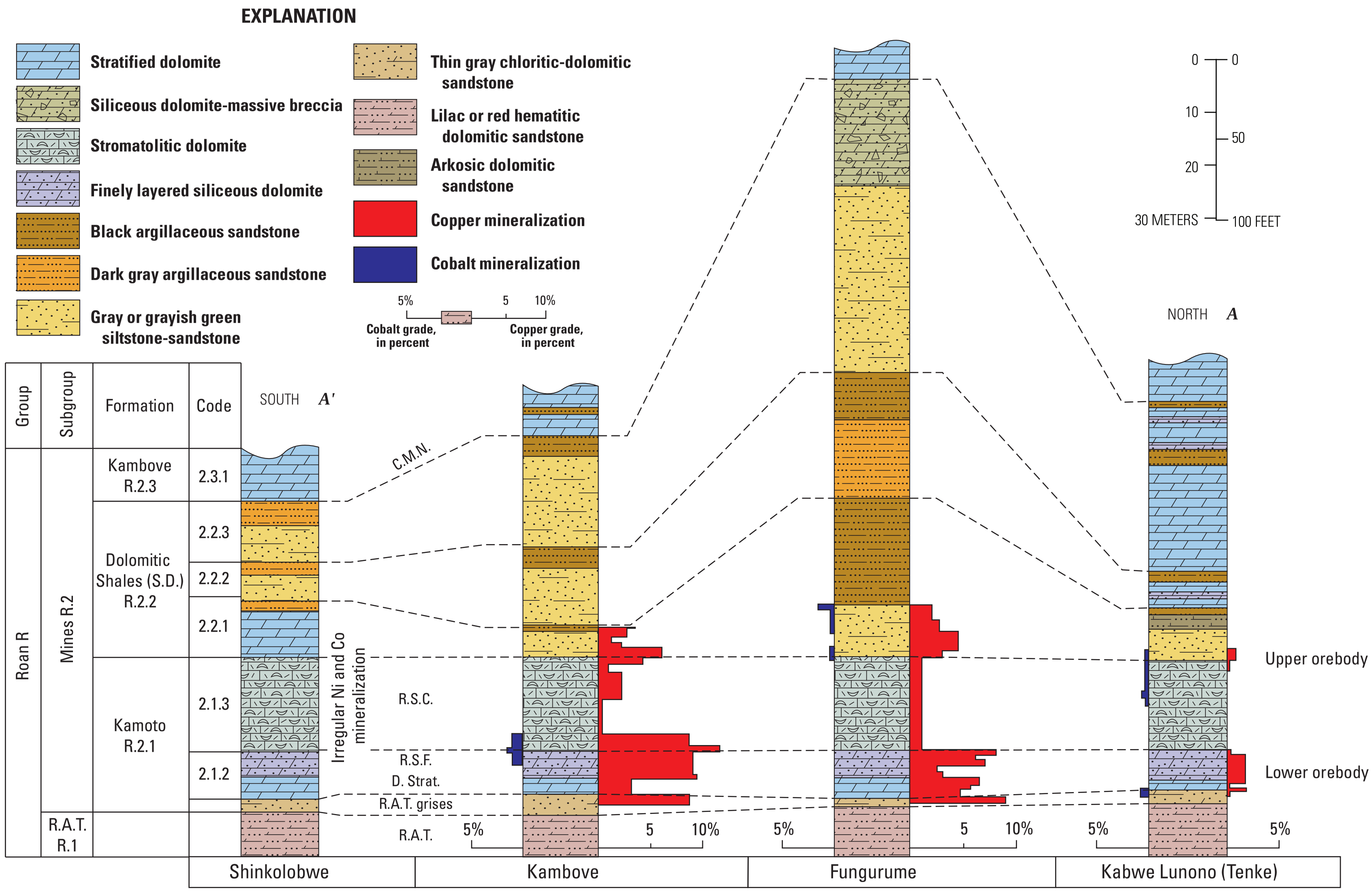


Figure E2. Stratigraphic columns showing north to south correlation of the Mines Subgroup and associated mineralization in the Central African Copperbelt, Democratic Republic of the Congo. Section line locations are shown in figure E1. Stratigraphic abbreviations: C.M.N.—"Calcaire à Minerais Noirs" (black limestone ore); R.S.C.—"Roches Siliceuses Cellulaires" (cellular siliceous rocks); R.S.F.—"Roches Siliceuses Feuilletées" (laminated siliceous rocks); D. Strat.—"Dolomies Stratifies" (laminated dolomites); R.A.T. grises—"Roches Argilo-Talqueuses Grises" (gray clayey talcose rocks); and R.A.T.—"Roches Argilo-Talqueuses" (clayey talcose rocks). Modified from François (2006).

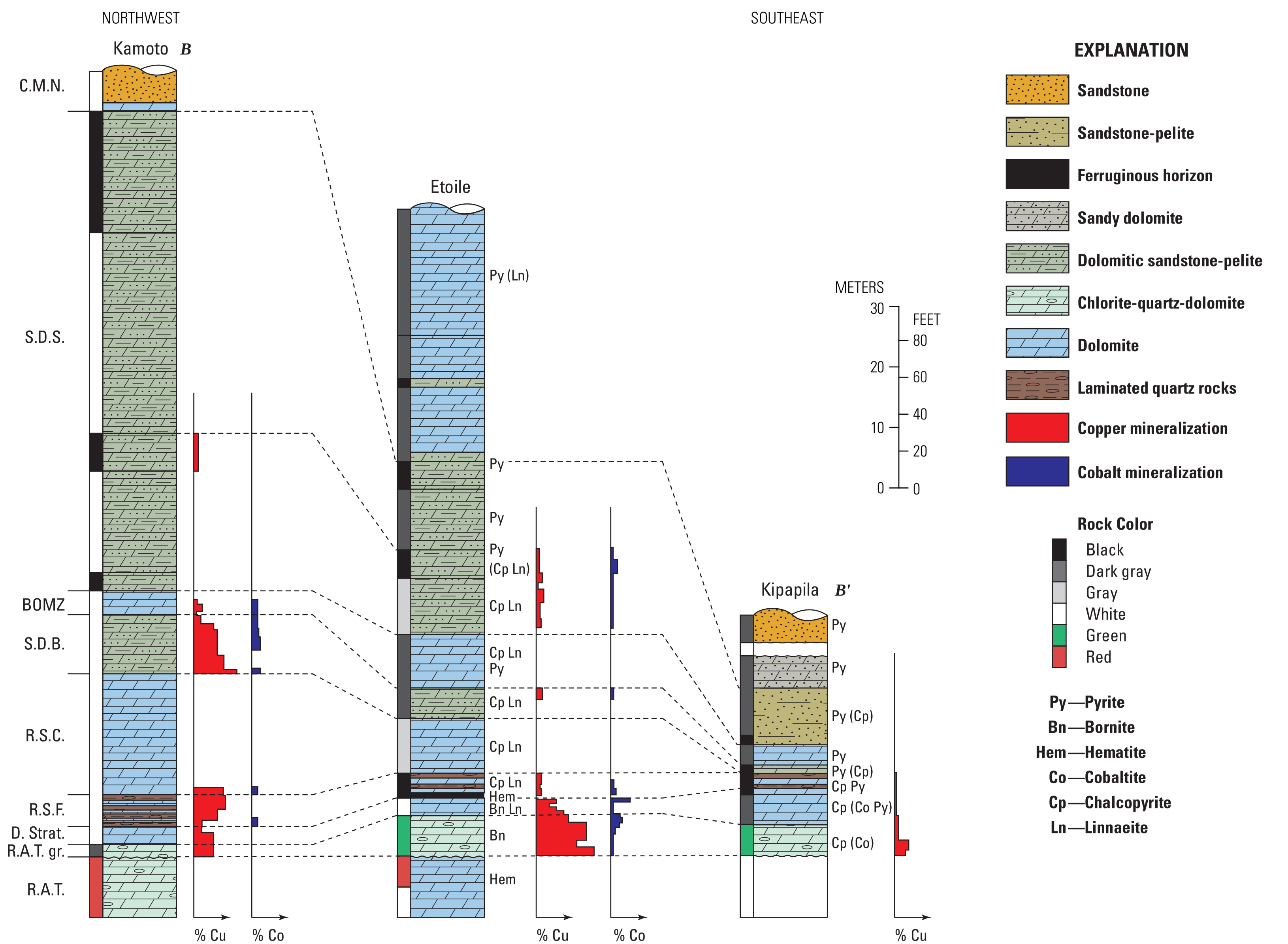


Figure E3. Stratigraphic columns showing northwest to southeast continuity of reduced-facies—carbonate écaille copper mineralization in the Mines Subgroup, Central African Copperbelt, Democratic Republic of the Congo. Section line locations are shown in figure E1. Stratigraphic abbreviations: C.M.N.—"Calcaire à Minerais Noirs" (black limestone ore); S.D.S.—"Schistes Dolomitiques Supérieures" (upper dolomitic shales); BOMZ—(black ore main zone); S.D.B.—"Schistes Dolomitiques De Base" (basal dolomitic shales); R.S.C.—"Roches Siliceuses Cellulaires" (cellular siliceous rocks); R.S.F.—"Roches Siliceuses Feuilletées" (laminated siliceous rocks); D. Strat.—"Dolomies Stratifies" (laminated dolomites); R.A.T. gr.—"Roches Argilo-Talqueuses Grises" (gray clayey talcose rocks); and R.A.T.—"Roches Argilo-Talqueuses" (clayey talcose rocks). Modified from Cailteux and Lefebvre (1975).

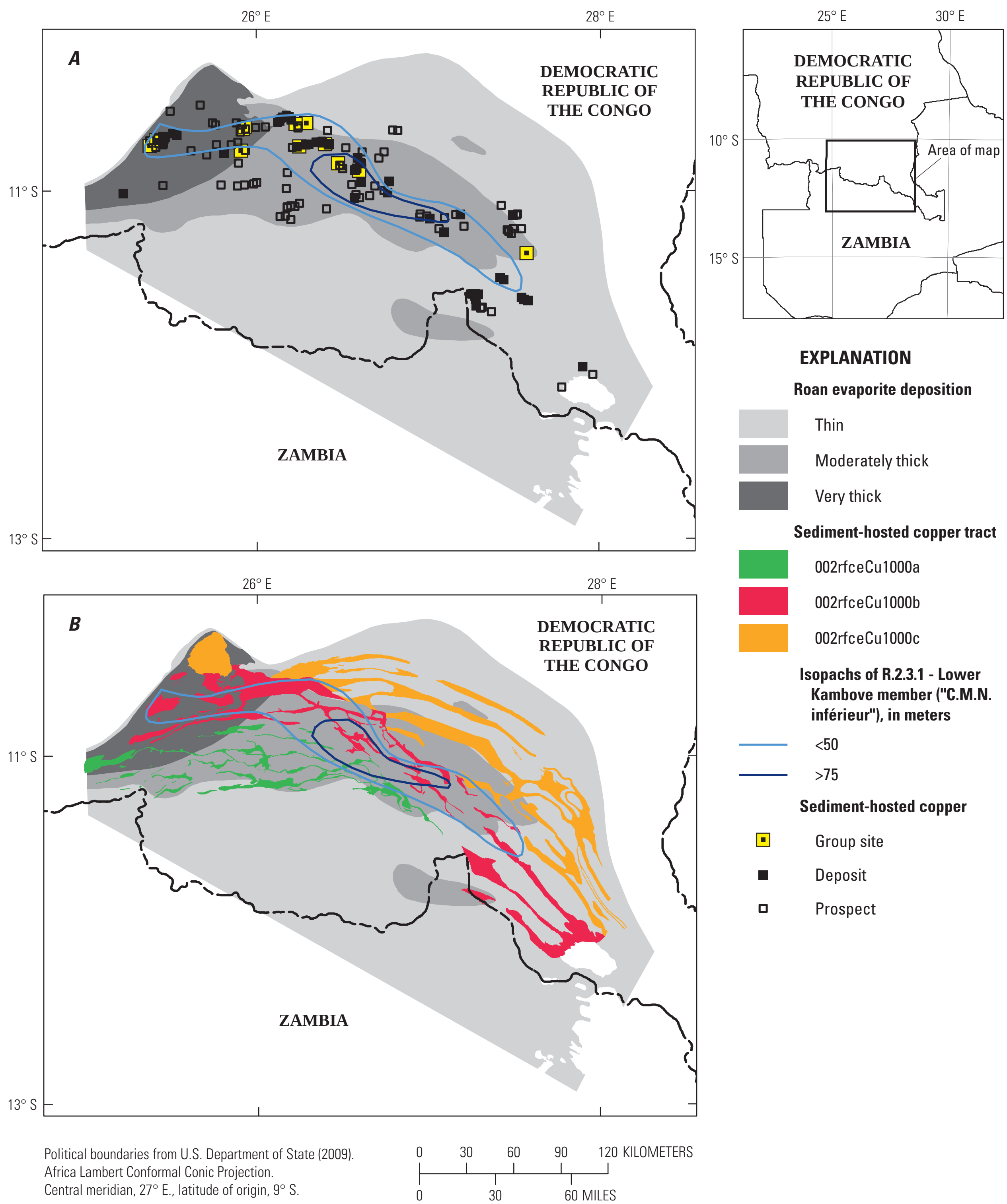


Figure E4. Maps showing inferred Roan evaporite thicknesses and isopach of the Lower Kambove member in relation to (*A*) the distribution of deposits and prospects associated with the Roan Group, and (*B*) tracts permissive for the occurrence of undiscovered sediment-hosted stratabound copper deposits in the Roan Group. Modified from Jackson and others (2003) and Cailteux (1994).

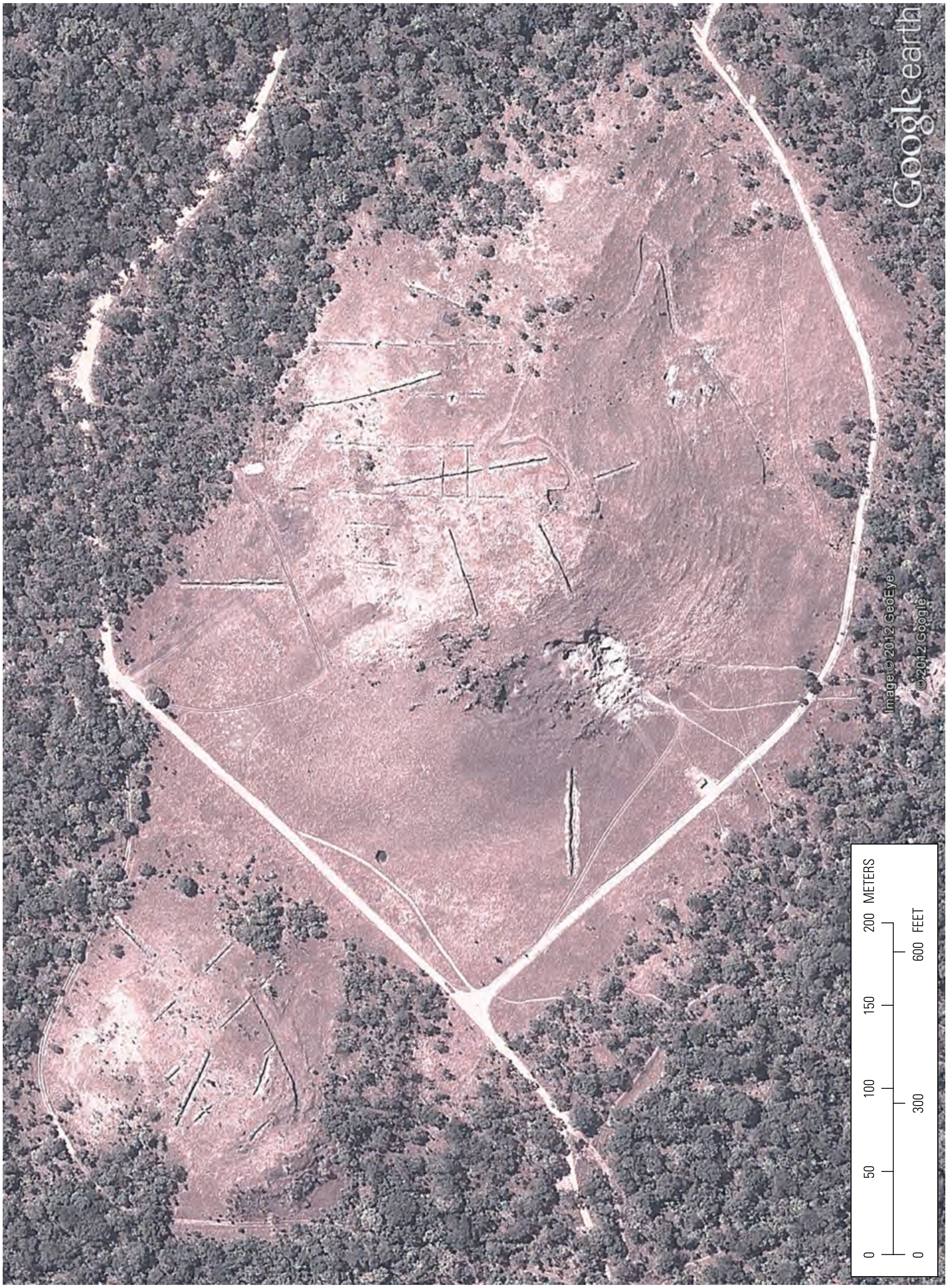


Figure E5. Google Earth™ image of the Menda prospect, Democratic Republic of the Congo, showing a large copper clearing and exploration trenches.

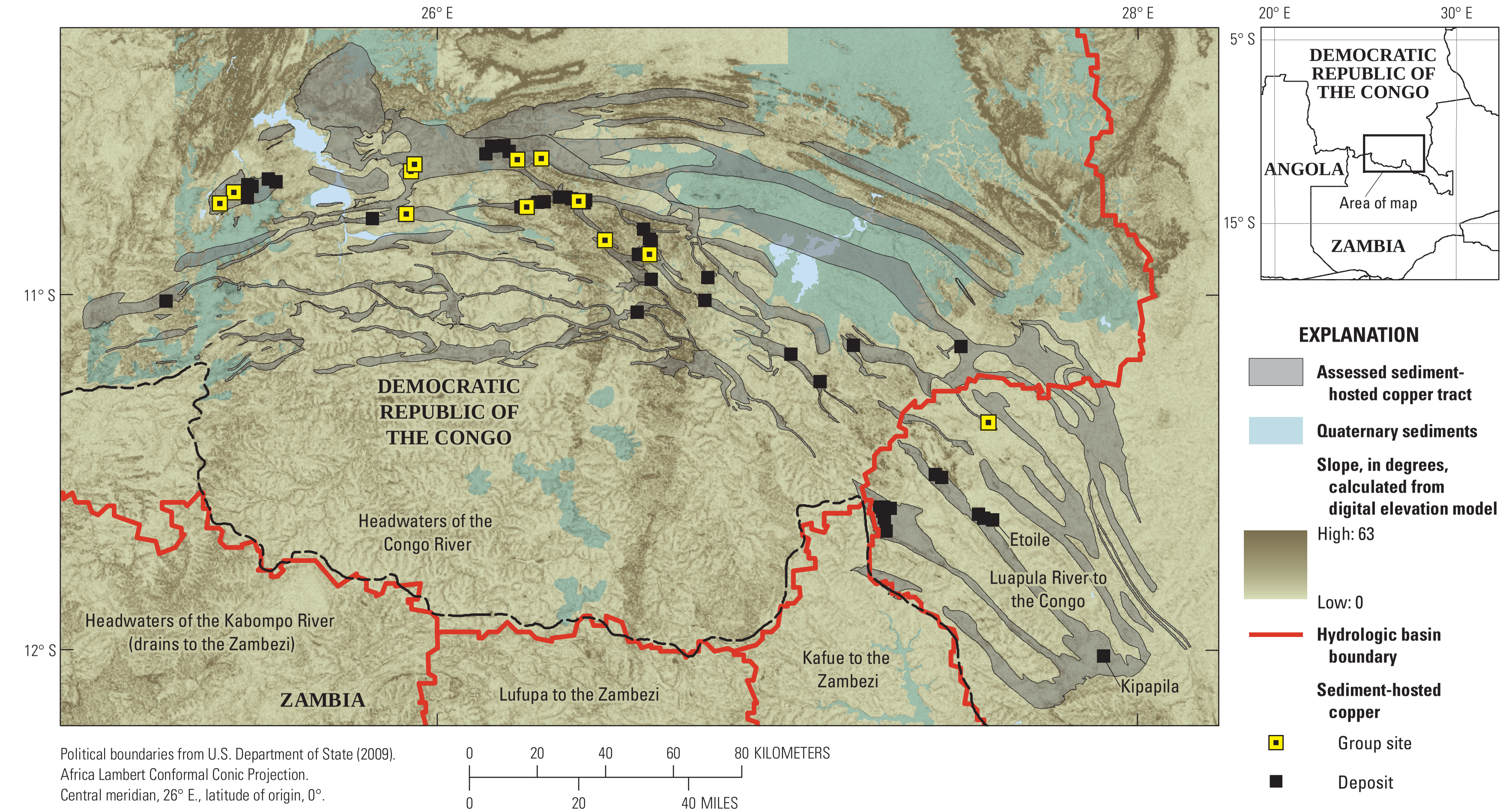
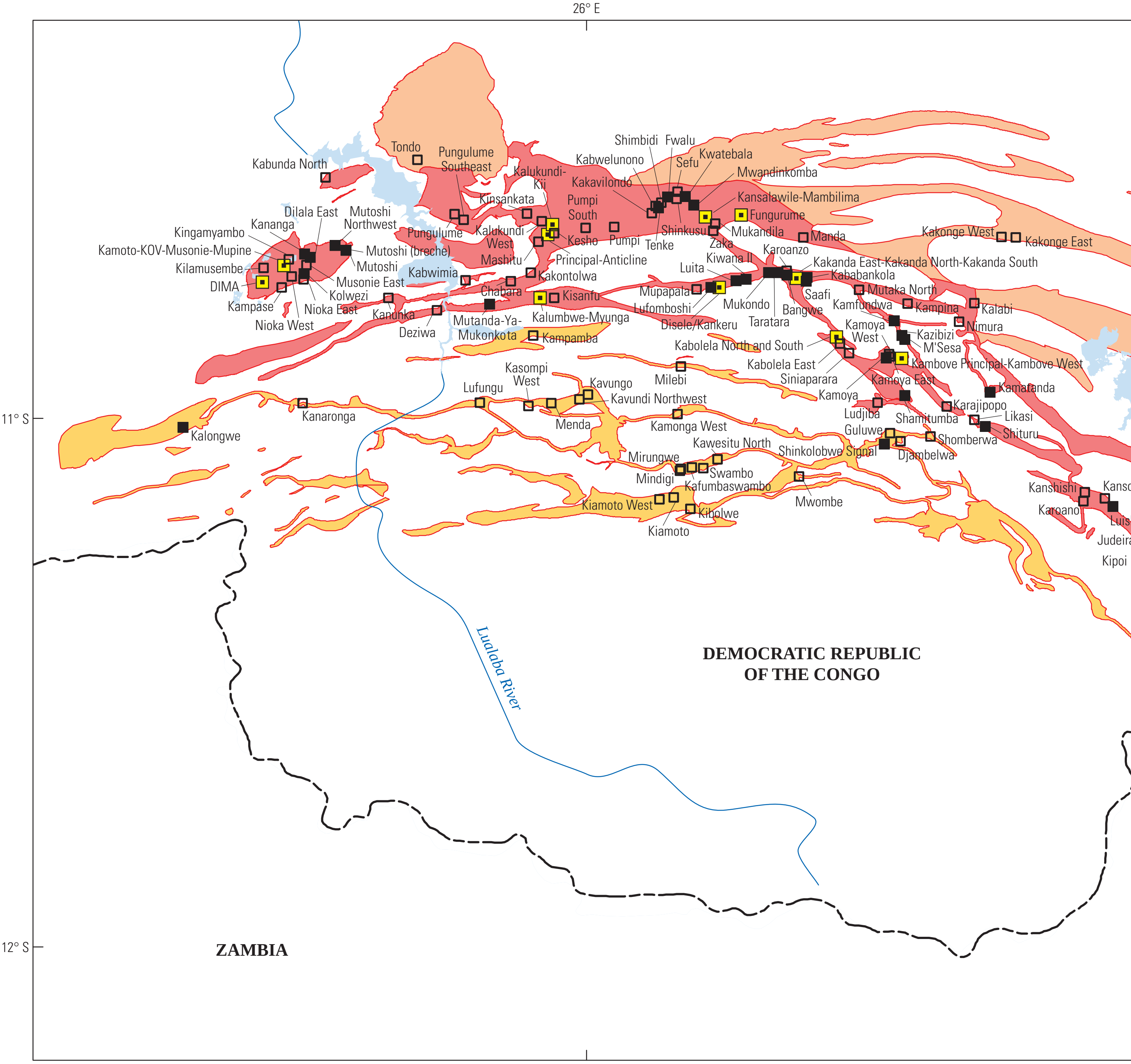


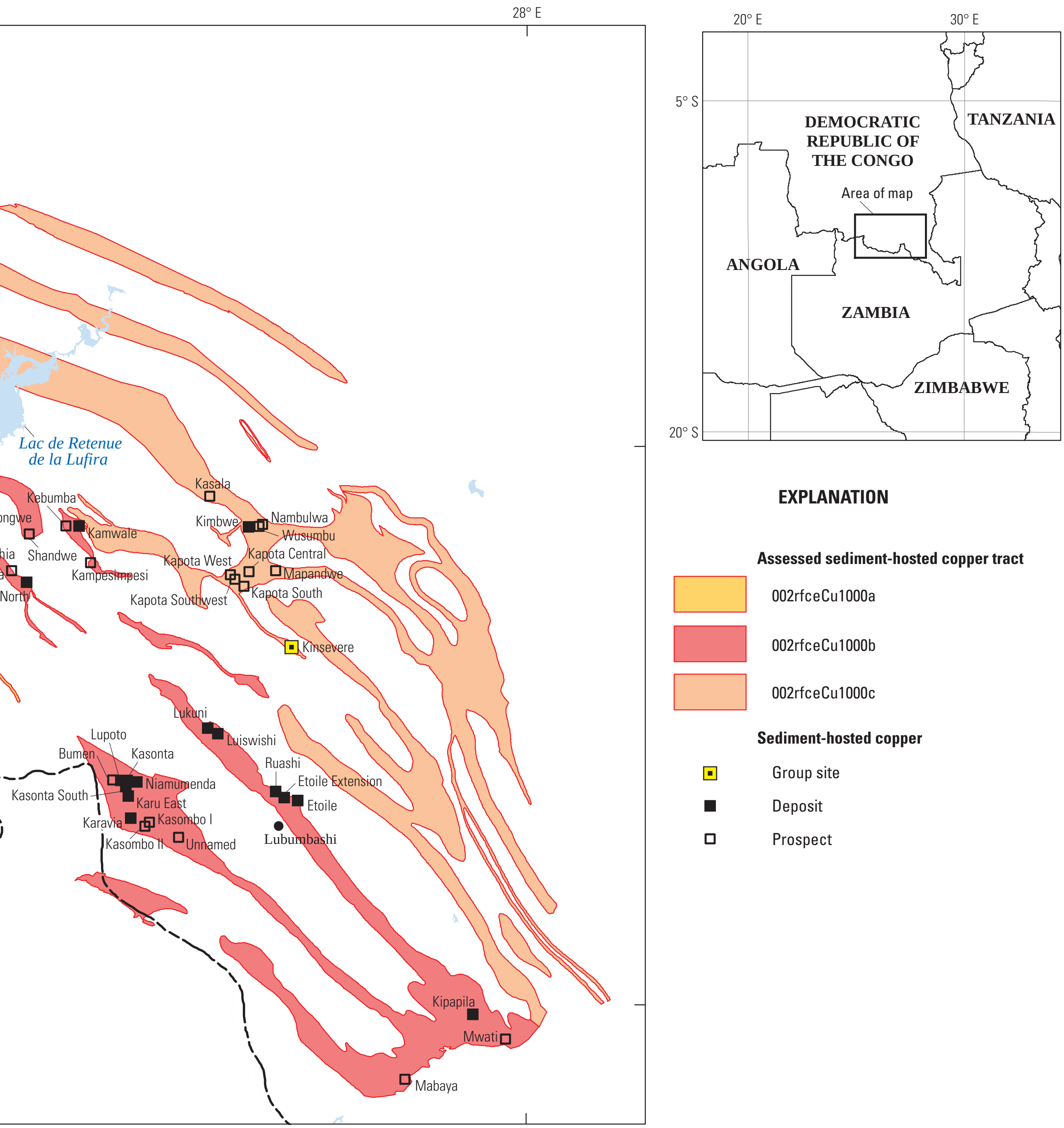
Figure E6. Slope map derived from Shuttle Radar Topography Mission digital elevation data. Map also shows hydrologic basins, sediment-hosted stratabound copper deposits, permissive tracts, and areas covered by Quaternary sediments. Slope map is symbolized such that areas with low slope are greenish gray and areas with high slope are brown. Quaternary sediments from Musée royal de l'Afrique centrale (2008a). Hydrologic basins from Hearn and others (2003).



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 26° E., latitude of origin, 0°.

0 20 40 60 80 KILOMETERS
0 20 40 MILES

Figure E7. Map showing tract location, known sediment-hosted stratabound copper deposits and prospects for tracts 002rfceCu1000a, b, and c (Southern, Central, and Northern carbonate écaille), Democratic Republic of the Congo and Zambia.


28° E
Lac de Retenue de la Lufira
Kasala
Kebumba
Kimbwe
Nambulwa
Wusumbu
Kamwale
Shandwe
Kapota West
Kapota Central
Mapandwe
Kampesimpesi
North
Kapota South
Kapota Southwest
Kinsevere
Lukuni
Luiswishi
Lupoto
Kasonta
Bumen
Ruashi
Etoile Extension
Niamumenda
Kasonta South
Karu East
Etoile
Karavia
Kasombo I
Lubumbashi
Kasombo II
Unnamed
Kipapila
Mwati
Mabaya
20° E
30° E
5° S
20° S
DEMOCRATIC REPUBLIC OF THE CONGO
TANZANIA
Area of map
ANGOLA
ZAMBIA
ZIMBABWE
EXPLANATION
Assessed sediment-hosted copper tract
002rfceCu1000a
002rfceCu1000b
002rfceCu1000c
Sediment-hosted copper
Group site
Deposit
Prospect

On the 1:500,000-scale map, the Roan Group is divided into four map units: (1) a basal conglomerate; (2) a combined unit consisting of the R.A.T., Mines, and Dipeta Subgroups (R.1-2-3); (3) the lower Mwashia Subgroup (R.4.1 Formation); and (4) the upper Mwashia Subgroup (R.4.2 Formation). A fifth map unit containing Roan strata is also shown and consists of an undifferentiated tectonic breccia composed of Roan and Nguba Group lithologies. Polygons for these Roan units were selected from a digital version of the 1:500,000 Arc Cuprifère du Katanga geologic map (Musée royal de l'Afrique centrale, 2008b) in order to show the mapped extent of the units.

The subsurface extent of the Roan units is based on stratigraphic analysis and published cross sections in the western part of the study area. Subsurface projections were made utilizing the stratigraphic thickness of overlying units and variation in width of the units on geologic maps. The Grand Conglomérat at the base of the Nguba Group is about 2,000 m stratigraphically above the Mines Subgroup (Maree, 1963; Unrug, 1988; Jackson and others, 2003). Therefore, the mapped distribution of Katangan sedimentary rocks up to and including the Grand Conglomérat in outcrop was used to indicate the presence of the Roan Group at depths to 2 km. This estimate of the presence of the Mines Subgroup at depth was then compared to published cross sections. The Likasi map area has 10 cross sections (Musée royal de l'Afrique centrale, 2006b) and the Kolwezi map area has two (François and Cailteux, 1981; Jackson and others, 2003). For each of the 12 cross sections, the extent of the Roan Group, shallower than 2 km, was projected to the surface and plotted along cross section lines on the geologic maps. The polygons developed using stratigraphic arguments generally correspond to the data derived from the cross sections.

Structural analysis was used to extend and modify permissive tract boundaries, particularly in the northeastern part of the Katangan Copperbelt. Diapirs that contain Roan Group rocks cut across multiple stratigraphic layers and have near-vertical subsurface projections. Folds cored by the Roan Group are tight to open (interlimb angles of 10° to 90°) and upright to slightly inclined. The slight inclination produces fold asymmetry that is visible in map view; consequently, tract boundaries (fig. E7) were extended over shallowly dipping limbs and receded over steeply dipping limbs to account for inferred fold geometry at depth. This structural style was also used to extend permissive tracts under cover. Topographic relief in the region is sufficiently low to allow for straightforward interpretations of kilometer-scale folds. The permissive tracts also were extended by putting a 250 m buffer zone surrounding faults along which diapiric intrusions are found. The diapirs can be small, occurring as lenses within a fault zone; therefore, this buffer distance maps faults that could have diapirs too small to be shown on maps used for assessment. Tracts were finalized by filling in areas covered by Quaternary deposits and and applying a smoothing algorithm. The smoothing algorithm is an ArcMap tool called "smooth polygon" that smooths sharp angles in polygon outlines to improve aesthetic or cartographic quality. The distribution of deposits and prospects was then compared to the tract, and slight adjustments were made to encompass all deposits and prospects within the Mines Subgroup (fig. E7).

Known Deposits

In the reduced-facies, Carbonate écaille permissive tract, at least 56 deposits contain approximately 65 million metric tons of copper, or about 40 percent of the total endowment of the Katangan Copperbelt. Approximately 19 million metric tons of copper were produced from these deposits. An aggregation rule was applied to the deposits database such that ore bodies within 500 m of each other are considered to represent a single deposit. Among the 56 deposits, 33 are significant deposits that individually contain more than 50 thousand metric tons of copper; 10 are giant deposits, each containing more than 2 million metric tons of copper (appendix D). The largest deposit corresponds to a cluster of gigabreccia fragments within the Kolwezi Klippe at the far west end of the province that include the Kamoto–KOV–Musonie–Mupine fragments (figs. E7, E8, and E9). An extensive literature describes known deposits within this tract, including reports by Cailteux (1994), Cailteux and others (2005), François (1973, 1974, 1987, 2006), and François and Cailteux (1981).

Prospects

About 80 mineral prospects have been mapped in the Mines Subgroup (appendix D). Mineral prospect information provides an important constraint on estimates of undiscovered deposits. Ranking prospects to indicate those that are significant is a useful part of the assessment process. Ideally, the same criteria would be used in all assessment studies to determine significance; however, the metrics vary by deposit type, and the quality of information is not uniform among the study areas. Despite this limitation, similar strategies are used to determine significance for assessment studies.

Ideally, sediment-hosted stratabound copper prospects could be ranked on the grade, thickness, and continuity of mineralized intervals, mineralogy of the ore (bornite is better than chalcopyrite because it contains more copper), and intensity of geochemical or geophysical anomalies that possibly indicate the presence of sulfide minerals. However, for this study, no geologic, geochemical, or geophysical data are available. Instead, the intensity of surface disturbance related to exploration activity as seen on satellite images was used to evaluate the significance of a prospect (assuming that sites showing more disturbances have more indications of the degree and extent of mineralization). Every prospect in our database was examined to record evidence of (1) recency of activity, (2) type of disturbance, and (3) intensity of disturbance.

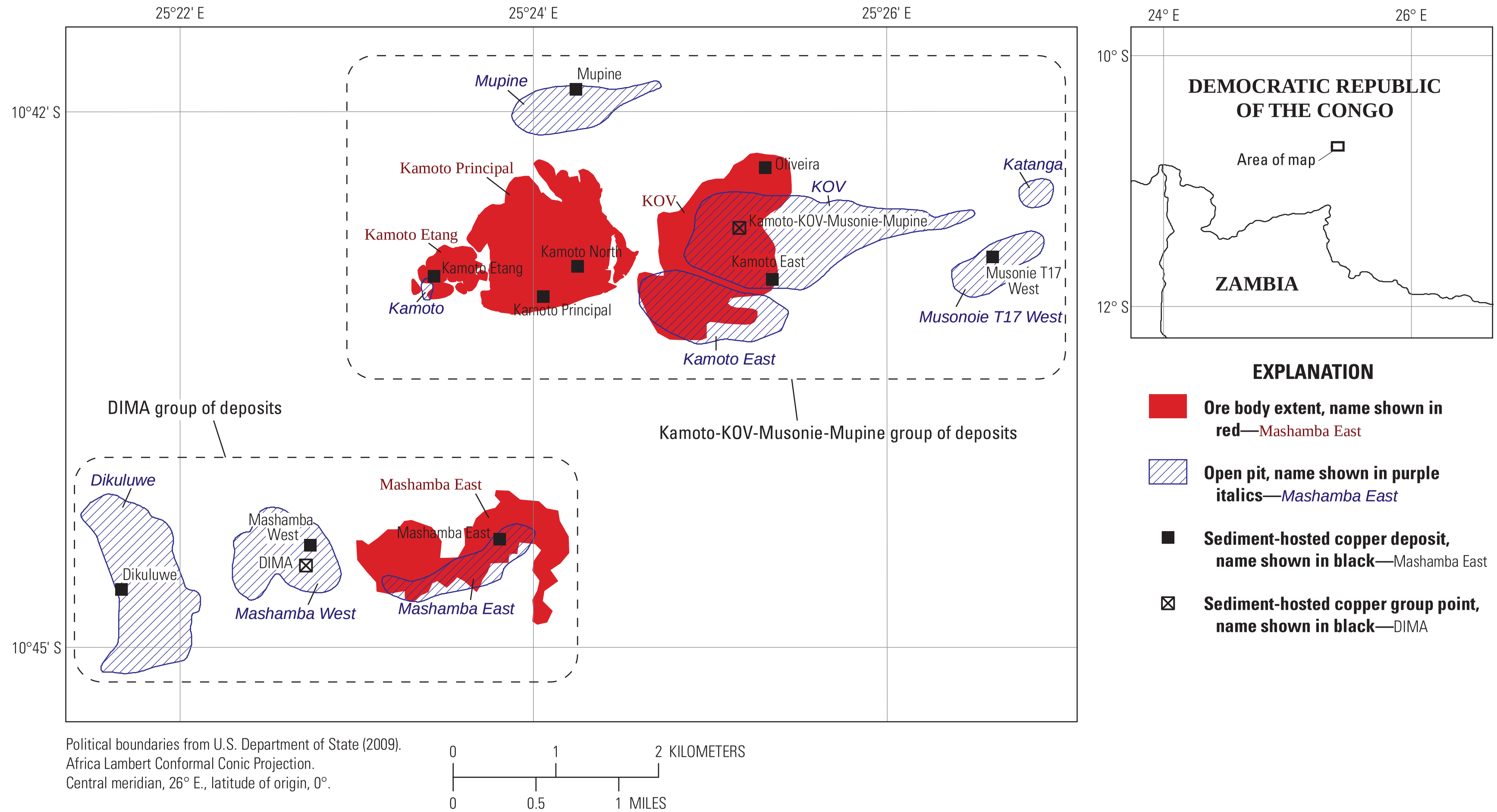
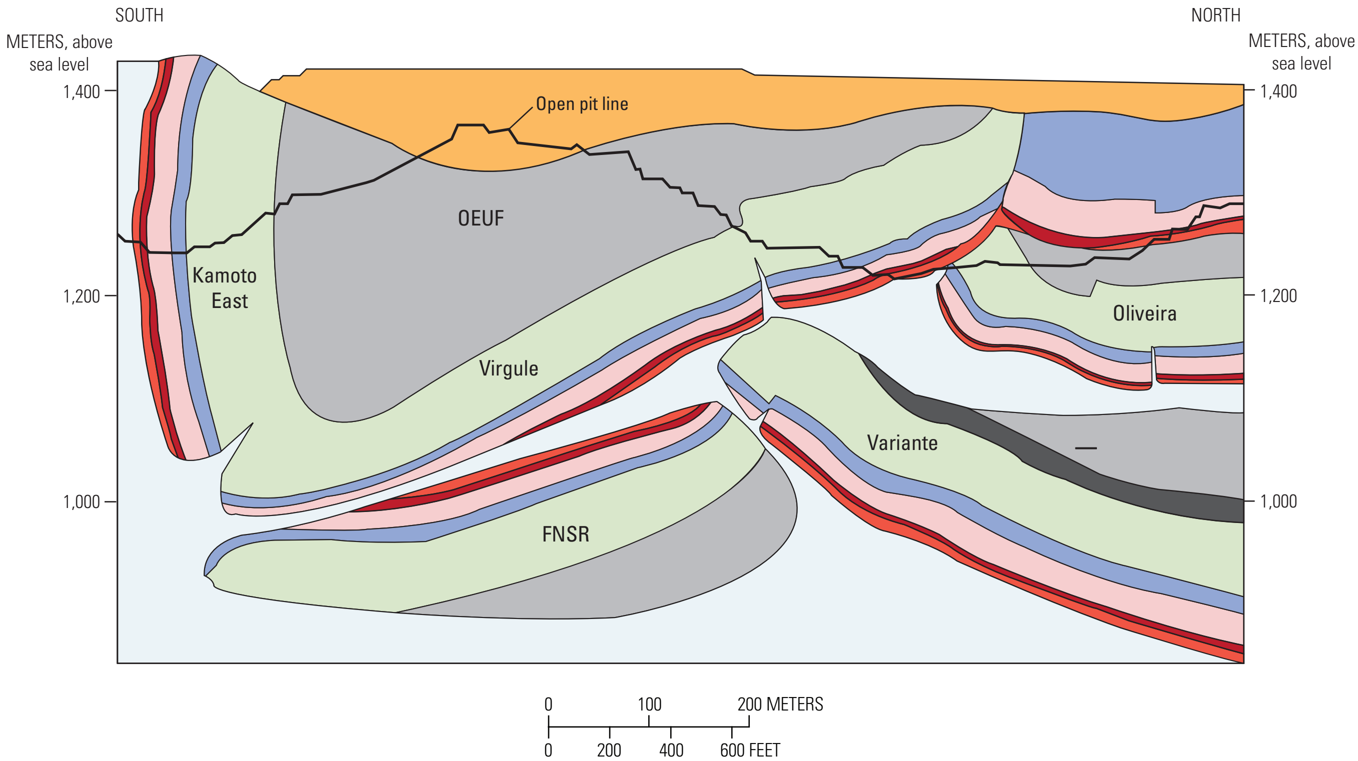


Figure E8. Map showing point locations for deposits, the areal extent of ore bodies, and open pits in the northwestern part of the Central African Copperbelt, Democratic Republic of the Congo. Dashed boxes show the clusters of mineralized deposits that are grouped using the spatial aggregation rule used in this report. Ore body outlines modified from Dixon and others (2009).



EXPLANATION

Overburden

Roan Group

Breccia matrix of pelite or siltstone derived from units R.1 to R.3

Mines Subgroup, as mega- and gigaclasts

R.2.3—Kambove Formation (also C.M.N.—"Calcaire à Minerais Noirs")

R.2.3.2—Upper Kambove member (also "C.M.N. supérieur")

R.2.3.1—Lower Kambove member ("C.M.N. inférieur")

R.2.2—Dolomitic Shales Formation (also S.D.—“Schistes Dolomitiques”)

R.2.2.1.2 to R2.2.3 members (also S.D.S.—"Schistes Dolomitiques Supérieures")

R.2.2.1.1 member, upper part (also BOMZ—"Black Ore Mineralized Zone") and R.2.2.1.1 member, lower part (also S.D.B.—"Schistes Dolomitiques De Base")

R.2.1—Kamoto Formation

R.2.1.3 member (also R.S.C.—"Roche Siliceuse Cellulaire")

R.2.1.2.2 member (also R.S.F.—"Roches Siliceuses Feuilletées")

R.2.1.2.1 member (also D. Strat.—"Dolomies Stratifiées") and R.2.1.1 member (also R.A.T. grises—"Roches Argilo-Talqueuses grises")

Figure E9. Geologic section from Kamoto East to Oliveira, showing the distribution of mineralized Roan Group rocks in Roan breccia fragments, Kolwezi area, Democratic Republic of the Congo. Modified from Dixon (2007).

Surface disturbance was assessed by examination of Google Earth™ Imagery. The resolution was sufficient to discern vehicles on the ground. Recency was assessed by comparing consecutive scenes and the color and type of disturbed ground. Newer excavations have lighter color; road construction and excavations produced by front-end loaders and bull dozers are typical of recent disturbance. The types of disturbance include pits and quarries (fig. E10), drill pads, exploration trenches (figs. E11 and E12), exploration pits (fig. E12), and artisanal workings (figs. E12 and E13). Disturbance intensity is recorded by areal extent of the pits, quarries, and artisanal workings and the number of trenches and drill pads. Among the 87 reduced-facies, carbonate écaille prospects in the database, 59 show some evidence for surface disturbance (table E2). This information was then integrated in order to group the prospects into five categories, three of which are considered significant (fig. E14). In general, the highest-ranked category of significant prospects (Rank 1) has active pits or quarries or active exploration activity. The next category of significant prospects (Rank 2) has more than 10 exploration trenches or large areas of artisanal workings. The next ranked category of significant prospects (Rank 3) is characterized by fewer than 10 trenches, small inactive pits, or quarries. Prospects without evidence for surface disturbance (25 sites), with small areas of artisanal workings, or with pits along the trace of mineralized strata in outcrop (15 sites), are not considered significant for this assessment.

Exploration History

The early history of mineral exploration in this area is summarized in the main report. After decades of political and economic instability, beginning in the 1960s, exploration activity has resumed in the DRC. Information about the location and level of exploration can be gleaned from several sources.

In the fall of 2011, Cadastre Minier de la RD Congo (CAMI) (2011) launched an online mining cadastre[13] portal, accessible from http://www.flexicadastre.com/drcmapportal/. This mapping platform provides information on official claims held in the DRC that is available to the public. Lists of mining and quarry rights, assets, approved applications, and applications being processed are available at http://www.flexicadastre.com/dotnetnukedrc/MineralTitleReports/Listesdesdroitsminiersetdecarrières/tabid/132/language/en-GB/Default.aspx (accessed October 25, 2012). The Web site www.congomines.org (accessed October 25, 2012) was developed by The Carter Center in Katanga to facilitate access to information on the industrial mining sector in the DRC. This site also has a Web-based map server to display information related to the mining sector (http://www.congomines.org/map/, accessed October 25, 2012). Maps of mining tenements are useful for showing areas where mineral development and exploration are occurring; however, the names of tenement holders in the database records may not identify the company doing the exploration work. For example, Ivanplats, a privately owned Canadian exploration company, holds dozens of exploration permits in the Katanga province of the Democratic Republic of the Congo, but the tenements database lists African Minerals (Barbados) Limited Sprl, a wholly-owned subsidiary of Ivanplats, as the party holding the license.

Web research indicates that more than 35 publicly traded stock companies and several private or government-owned companies have conducted exploration activities in the DRC since 2000. Technical reports for advanced exploration projects conducted by companies traded on Canadian securities markets are available at www.sedar.com; however, little information is available regarding early stages of exploration activity conducted by public or private companies. Opportunities and risks for mineral investment in the DRC are summarized by Fortin (2006), Mining Journal (2010), André-Dumont (2011), and Tambwe (2012). Collectively, tenement maps and information on company Web sites indicate that most of the permissive tract area is being explored or developed; the only part of the tract not covered by exploration tenements is surrounding Lac de Retenue de la Lufira.

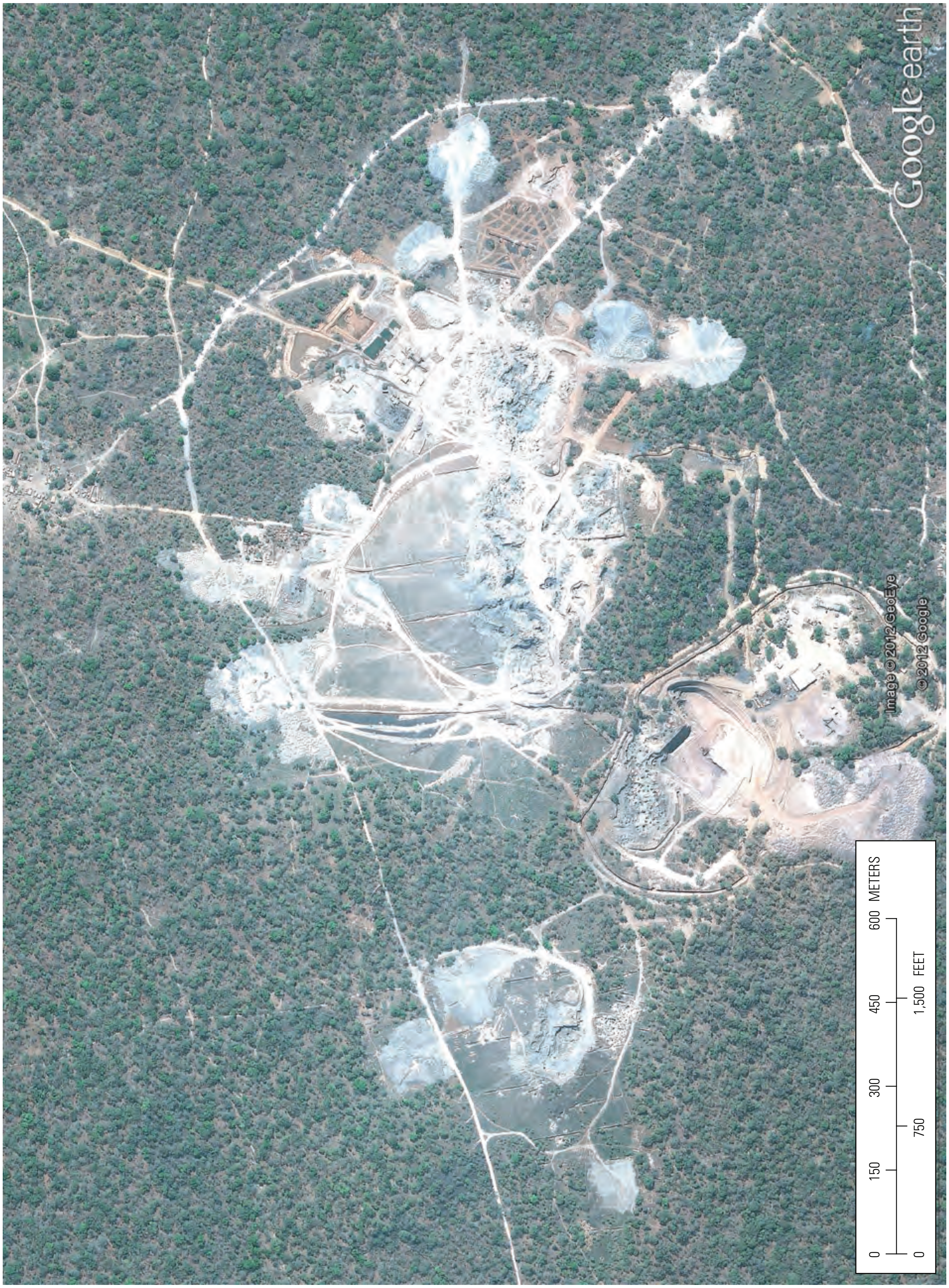
Sources of Information

Principal sources of information used to assess the Carbonate écaille tracts (002rfceCu1000a, b, c) are listed in appendix C.

[13]A cadastre (also spelled cadaster) is a comprehensive register of the metes-and-bounds real property of a country.

A

Figure E10. Google Earth™ images of the Chabara prospect, Democratic Republic of the Congo. *A*, Exploration trenches and artisanal working in 2006. *B*, Active open-pit mining operations in 2010.



B

Figure E10.—Continued

Figure E11. Google Earth™ image of the Shomberwa prospect, Democratic Republic of the Congo, showing exploration trenches.

Figure E12. Google Earth™ image of the Mutaka North prospect, Democratic Republic of the Congo, showing exploration trenches, exploration pits, excavations along the outcrop trace of mineralized strata (left center), and artisanal mining.

Figure E13. Google Earth™ image of the Milebi prospect, Democratic Republic of the Congo, showing artisanal mining.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.

[BOMZ, black ore main zone; CAMEC, Central African Mining and Exploration Company; Au, gold; Co, cobalt; Cu, copper; Ni, nickel; Pd, palladium; Pt, platinum; DD, diamond drill; km, kilometers; km^2, square kilometers; m, meters; RC, reverse circulation; R.S.C., Roches Siliceuses Cellulaires; R.S.F., Roches Siliceuses Feuilletées. Imagery notes in comments based on Google Earth™ images available in September 2012; all other comments from sources given in the GIS, Appendix B; –, no data]

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Central carbonate écaille tract	Chabara (Kamwana)	−10.7402	25.8548	1	Yes	–	Large	Large	10–15	Radiometric anomaly found in 1975 airborne survey. Interesting grades at surface, some with high Co. Imagery notes: Three areas of disturbance extending 6 km on strike. Central area has extensive areas of artisanal workings and older machine-excavations. New pit/quarry to the southwest of the older mine area with excavator in the mine. Areas to east and west have artisanal working and exploration trenches.
Central carbonate écaille tract	Judeira	−11.2235	27.0645	3	Yes	–	–	Small	5	–
Central carbonate écaille tract	Kabunda North	−10.5432	25.4995	3	–	–	–	–	4	Imagery notes: A dozen or so test pits and 4 machine-excavated trenches.
Central carbonate écaille tract	Kabwimia	−10.7386	25.7674	1	Yes	–	Small	–	10–15	Imagery notes: Roads, machine-excavated trenches, and minor surface excavation over a distance of 600 m.
Northern carbonate écaille tract	Kakonge West	−10.6559	26.7947	3	No, only artisanal	–	Small	–	2	Not prospected by pits, trenches, or drill holes.
Central carbonate écaille tract	Kalabi	−10.7815	26.7426	3	No, only artisanal	3,875 m from 1922 to 1925	Medium	Small [produced 352,363 tons of ore with 8.53% Cu]	–	Kalabi has been mined for a few hundreds of years yielding thick layers of banded malachite, together with widespread occurrence of cornetite. Produced 352,363 metric tons of ore with 8.53% Cu. Imagery notes: Artisanal mining and small, flooded open pit, 300 m by 120 m. No recent activity.
Central carbonate écaille tract	Kalukundi West	−10.6262	25.9139	3	Yes	–	–	Small	5–10	–

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Central carbonate écaille tract	Kamoya West	−10.8782	26.5792	3	No	–	–	Small [mined from 1990 to 1996]	–	Mineralization is thin, shallow, and poor. Imagery notes: Small open pit on east flank of Kamoya West Écaille body. Pit is 110 by 120 m.
Central carbonate écaille tract	Kampina	−10.7824	26.6151	2	Yes	–	Medium	Small	20–25	Permitted Artisanal Mining. A copper clearing 450 m long is present. Outcrop of siliceous rocks, shale, and white talc, with crusts and coatings of malachite and azurite. Imagery notes: Area of artisanal mining approximately 300 m long. Cut by at least 4 exploration trenches
Central carbonate écaille tract	Kanshishi	−11.1400	26.9546	1	Yes	–	Small	Small	10	Small amount of mineralization on the surface (a bit of malachite in the R.S.C., near their contact with the R.S.F.; interesting occurrence because of the size of the fragment. Imagery notes: Small quarry ~120 m in diameter; excavated recently. Previous image shows about a dozen exploration pits over a distance of 350 m.
Central carbonate écaille tract	Kansongwe	−11.1517	26.9932	3	No, only artisanal	2,175 m drilled between 1925 and 1931	Large	Small	–	Most of the ore was extracted from the BOMZ horizon. Imagery notes: Extensive area of artisanal mining; small pit/quarry that shows no signs of recent activity. Disturbed area is about 700 m in diameter.
Central carbonate écaille tract	Kanunka	−10.7719	25.6201	2	No, only artisanal	–	Small	–	10–15	–
Central carbonate écaille tract	Karoano	−11.1571	26.9519	1	Yes	–	Large	Small	–	A few crusts of malachite. The écaille fragment is small. Imagery notes: Image in 2007 shows area of artisanal mining extending for about 900 m. Image from 2009 shows extensive mechanized ground disturbance including two pits—100 and 150 m long.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Northern carbonate écaille tract	Kasala	−11.0898	27.4241	1	Yes	50 drill holes, 2008	–	–	–	The mineralized strike length of Kasala Block “A” is 750 m with a width of as much as 250 m. “Mineralized strike length is 2,500 m. The 2008 drill program identified consistent mineralization over large widths, from 50 m to 91 m. The 50 drill hole, 5,920 metre 2008 drill program consisted of 35 Reverse Circulation (“RC”) drill holes totaling 3,336 meters and 15 diamond drill (“DD”) holes totaling 2,584 meters. High-grade intercepts include: 22 m @ 3.28% Cu; 29 m @ 2.82% Cu; 31 m @ 2.19% Cu; and 11 m @ 3.68% Cu.” Imagery notes: Poor image resolution. No ground features can be seen.
Southern carbonate écaille tract	Kasompi West	−10.9765	25.8882	1	Yes	–	–	–	15–20	No interesting results in drifts or drill holes. Imagery notes: Drill road with more than a dozen drill pads; superimposed on older closely spaced trenches.
Southern carbonate écaille tract	Kavundi Northwest	−10.9641	25.9859	1	Yes	Yes, recent	Large	–	15–20	Imagery notes: Large areas of artisanal mining (1.4 km by 300 m). Systematic line of drill pads and exploration trenches extending for about 2 km.
Central carbonate écaille tract	Kesho	−10.6496	25.9372	1	Yes	–	Small	–	6	“… a core drilling programme was initiated in August and started in October 2008 on the Kesho Fragment, achieved 2280 m of drilling from 18 boreholes. This established the continuity of Cu and Co-rich oxide mineralisation over a strike of 400m, a down-dip extent of +200m and down to depths of up to 110m vertically below surface.” Harwood (2009) Imagery notes: Artisanal mining (280 by 140 m) and about 6 machine excavated trenches.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Southern carbonate écaille tract	Kiamoto	−11.1497	26.1664	2	No	Yes	–	–	10–15	Presence of finely disseminated pyrite, in geodes lined with chlorite, and coatings of malachite. Mineralization occurs within a 700 m strike length of Mines Subgroup strata. Encouraging mineralized intersections were made in a number of the holes. Imagery notes: A few exploration trenches over 700 m strike. Minor surface disturbance.
Southern carbonate écaille tract	Kibolwe	−11.1713	26.1991	1	Yes	Yes, 2004–2010	–	–	10–15	"RC and core drilling programs carried out from 2004 to 2010 have outlined a near-surface, flat-lying mineralised zone up to 40 m thick extending over a strike of 2,200 m. A diamond core drilling program carried out in 2010 on the Eastern, Southern and Western extensions of Kibolwe (5,685.90 m) yielded encouraging results." Mwana Africa plc (no date).
Central carbonate écaille tract	Kinsankata	−10.6123	25.8851	1	No	–	–	Medium		–
Central carbonate écaille tract	Kisanfu	−10.7720	25.9375	1	Yes	–	–	Medium	1–5	Interesting copper ore found in small pits. Imagery notes: Active quarry/open pit, with loader and haul trucks visible. Pit is 300 by 50 m. New pit obscures older machine-excavated trenches.
Central carbonate écaille tract	Ludjiba	−10.9702	26.5572	1	Yes	–	–	Small	3	The inhospitable hills of Ludjiba were almost not prospected before 1975. Then, some 50 small shafts were excavated into the eastern hills. One hit a small fissure vein of libethenite in the form of radial spherical rosettes. Imagery notes: Small open pit (about 150 m across). Many machine-excavated exploration trenches surround the pit.
Southern carbonate écaille tract	Lufungu	−10.9703	25.7950	3	No	–	–	–	2	Imagery notes: Two copper clearings (about 330 m on strike) with about 10 test pits and two machine-excavated trenches.
Central carbonate écaille tract	Mabaya	−12.1331	27.7797	3	No	–	–	–	2	Imagery notes: Copper clearing about 330 meters long with 2 machine excavated trenches.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Central carbonate écaille tract	Mashitu	−10.6656	25.9074	3	Yes	1988–1989	Medium	–	5	Imagery notes: Limited amount of artisanal mining. Drill roads, small exploration pits, and machine-excavated trenches.
Southern carbonate écaille tract	Menda	−10.9712	25.9324	2	No	–	–	–	20–25	In dolomitic shale. Gécamines gave access to extensive records held in its Likasi archive and after a general study CAMEC made the Menda area (154 km^2) a primary exploration target. Imagery notes: Large copper clearing. At least 20 machine-excavated exploration trenches.
Southern carbonate écaille tract	Milebi	−10.9018	26.1800	2	No, only artisanal	–	Large	–	–	Two well-mineralized samples taken at random gave these results: 7.4% Cu, 2.29% Co, and 7% Cu, 11.3% Co. Imagery notes: Area of intensive artisanal mining extending 800 m on strike.
Southern carbonate écaille tract	Mindigi	−11.0994	26.1784	3	No, only artisanal	Yes, in 1930s	Medium	Small	–	Holes drilled in 1930s found rich Cu and Co. In WWII, site produced 497,127 tons of ore containing 12.24 % Cu and about 1.5% Co. Imagery notes: Small open pit at Mindigi. No signs of recent activity. Dumps and exposures east of pit have extensive artisanal excavations.
Southern carbonate écaille tract	Mirungwe	−11.0957	26.1807	2	No, only artisanal	Yes, 1970s	Large	–	–	Good surface mineralization, but the holes drilled during the 1970s gave disappointing results. Imagery notes: Area with intense artisanal mining over an area about 400 m in diameter.
Central carbonate écaille tract	Mupapala	−10.7553	26.2102	1	Yes	Yes, recent	Small	–	10–15	This deposit shows poor and irregular mineralization of malachite. Imagery notes: Roads, drill pads, exploration pits, several bulldozer trenches over a strike length of 900 m. Artisanal workings only over trace of layer. Recent drill roads and pads.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Central carbonate écaille tract	Musonie East	−10.7096	25.4631	1	Yes	Yes	–	Medium	–	Copper and cobalt prospect near Kolwezi. Drill results highly prospective. Imagery notes: In 2010, only a few exploration pits. Now an open pit or quarry.
Central carbonate écaille tract	Mutaka North	−10.7567	26.5220	2	No, only artisanal	–	Medium	–	25–30	Contains flecks of chalcocite and malachite coatings or crusts in a finely stratified dolomite talc sometimes. Some analyses give less than 0.60% Cu and 0.04% Co. Imagery notes: Area of artisanal mining approximately 180 m long. More than a dozen machine-excavated exploration trenches over a much larger area.
Southern carbonate écaille tract	Mwombe	−11.1106	26.4069	1	Yes	In 2008, 1,898 m of core drilling and 256 m of RC drilling	–	–	6	Outcropping over a 600-meter strike length. Assay results from trench and pit sampling programs have yielded elevated Ni and Co concentrations (up to 2% Ni and 0.38% Co over 1 meter) as well as Au, Pt, and Pd (up to 1.1g/t Au, 0.1g/t Pt, and 0.1g/t Pd). Imagery notes: Foot trails, small pits on 2005 image. By 2009, new road, more trenches and pits.
Northern carbonate écaille tract	Nambulwa	−11.1402	27.5203	3	No, only artisanal	–	Small	–	–	Some pits, trenches, and drifts were carried out in the 1930s; no drilling; 1978 reserves 241,360 t of oxidized ore at 3.95 Cu; no cobalt Imagery notes: Écaille fragment about 580 m on strike; roads and trails; continuous excavations on outcrop of mineralized layers, old drill pads, at least two trenches; artisanal or exploration pits down dip of the outcrops.
Central carbonate écaille tract	Nimura	−10.8169	26.7132	1	Yes	–	–	Medium	–	Shows interesting mineralization: 4.75% Cu and 0.14% Co in the lower ore body, 2.41% Cu and 0.58% Co in the upper ore body. Imagery notes: Very recent small scale mining. Open cut, dumps, and large haul trucks in the prospect area.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Central carbonate écaille tract	Pumpi South	−10.6395	25.9979	1	Yes	Yes, recent	Medium	–	10	Imagery notes: Drill roads, drill pads, some machine-excavated trenches. Some small exploration pits.
Central carbonate écaille tract	Pungulume	−10.6126	25.7470	1	Yes	Yes, recent	Small	–	10	Imagery notes: Minor areas of artisanal mining; drill roads, drill pads; about a dozen machine-excavated trenches over strike length of 1.8 km.
Central carbonate écaille tract	Pungulume Southeast	−10.6242	25.7638	3	No, only artisanal	–	Small	–	5-10	Imagery notes: Small areas with intense artisanal mining; several machine excavated trenches. Three small areas scattered along 1.3 km strike.
Central carbonate écaille tract	Sefu	−10.5704	26.1738	1	Yes	–	–	Large	–	Imagery notes: Massive surface disturbance in new images. All related to development of Kwatebala.
Central carbonate écaille tract	Shandwe	−11.1583	27.0963	3	No, only artisanal	2,144 m drilled in 1920s	Small	Small [mined 1930s; produced 131,077 tons of ore with 8.32 % Cu]	–	Explored in the 1920s; 2,144 m drilled; mined in the 1930s; production was 131,077 tons of ore with 8.32 % Cu. Imagery notes: Very small water filled open pit (60 by 200 m); artisanal workings on the dumps.
Southern carbonate écaille tract	Shomberwa	−11.0346	26.6590	2	No	–	–	–	20–25	Some coatings of malachite and chrysocolla. Traces of yellow vanadium salts. Imagery notes: More than a dozen machine-excavated trenches. Some pits.
Central carbonate écaille tract	Siniaparara	−10.8769	26.5029	2	No, only artisanal	–	Small	–	20–25	Imagery notes: Area of some artisanal mining, approximately 160 m in diameter. More than 20 exploration trenches extending for about 1 km on strike.

Table E2. Significant prospects for the Carbonate écaille tracts, Democratic Republic of the Congo.—Continued

Tract name	Prospect name	Latitude	Longitude	Rank	Recent activity	Drilling	Artisanal mining	Mining and excavation	Trenches	Comments
Southern carbonate écaille tract	Swambo	−11.0951	26.2235	3	No, only artisanal	Drilled for uranium 1955–1958	Small	–	1–5	The mineralization is located in a fragment of the Mines Group included in a megabreccia of the Roan Group. Uranium discovered in 1955 using airborne scintillometry. Drilled 1955–1958. Uranium and gold mineralization in a fault; 190,000 metric tons of ore with 0.38% U_3O_8; copper mineralization in the R2 stratigraphy not investigated. Imagery notes: Small area of artisanal mining (140 m in diameter); at least two machine-excavated trenches.
Northern carbonate écaille tract	Tondo	−10.5100	25.6751	1	Yes	Yes, recent	Small	–	1–5	Copper anomalies in soil; good grades from surface samples. No other exploration. Imagery notes: Drill roads, drill pads, and some machine-excavated trenches extend for about 500 m. Exploration activity is recent.

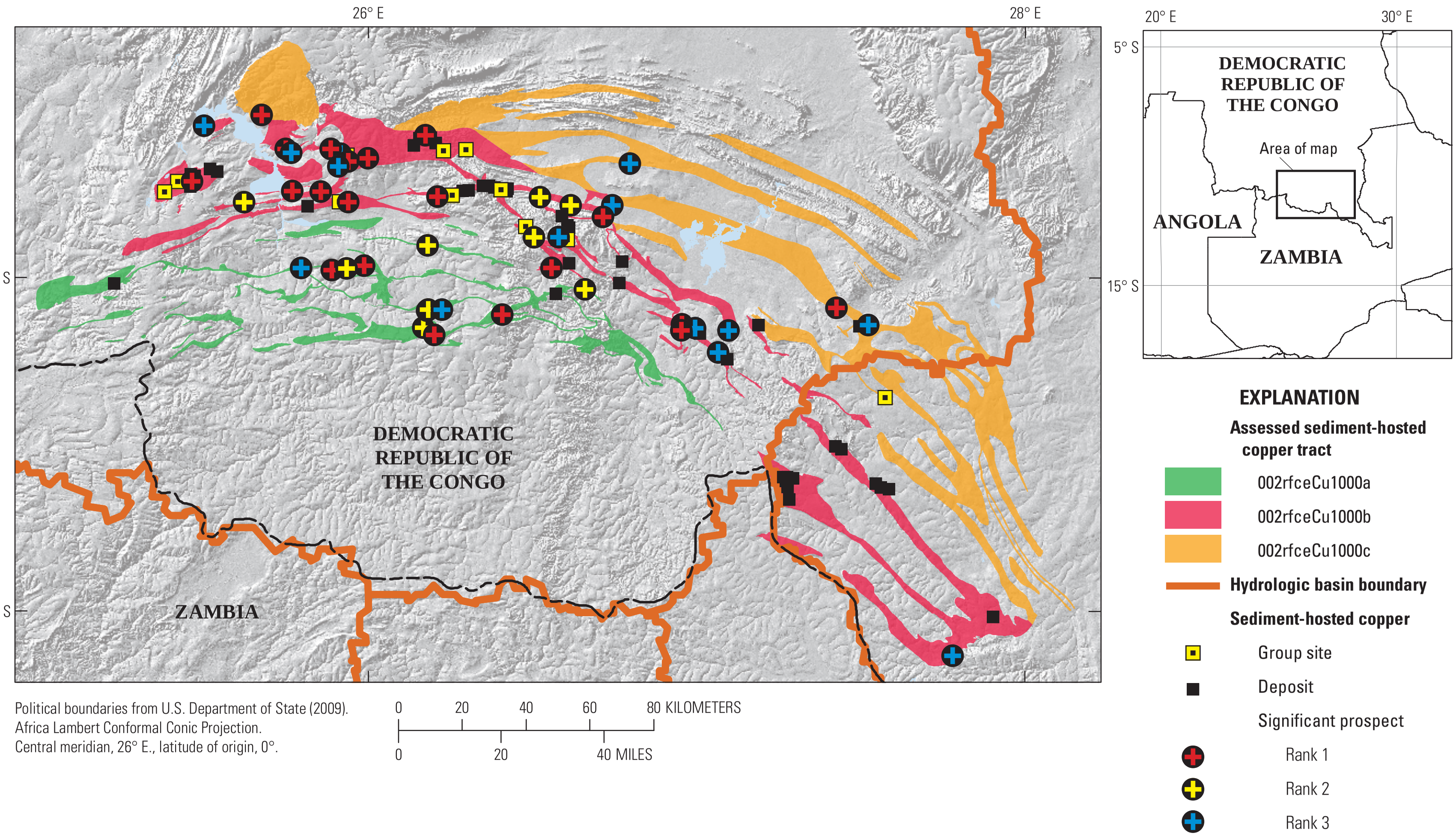


Figure E14. Map showing the location of significant sediment-hosted stratabound copper prospects and associated permissive tracts for the Roan Group, Democratic Republic of the Congo.

Grade and Tonnage Model Selection

A grade and tonnage model prepared specifically for deposits hosted in the Mines Subgroup breccia fragments in the DRC is used to model in-place metal contents of the mineralization within the Mines Subgroup tract in the DRC (Zientek, Hayes, and Taylor, 2013).

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

The presence of copper deposits and occurrences in the Katanga Basin provides direct evidence for a sediment-hosted stratabound ore system that was capable of mineralizing favorable strata (reduced rocks overlying a red bed sequence) over the entire strike length of the Katanga Basin. Sediment-hosted stratabound ore deposition in the Roan Subgroup in the DRC preceded the tectonic events that formed the Roan megabreccias and gigabreccias. Stratigraphic layering is preserved within individual mega- and gigabreccia fragments. However, stratabound copper mineralization is not found in every fragment. If the original bedding could be restored, the Mines Subgroup would be relatively flat lying and have areas of copper-cobalt mineralization concentrated along diagenetic reaction fronts that would be separated by large expanses of pyrite-bearing, barren rocks. This pattern is likely the result of flow pathways of mineralizing brines or facies variations of the host unit—features not mapped or shown on geologic maps.

Two guidelines to constrain estimates of undiscovered deposits were offered to the assessment panel: (1) analogy with well-explored parts of the copperbelt to estimate the number of deposits that may occur at depth in an area; and (2) counting and ranking prospects and mineral occurrences, or visualizing exploration targets.

Guideline method 1 was applied using the areal proportion of the breccia fragments that is exposed and mineralized and was also used to guide estimates for the number of undiscovered deposits at depth. The underlying assumptions are that (1) areas lacking cover are relatively well explored, (2) historical exploration has focused on rocks within 300 m of the surface, and (3) surface deposit densities can be extrapolated to the 2 km assessment depth. The proportion of fragments that is mineralized was estimated for part of the permissive tract using 1:100,000-scale geologic maps of the Kolwezi-Kalukundi and Likasi sheets (Musée royal de l'Afrique centrale, 2006a,b), where the stratigraphic interval in the Mines Subgroup containing mineralized breccia fragments has been mapped. The polygons corresponding to the unit are referred to as "groupe R.2 – corps mineralizes – ROAN" and were extracted from the GIS database. The extent of ore bodies and open pits within mineralization in R.2 units was digitized from published literature, company reports, and satellite imagery. The extent of the R.2 units, ore bodies, and open pits were imported into Google Earth™ so that each fragment could be analyzed using satellite imagery. Information on differential weathering (are the resistant units in the favorable strata present?) and land cover (are copper clearings evident?) was recorded. In addition, the nature of ground disturbance for each fragment was documented using the assumption that mineralized rocks exposed near the surface will have some type of manmade disturbance that can be seen on the satellite images. Each R.2 polygon was examined to determine if it coincides with an ore body, an open pit, roads or other types of mechanized ground disturbance, or an area impacted by artisanal mining.

Three categorical levels (none, some, substantial) were coded for seven data fields for each polygon by two investigators. The seven data fields were (1) presence of an open pit; (2) presence of a known ore body; (3) ground disturbance by trenching, drilling, or road building; (4) presence of artisanal mining activities; (5) distinct greenish or bluish tint to disturbed areas; (6) lack of vegetation that may be a copper clearing; and (7) topographic ridge that corresponds with the presence of carbonate-rich rocks. Observations were scored numerically, weighted, and combined into a single value for each fragment, allowing the fragment to be assigned to one of four categories that reflect relative scores for disturbance (table E3). The analysis was conducted in 2009 and 2010. Results for the two observers are similar: approximately 20 to 30 percent of the fragments by area show significant disturbances by mining or exploration and thus are interpreted as mineralized. Another 30 percent by area show disturbances indicating that the favorable stratigraphic interval is probably mineralized. About 10 to 20 percent of the fragments by area lack any indication of mineralization.

The R.2 polygons were symbolized according to the weighted score and plotted on a map together with the location of deposits and prospects, ore bodies, and open pits. Maps for well-explored areas, like the Kolwezi Klippe (fig. E15) and the Tenke-Fungurume area (fig. E16), indicate that both mineralized and unmineralized fragments are present. In addition, R.2 polygons coded by values of potential show patterns and trends suggesting that additional mineralization could be found if further exploration is conducted. A map for the Shinkolobwe area shows that most mineralized R.2 polygons are near points in the mineral occurrence database but some are not (specifically R.2 exposures in the western part of the diapir; fig. E17). This result indicates that the mineral occurrence database is incomplete and additional sites with near-surface mineral exploration and (or) mining activity may be present.

Table E3. Evaluation of écaille fragments mapped on the Likasi and Kolwezi-Kalukundi 1:100,000 geologic maps, Democratic Republic of the Congo.

[m^2, square meters]

Rank	Total area (m^2)	Proportion of area (percent)	Number of fragments	Proportion of fragments (percent)
Scoring—scientist 1				
Low	3,371,705	10	115	23
Moderate	10,378,659	30	179	23
High	10,755,310	31	116	23
Very high	10,067,643	29	101	23
Total	34,573,317		511	
Scoring—scientist 2				
Low	9,756,971	28	135	26
Moderate	6,995,915	20	132	26
High	10,996,791	32	161	32
Very high	6,823,640	20	83	16
Total	34,573,317		511	

Differences in structural style, deposit density, and cover were used to divide the tract into three domains for which undiscovered deposit estimates were made (figs. E7 and E18). One subdivision, the Central carbonate écaille tract (002rfceCu1000b), corresponds to the central axis of the tract with the thickest sections of Mines Subgroup formations that may have had the thickest evaporite beds (fig. E4). This subdivision hosts most of the known copper deposits and prospects in the Roan Subgroup that are exposed in diapirs, folds, and regional detachments. The part of the tract southwest of the central axis, the Southern carbonate écaille tract (002rfceCu1000a), consists of Roan Subgroup strata in diapirs and fault structures with few deposits and many prospects, some of which are significant. The part of the tract north and northeast of the central subdivision, the Northern carbonate écaille tract (002rfceCu1000c), consists of the Roan Subgroup in folds and regional detachments, which are poorly exposed and covered (fig. E18).

The assessment panel considered the extent of cover in each tract and the level of exploration as they made their estimates. In general, most previous mineral exploration investigated only those rocks within 300 m of the surface. Recent exploration work using deep drill holes indicates mineralization continues at depth and that zones of supergene alteration extend to depths of 1 km or more. The northern subdivision, Northern carbonate écaille tract (002rfceCu1000c), is largely covered by younger lakebed deposits around Lac de Retenue de la Lufira. Kalahari sands cover part of the Senia Thrust Sheet and the highly mineralized Kolwezi Klippe (figs. 11 and E18). The area between the Etoile deposit and Kipapila deposit is mostly concealed beneath laterite within the African Surface (fig. E6). The background to figure E6 is a slope map that symbolizes areas with low slope as pale green and areas with high slope as brown. Areas with low slope are areas where the African Surface is preserved; areas with high slope are places where it has been removed by erosion. Most deposits have been found in areas of higher slope. Parts of the tract isolated from roads would not have been explored intensely. The regional road system in the Democratic Republic of the Congo largely runs parallel to the high density of deposits and prospects in the central part of the tract.

Each member of the assessment panel made individual estimates. These estimates included an evaluation of proportions of mineralized breccia fragments, regional trends and patterns of mineralization, degree of cover, and potential for subsurface deposits. In addition, each person made their own evaluation of trends and patterns shown on the map in order to evaluate parts of the tract where maps did not subdivide units in the Roan Subgroup (virtually all areas south of 11° S) or where there is cover. Individual estimates are summarized in appendix H. The distribution of known deposits and occurrences likely influenced estimates of undiscovered deposits at the 90th and 50th percentile for each subdivision of the tract (table E4). Consensus estimates used in the simulation process are given in table E5.

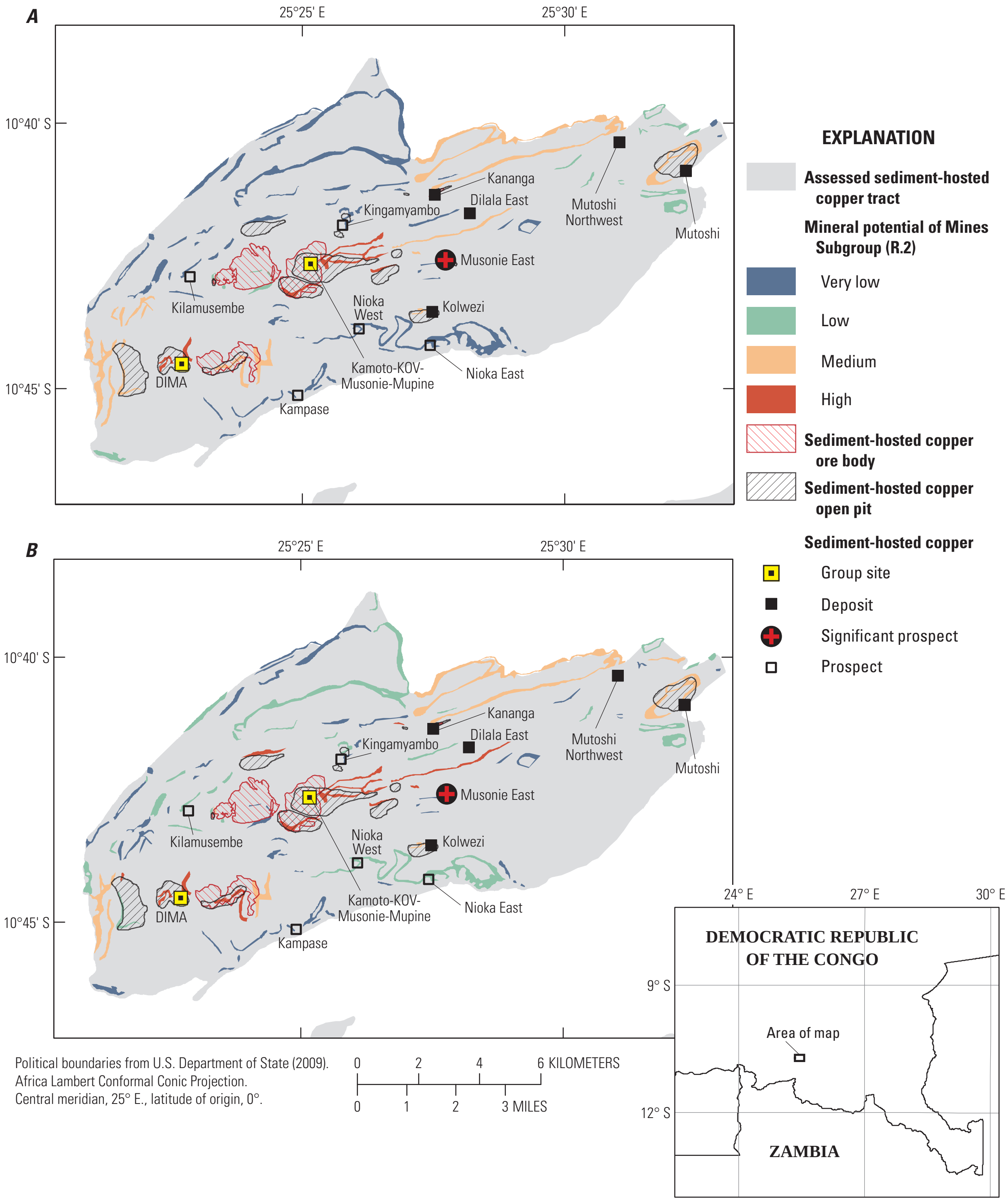


Figure E15. Map of the Kolwezi area showing exposures of the Mines Subgroup ranked according to their mineral potential. The distribution of polygons for ore bodies and open pits, points for deposits and prospects, and the associated permissive tract are shown to provide context. Two versions of the map, *A* and *B*, show rankings by different scientists. Mines Subgroup modified from Musée royal de l'Afrique centrale (2008a).

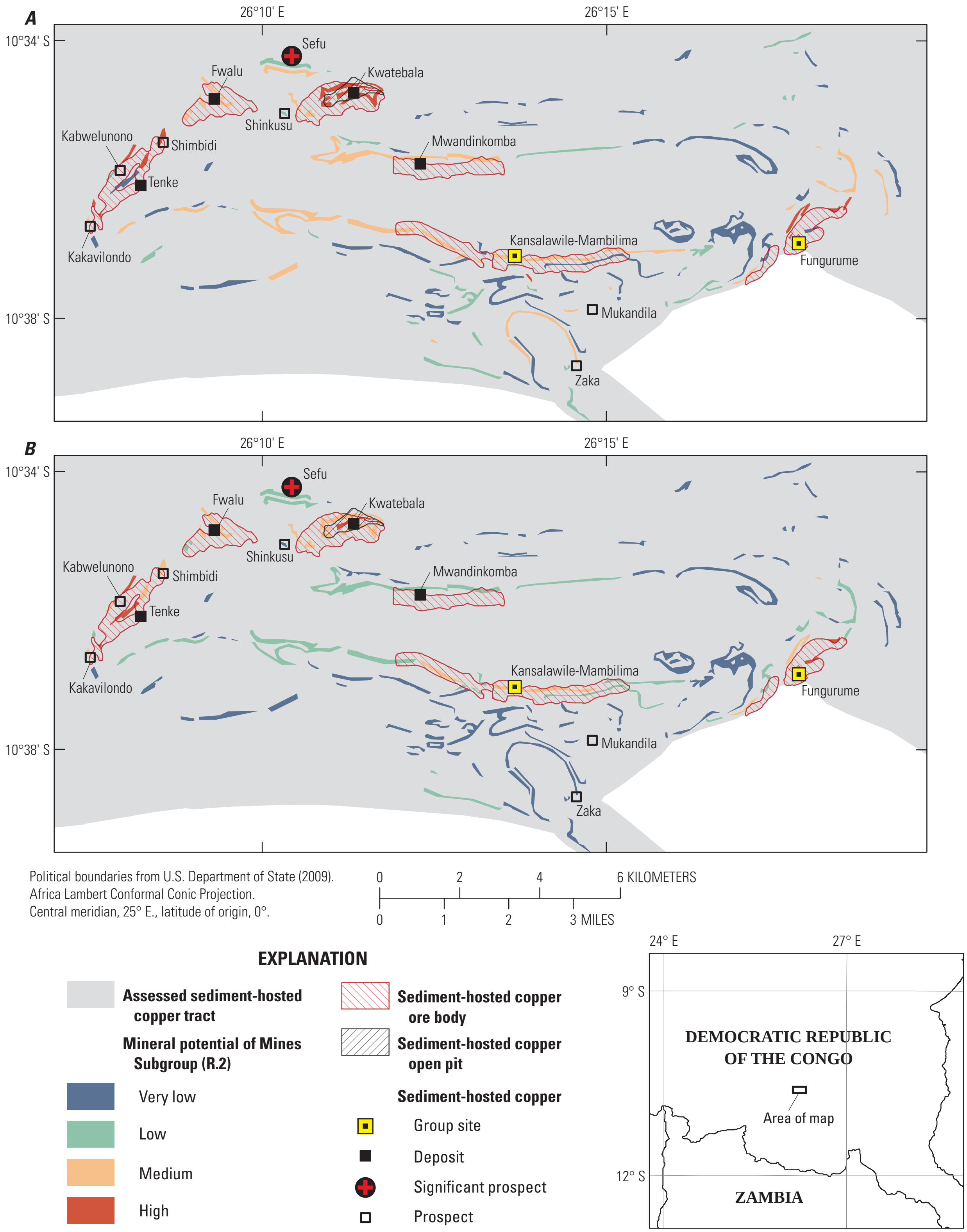


Figure E16. Map of the Tenke-Fungurume area showing exposures of the Mines Subgroup ranked according to their mineral potential. The distribution of polygons for ore bodies and open pits, points for deposits and prospects, and the associated permissive tract are shown to provide context. Two versions of the map, *A* and *B*, show rankings by different scientists. Mines Subgroup modified from Musée royal de l'Afrique centrale (2008a).

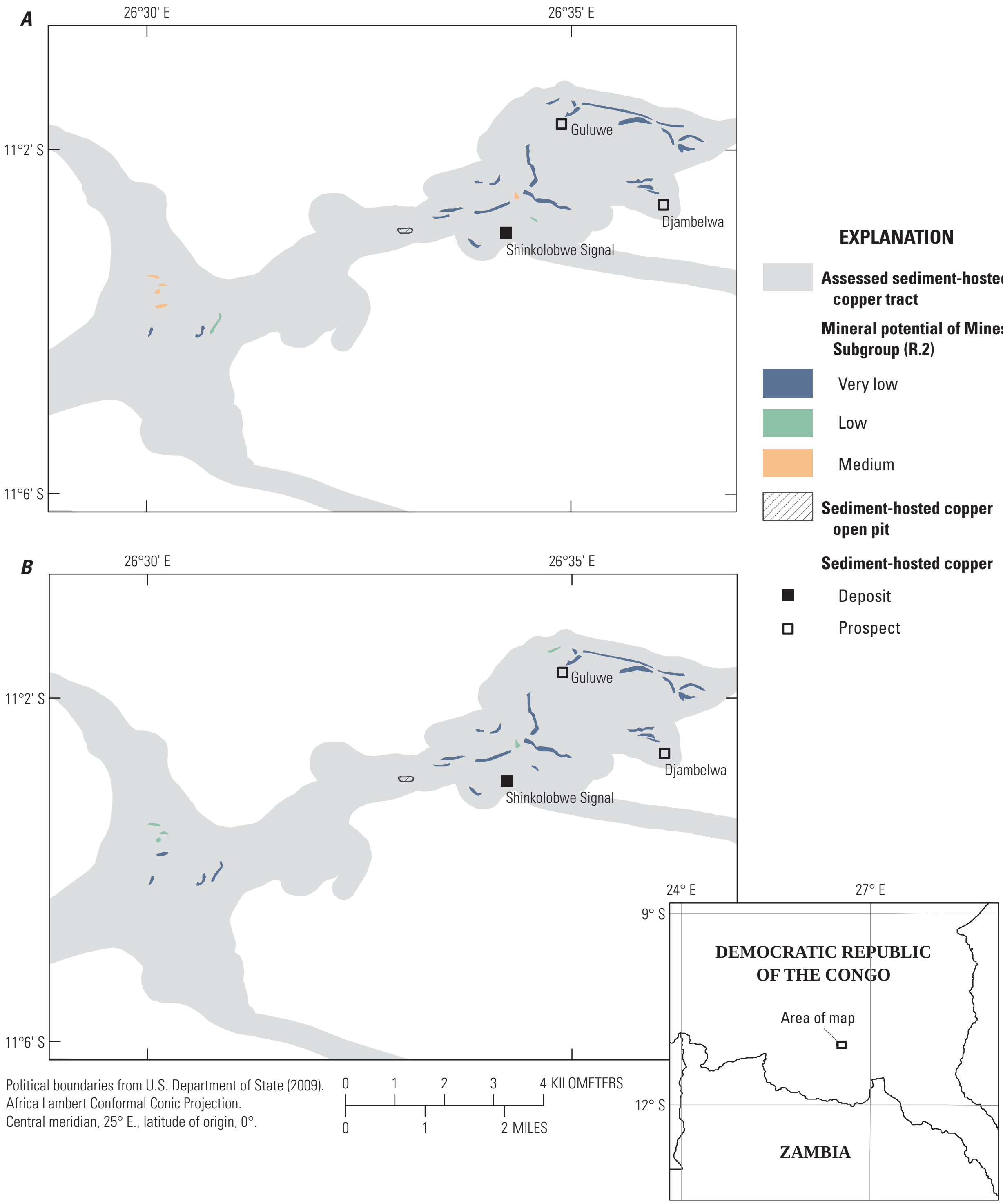
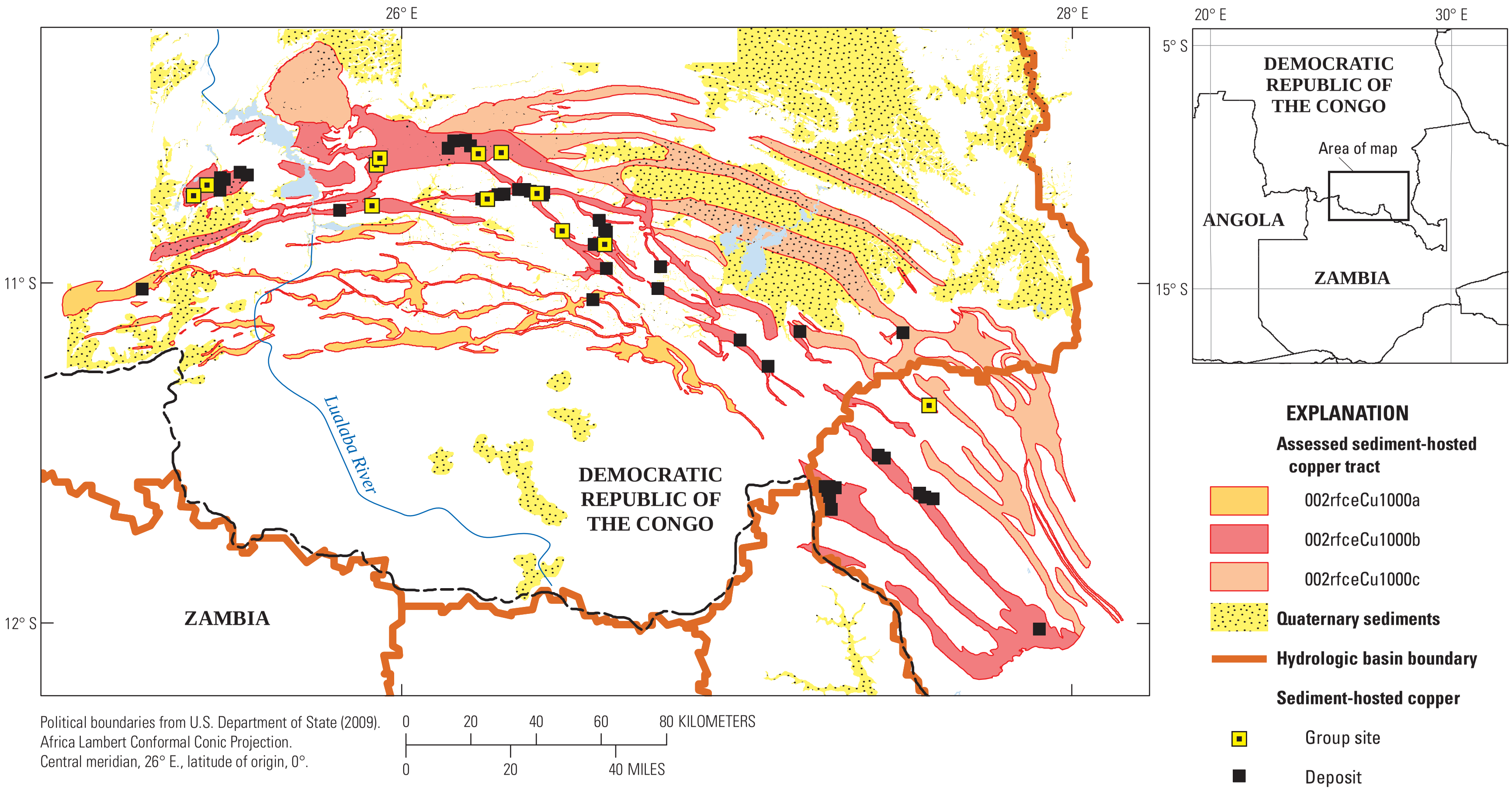


Figure E17. Map of the Shinkolobwe area showing exposures of the Mines Subgroup ranked according to their mineral potential. The distribution of points for deposits and prospects, and the associated permissive tract are shown to provide context. Two versions of the map, *A* and *B*, show rankings by different scientists. Mines Subgroup modified from Musée royal de l'Afrique centrale (2008a).



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 26° E., latitude of origin, 0°.

Figure E18. Map showing areas of Quaternary cover and permissive tracts for sediment-hosted stratabound copper associated with the Roan Group, Democratic Republic of the Congo. Geology modified from Musée royal de l'Afrique centrale (2008a).

Table E4. Summary of the number of deposits, prospects, and significant prospects in the Carbonate écaille tracts (002rfceCu1000a, b, c), Democratic Republic of the Congo.

[–, no data]

Tract coded ID and name	Number of deposits	Number of prospects	Number of significant prospects–total	Number of significant prospects–rank1	Number of significant prospects–rank2	Number of significant prospects–rank3
002rfceCu1000a–Southern carbonate écaille	2	21	12	4	5	3
002rfceCu1000b–Central carbonate écaille	52	55	28	14	4	10
002rfceCu1000c–Northern carbonate écaille	2	11	4	2	–	2

Table E5. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for Carbonate écaille permissive tracts (002rfceCu1000a, b, c), Democratic Republic of the Congo.

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

Tract coded ID and name	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
002rfceCu1000a–Southern carbonate écaille	3	8	18	35	35	11	8.8	83.0	2	13	1,330	0.0094
002rfceCu1000b–Central carbonate écaille	50	85	180	180	180	100	49	49.0	52	150	3,540	0.043
002rfceCu1000c–Northern carbonate écaille	3	8	20	20	20	9.9	6.2	63.0	2	12	4,310	0.0028

Quantitative Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered sediment-hosted copper deposits with the reduced-facies, carbonate écaille model using the Economic Mineral Resource Simulator (EMINERS) program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in tables E6, E7, and E8. Results of the Monte Carlo simulation are presented as cumulative frequency plots (figs. E19, E20, and E21), which show the cumulative probability of a given tonnage of any metal or mineralized rock.

Table E6. Results of Monte Carlo simulations of undiscovered resources in tract 002rfceCu1000a–Southern carbonate écaille, Democratic Republic of the Congo.

[Cu, copper; Co, cobalt; t, metric tons; Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	310,000	1,300,000	9,100,000	32,000,000	42,000,000	13,000,000	0.37	0.03
Co (t)	22,000	100,000	1,100,000	4,000,000	5,300,000	1,600,000	0.35	0.04
Rock (Mt)	9	44	320	1,100	1,400	450	0.38	0.03

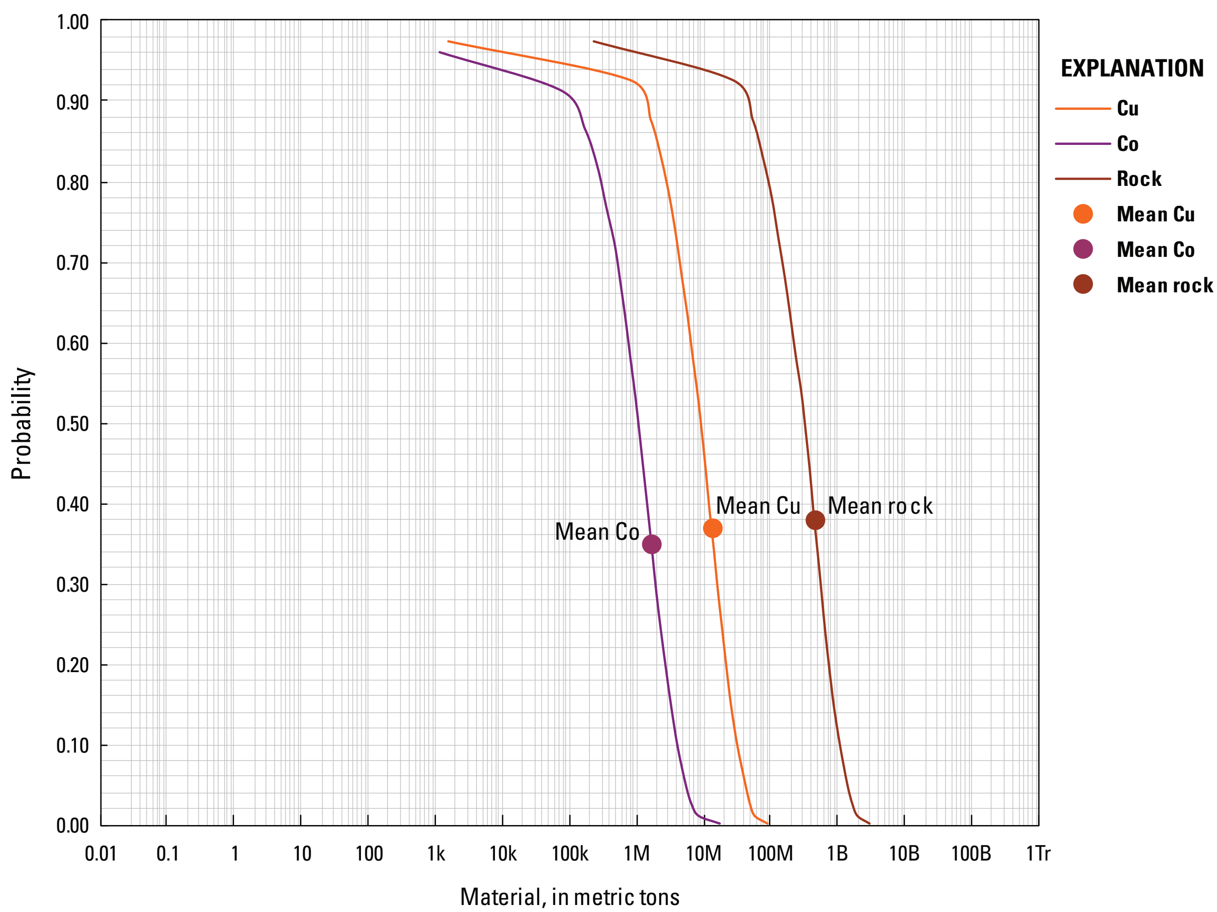


Figure E19. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 002rfceCu1000a, Southern carbonate écaille, Democratic Republic of the Congo and Zambia. k=thousands, M=millions, B=billions, Tr=trillions.

Table E7. Results of Monte Carlo simulations of undiscovered resources in tract 002rfceCu1000b–Central carbonate écaille, Democratic Republic of the Congo.

[Cu, copper; Co, cobalt; t, metric tons; Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	25,000,000	49,000,000	120,000,000	220,000,000	240,000,000	130,000,000	0.45	0.00
Co (t)	3,100,000	5,700,000	14,000,000	28,000,000	30,000,000	16,000,000	0.44	0.00
Rock (Mt)	870	1,700	3,900	7,500	8,100	4,300	0.45	0.00

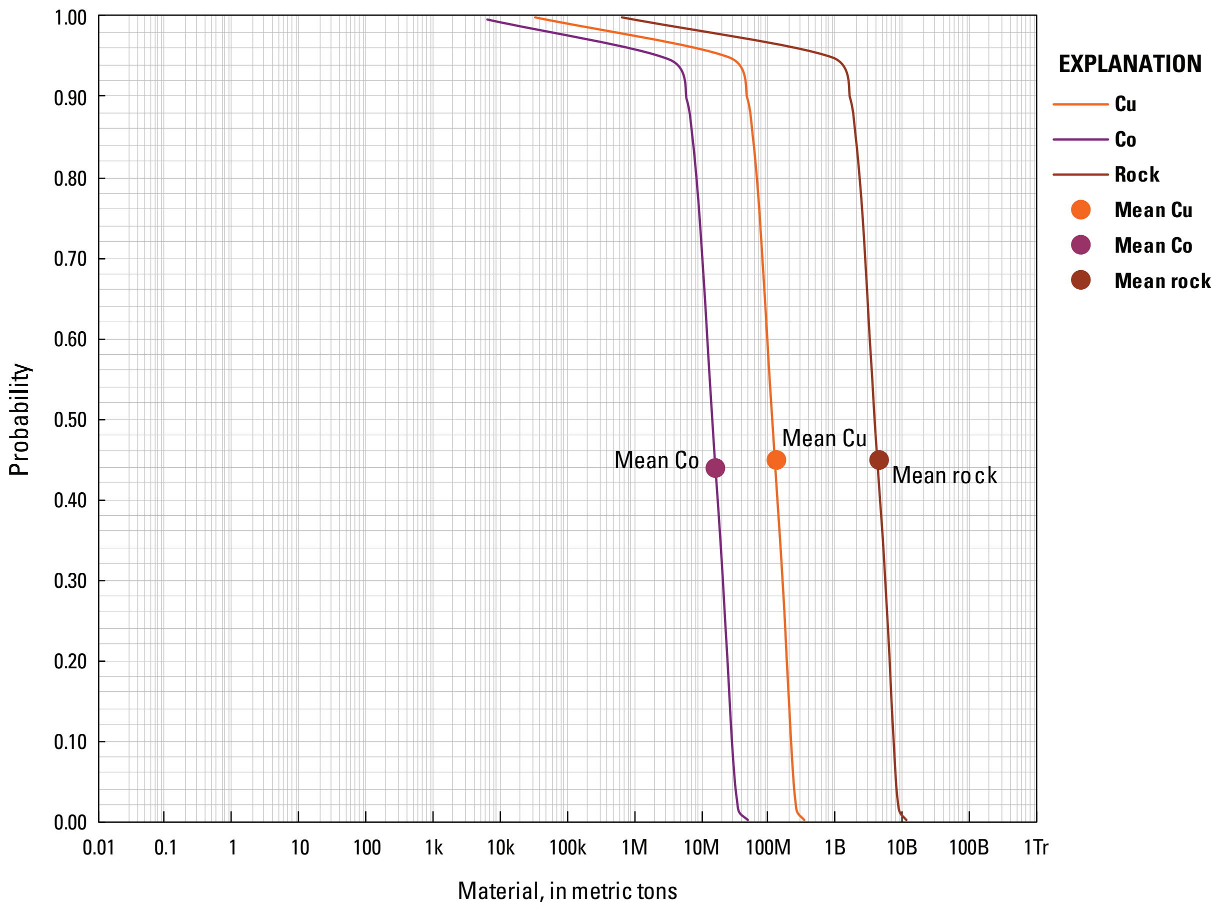


Figure E20. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 002rfceCu1000b, Central carbonate écaille, Democratic Republic of the Congo and Zambia. k=thousands, M=millions, B=billions, Tr=trillions.

Table E8. Results of Monte Carlo simulations of undiscovered resources in tract 002rfceCu1000c–Northern carbonate écaille, Democratic Republic of the Congo.

[Cu, copper; Co, cobalt; t, metric tons; Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	250,000	1,100,000	9,600,000	28,000,000	34,000,000	12,000,000	0.42	0.03
Co (t)	6,400	95,000	1,100,000	3,400,000	4,300,000	1,500,000	0.40	0.05
Rock (Mt)	8	38	340	930	1,100	420	0.43	0.03

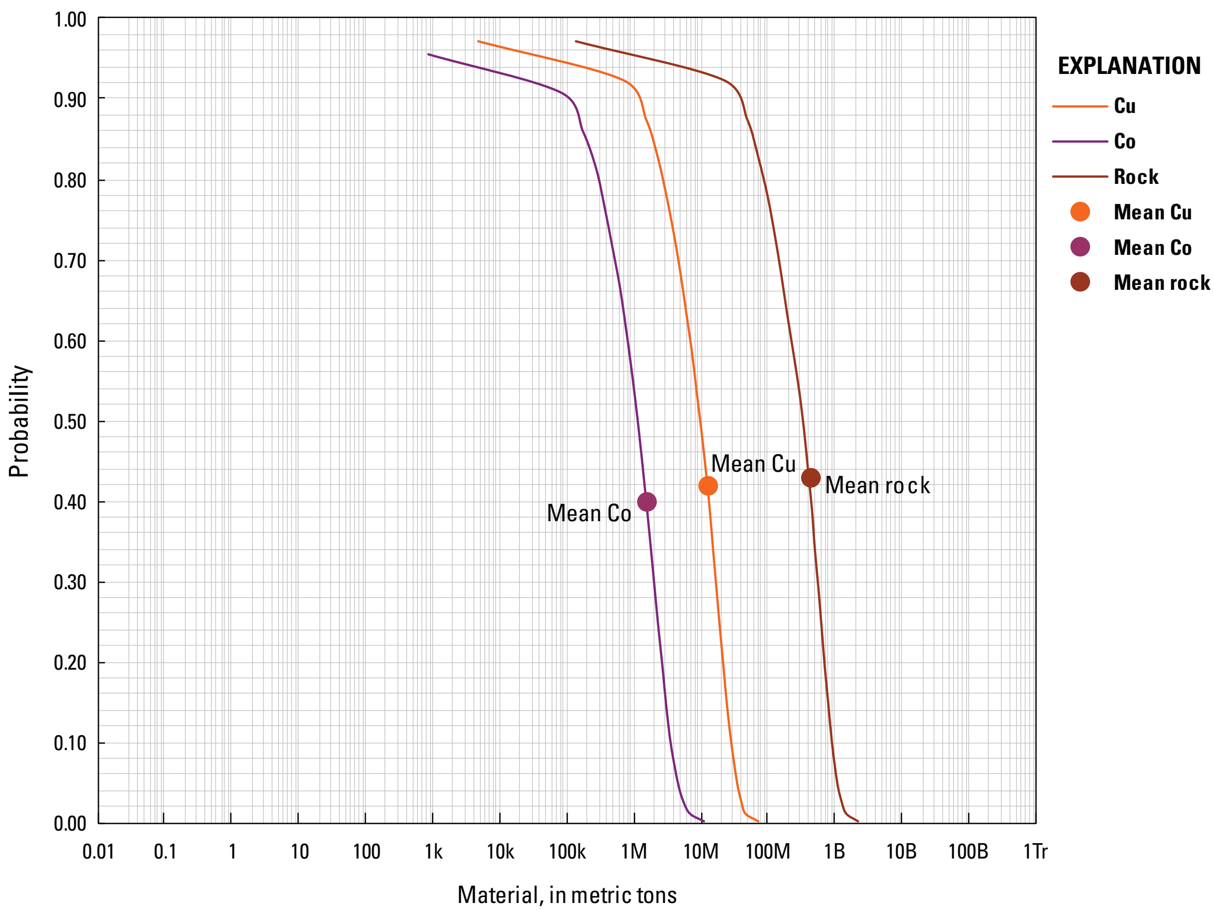


Figure E21. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 002rfceCu1000c, Northern carbonate écaille, Democratic Republic of the Congo and Zambia. k=thousands, M=millions, B=billions, Tr=trillions.

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Appendix F. Sediment-Hosted Stratabound Copper Assessment for Tract 002rfnbCu1001, Ore Shale—Zambia

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Deposit Type Assessed

Deposit type: Sediment-hosted stratabound copper

Descriptive model: Sediment-hosted stratabound copper, reduced-facies subtype (Cox, 2003; Hayes and others, in press; Zientek, Hayes, and Hammarstrom, 2013)

Grade and tonnage model: Sediment-hosted stratabound copper, reduced-facies-nonbrecciated (Zientek, Hayes, and Taylor, 2013)

Table F1 summarizes selected assessment results.

Table F1. Summary of selected resource assessment results for tract 002rfnbCu1001–Ore shale, Zambia.

Date of assessment	Assessment depth (kilometers)	Tract area (km^2)	Known copper resources (metric tons)	Mean estimate of undiscovered copper resources (metric tons)	Median estimate of undiscovered copper resources (metric tons)
January 2010	2	890	71,000,000	5,100,000	880,000

Location

The belt extends 125 km northwestwards from Luanshya, Zambia.

Geologic Feature Assessed

Neoproterozoic Ore Shale member of the Kitwe Formation of the Roan Group in the Katanga Basin.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

[10]Private Consultant, Duncraig, Perth, Western Australia.

Delineation of the Permissive Tract

Geologic Criteria

The assessment unit used to delineate permissive tracts in the Ore shale tract (002rfnbCu1001) is the Ore Shale member of the Kitwe Formation of the Roan Group (Selley and others, 2005), which hosts large, laterally continuous, stratiform copper-cobalt deposits in Zambia.

The permissive tract is delineated by estimating the location of the volume of rock containing the Ore Shale member to a depth of 2 km and projecting it to the surface. The Ore Shale is present in a narrow belt along the west side of the Kafue Anticline (fig. F1). The belt extends 125 km northwest from Luanshya and varies in width from 13 to 25 km (Annels, 1984, 1989). The tract polygon was derived by combining the mapped extent of the Lower Roan Subgroup from 1:100,000 and 1:500,000-scale geologic maps with the facies distribution maps published by Annels (1984). Drill information and geophysical surveys were not available to constrain the interpretation.

Specifically, the Ore shale tract (002rfnbCu1001) was delineated on the basis of two 1:500,000-scale geologic maps (Musée royal de l'Afrique centrale, 2008; De Swardt and Drysdall, 1963), three 1:100,000-scale geologic maps (Hickman, 1992; Garrard, 1994; Marjonen, 2000), cross sections, and structural data from these maps. The largest-scale map possible was used for permissive tract delineation in each quadrangle in order to use the highest resolution data available. The 1:100,000-scale maps were used to construct slightly less than half of the permissive tract. Maps from Musée royal de l'Afrique centrale (2008) and De Swardt and Drysdall (1963) were used for the northern Ore shale tract in the Konkola-Musoshi area. Surface exposure of the Roan Group was digitized into polygons in ArcGIS from rectified 1:100,000-scale maps. The lower contacts of the Roan Group with underlying Kibaran basement gneiss were strictly followed because these older units are nonpermissive for undiscovered copper deposits. However, basaltic sills that intrude the Roan Group were included within the tract because their geometry conforms with Roan strata. Downdip projections along fold limbs to a depth of 2 km were based on more than 75 strike and dip measurements and analysis of patterns of map units in relation to topography on geologic maps. A simple trigonometric calculation [2 km/tangent(dip°)] allowed for the projection of the downdip extension of the permissive unit to the surface. In addition, the apparent thickness of units overlying the Lower Roan Subgroup contributed to the downdip projection where structural data were unavailable. Greater apparent thickness of the map units at the surface was interpreted to represent shallowly dipping strata; thus, a wider permissive tract was drawn. Narrower permissive tracts were delineated over steeply dipping units. Polygons showing the distribution of the Ore Shale member and its facies zones were digitized from a rectified map (Annels, 1984). These Ore Shale polygons were combined with those obtained from the geologic maps to produce the complete permissive tract (fig. F2).

Known Deposits

Mineral deposits within the Ore Shale member contain about 70 million metric tons of copper, or about 50 percent of the total endowment of the Zambian Copperbelt (appendix D). After applying a spatial rule of 500 m to aggregate sites for modeling, nine deposits can be defined in the Ore Shale member. Of these, six are both significant and giant deposits (having more than 50 thousand metric tons copper and 2 million metric tons of contained copper, respectively).

From northwest to southeast, the significant/giant deposits are:

1. Konkola-Musoshi (figs. F2 and F3; Fleischer and others, 1976; Richards and others, 1988a,b; Sweeney and Binda, 1989; Chileshe and Kulkarni, 1992; Simposya and Hart, 2008);

2. Chingola-Nchanga (figs. F2 and F4; McKinnon and Smit, 1961; Fleischer and others, 1976; Roberts and others, 2005);

3. Chambishi Main and West (figs. F2 and F5; Garlick, 1961; Fleischer and others, 1976; Fleischer, 1984; Greyling and others, 2005);

4. Chambishi Southeast (fig. F2; Japan International Cooperation Agency, and Metal Mining Agency of Japan, 1996a,b);

5. Mindola-Nkana N-S (figs. F2 and F6; Jordaan, 1961; Fleischer and others, 1976; Brems and others, 2009); and

6. Baluba-Muliashi-Luanshya (fig. F2; Mendelsohn, 1961b; Fleischer and others, 1976).

All deposits, with the exception of Chambishi Southeast, have a long history of production. Other reports describing the known deposits in this tract include Freeman (1988), Annels (1989), Mendelsohn (1989), and Selley and others (2005).

Prospects, Mineral Occurrences, and Related Deposit Types

Only one occurrence, Luano, is in the database of deposits and prospects.

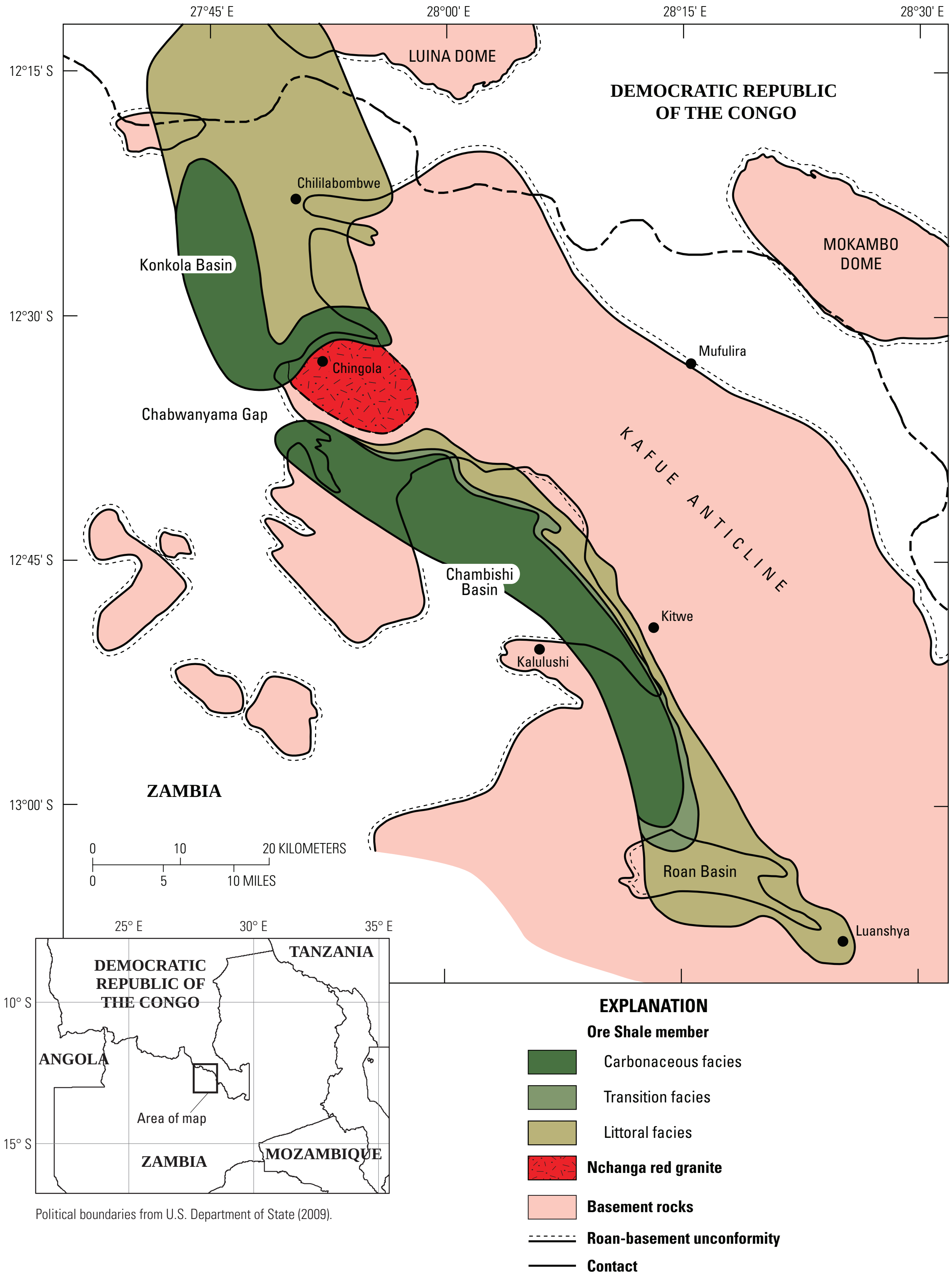
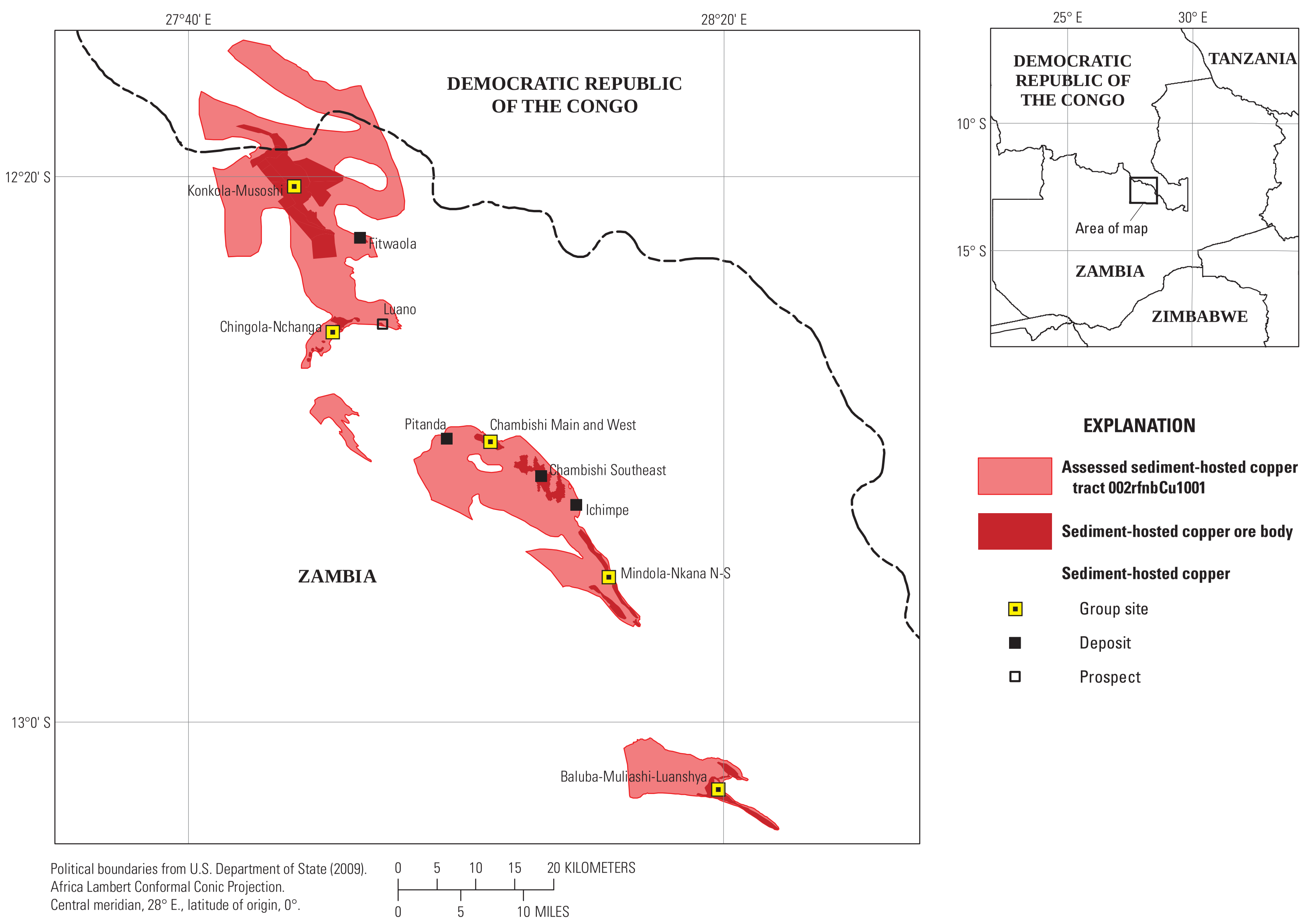


Figure F1. Geologic map showing the distribution of the Ore Shale member of the Kitwe Formation, Roan Group, Zambia. Modified from Annels (1984).



Political boundaries from U.S. Department of State (2009).
Africa Lambert Conformal Conic Projection.
Central meridian, 28° E., latitude of origin, 0°.

Figure F2. Map showing tract location, known sediment-hosted stratabound copper deposits and prospects for tract 002rfnbCu1001, Ore shale, Democratic Republic of the Congo and Zambia.

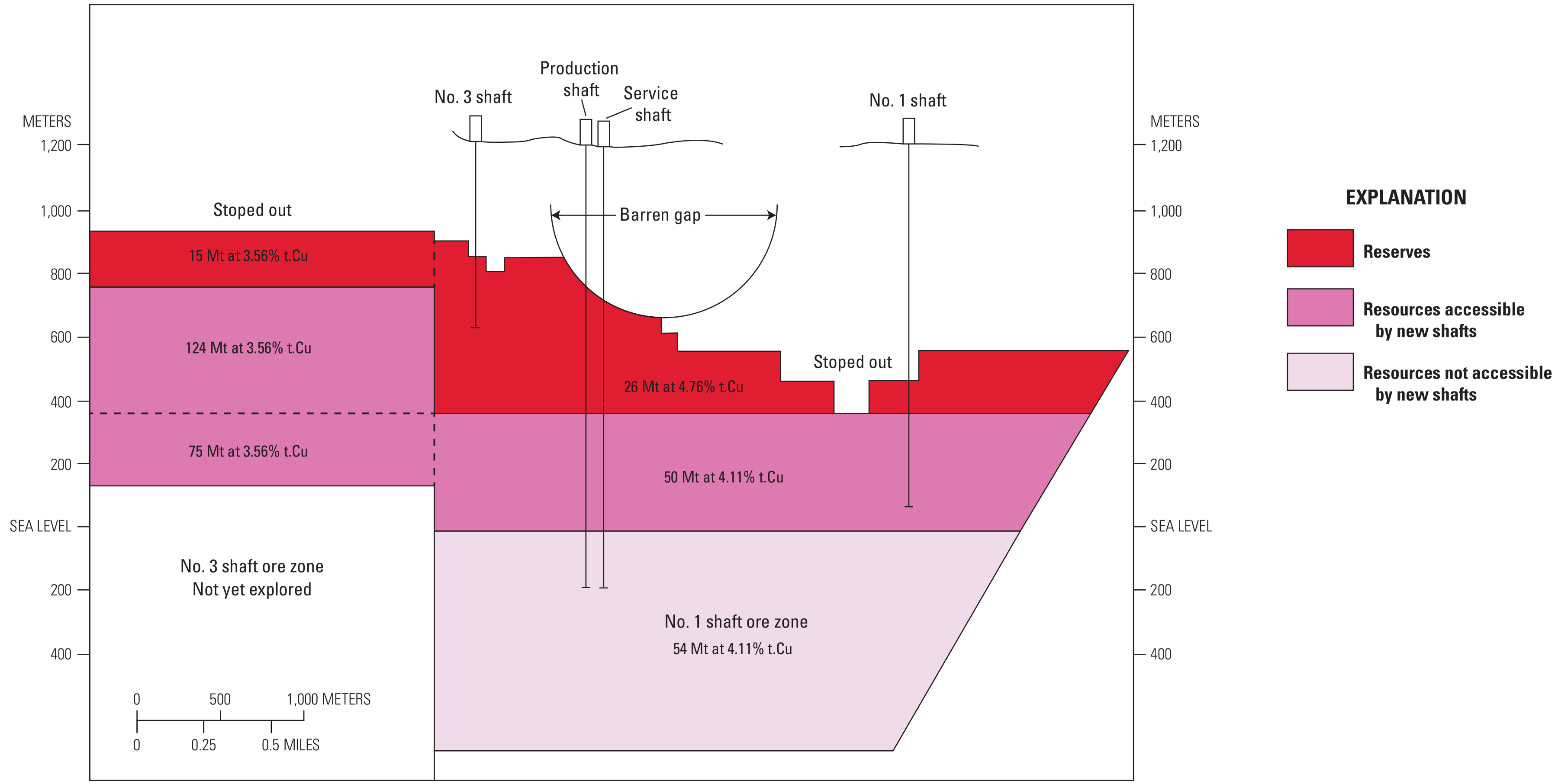


Figure F3. Longitudinal section through the Kirila Bomwe ore body of the Kinkola-Musoshi deposit, Zambia. The section shows the portion of the ore body that can be exploited by the No. 1 and No. 3 shafts. The ore body has been explored by surface boreholes down to a depth of 1,900 meters in the southern part and 1,150 meters in the northern part. Modified from Chileshe and Kulkarni (1992). Mt, million metric tons; t.Cu, metric tons of copper.

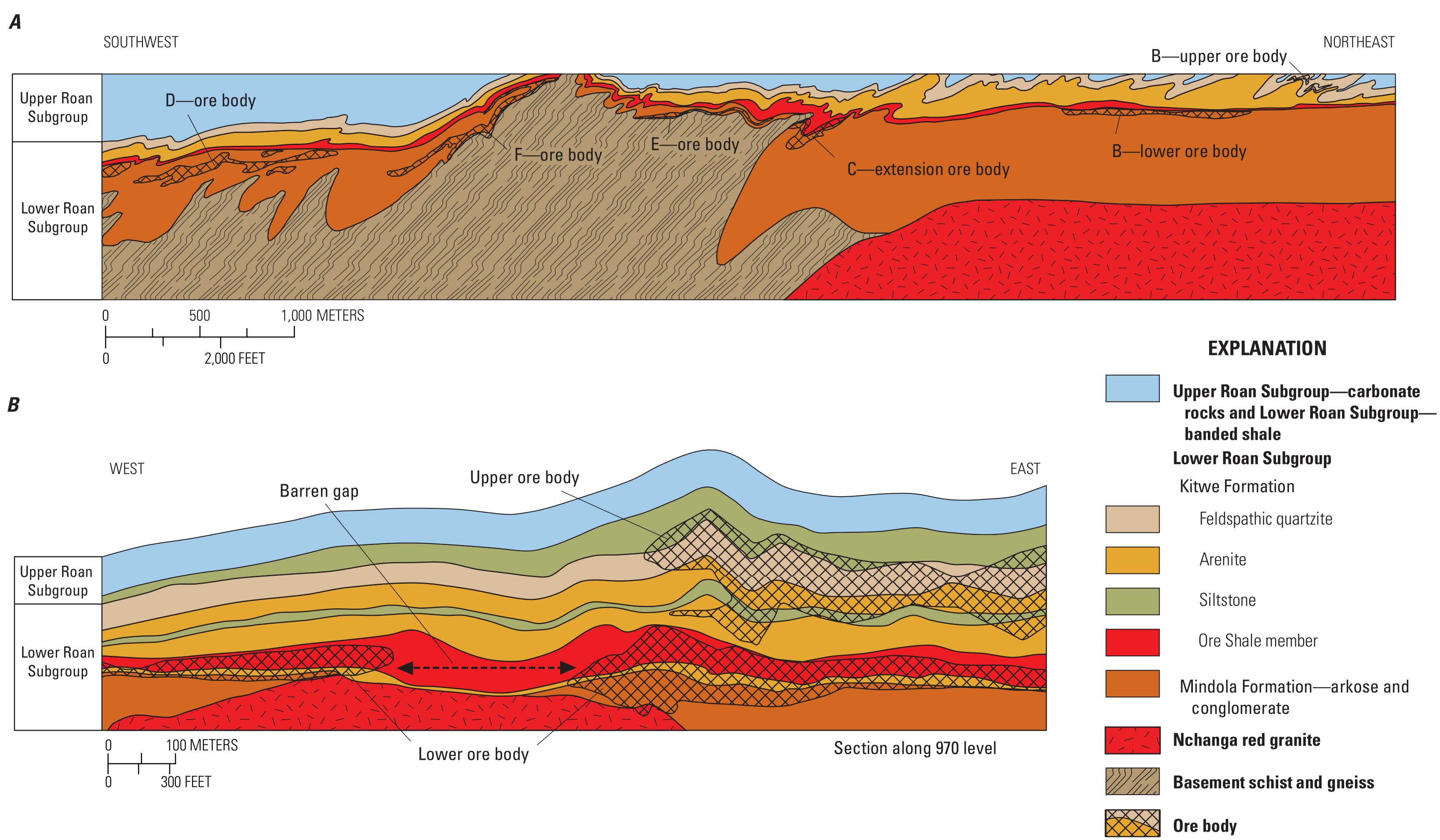
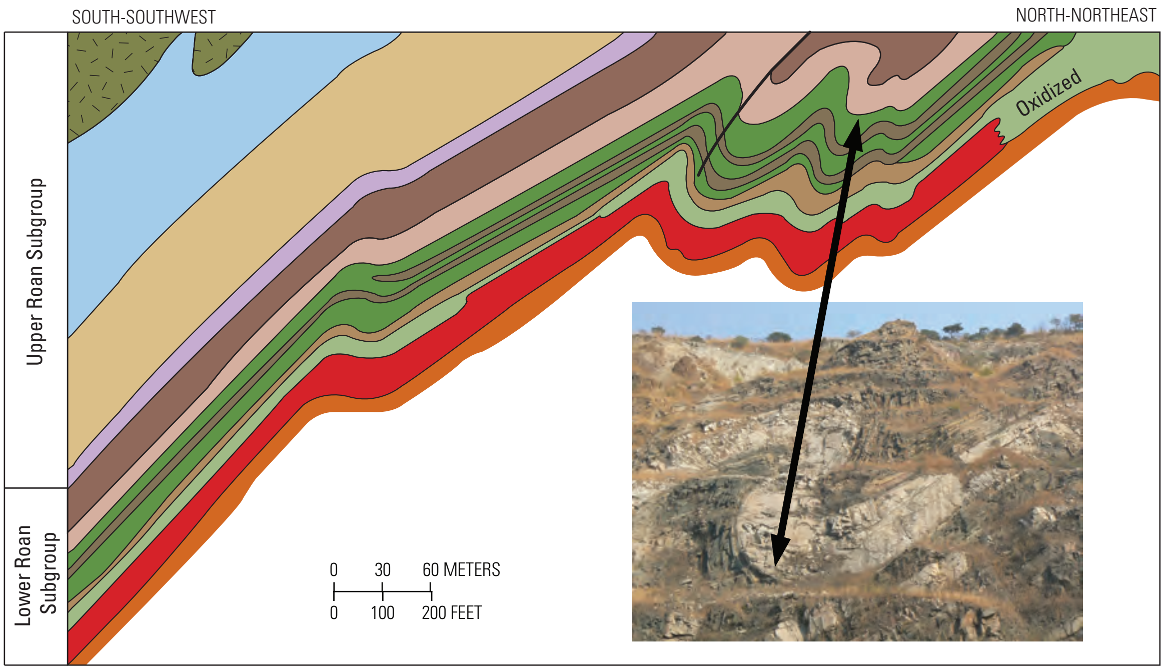


Figure F4. Geologic sections of the Chingola and Nchanga deposits, Zambia, showing the distribution of sediment-hosted stratabound mineralization in the stratigraphic interval below and into the Ore Shale member of the Kitwe Formation, Zambia. *A*, Diagrammatic section of the Chingola area. *B*, Section along the 970 level of the Nchanga ore body. Mineralization is dominantly hosted by arenites that underlie the Ore Shale member; however, each ore body extends into overlying argillaceous strata (siltstones). Modified from McKinnon and Smit (1961), Fleischer and others (1976), and Selley and others (2005).



EXPLANATION

Metagabbro intrusions

Upper Roan Subgroup

Dolomite of the Bancroft Formation

Kanwangungu Formation

Sandy Talc Schist

Cherty Dolomite

Interbedded schist and quartzite

Lower Roan Subgroup

Upper Quartzite of the Kitwe Formation

Interbedded quartzite and argillite

Argillite

Quartzite

Hanging Wall Quartzite

Ore Shale member

Barren

Mineralized

Mindola Formation

Fault

Figure F5. Geologic cross section of the Chambishi Main deposit, Zambia. An asymmetrical fold in the section is exposed in the open pit. Ore in the deposit is oxidized to a depth of approximately 60 m. Modified from Garlick (1961) and Greyling and others (2005).

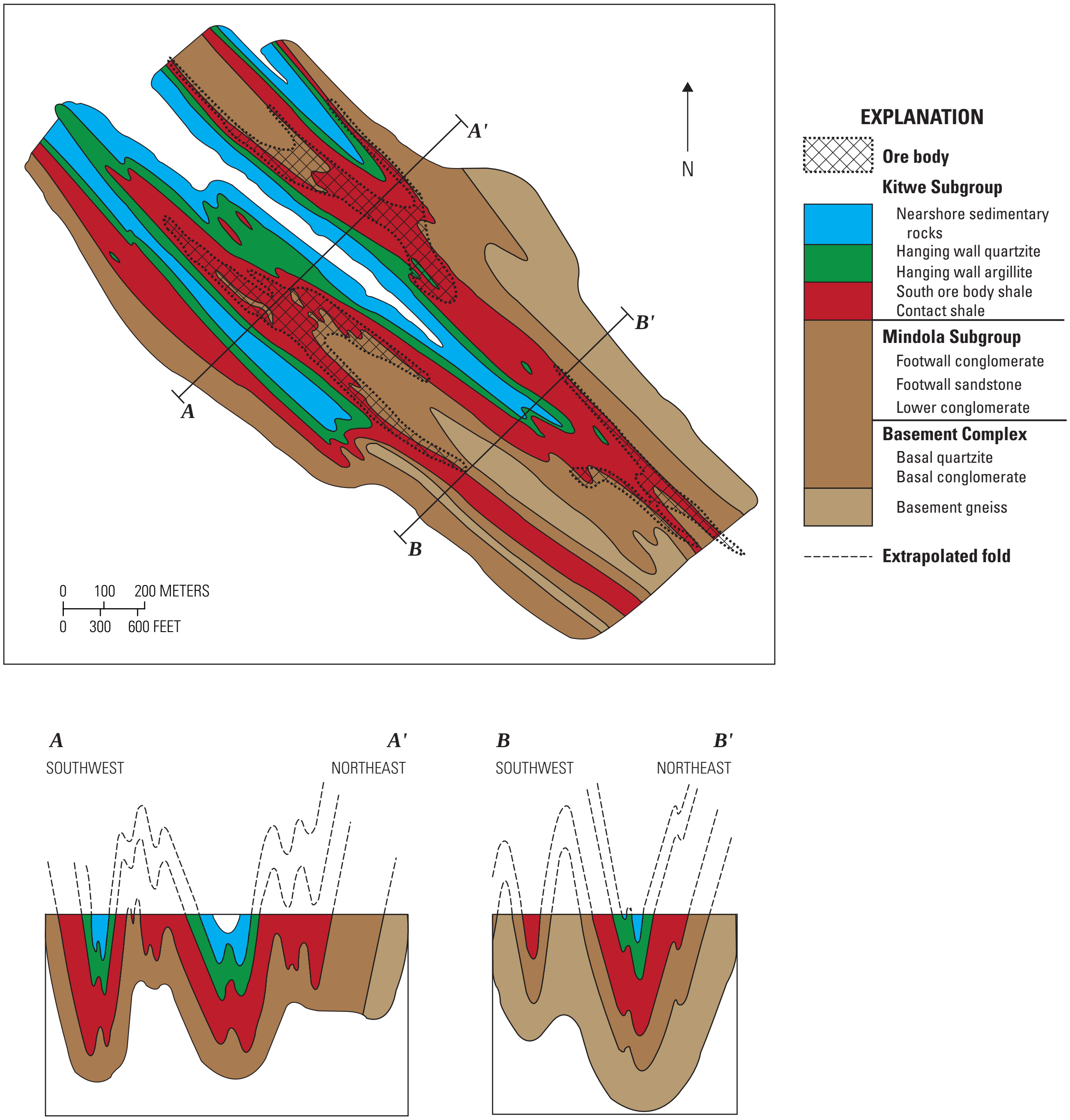


Figure F6. Geologic map and cross sections for the 3360 level of the Nkana "South Ore body" mine, Zambia. Folding is related to the Pan African Lufilian Orogeny. Sediment-hosted stratabound mineralization is now localized into ore bodies that occupy the hinge zones of tight to isoclinal folds. Modified from Brems and others (2009).

Exploration History

Most of the deposits in the Ore Shale member were discovered in the early part of the last century (Mendelsohn, 1961a; Coleman, 1971). Zambian Consolidated Copper Mines (ZCCM) was formed by a gradual process of nationalization and corporate concatenation. In 1996, ZCCM started privatizing its operations, and by the end of 2000, most assets had been transferred to a variety of international companies. ZCCM Investments Holdings plc (ZCCM-IH) has retained minority interests in several companies, specifically the Konkola Copper Mines plc, Luanshya Copper Mines plc, and Mopani Copper Mines plc, which control deposits within the Ore Shale member (Mudjadji Trading and others, 2008). Equinox Minerals, through its Zambezi Joint Venture with Anglo American, holds the majority of the tenements that cover the Ore Shale member outside of the mining sites. However, this company has not reported exploration activity on sites located in the Ore Shale member.

Sources of Information

Principal sources of information used by the assessment team for delineation of the Ore shale tract (002rfnbCu1001) are listed in appendix C.

Grade and Tonnage Model Selection

For this assessment, the global model for reduced-facies deposits that are not disrupted by salt tectonics is used to infer the in-place metal contents of mineralization within the Ore Shale member in Zambia (Zientek, Hayes, and Taylor, 2013).

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

This permissive tract is well explored. Known deposits were discovered early in the last century; the continuous nature of the mineralization and the strong stratigraphic control on its localization made it relatively easy to find the deposits. Additional deposits are not likely to be present within the upper kilometer of this tract. The geologists who conducted this assessment are confident, however, that undiscovered resources may exist at depth, either as extensions to known mineralization or as new deposits. Nevertheless, the large areal extent of the deposits relative to the area of the permissive tract does not provide confidence for the occurrence of many additional deposits (fig. F2).

Individual estimates are summarized in appendix H. Parallel plots compare estimates made by geologists in academia, government, and the private sector with the consensus value used for the undiscovered resource estimation. Consensus values used in the simulation process are given in table F2.

Quantitative Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered sediment-hosted copper deposits with the reduced-facies—nonbrecciated grade and tonnage model using the Economic Mineral Resource Simulator (EMINERS) program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012).

Table F2. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 002rfnbCu1001–Ore shale, Zambia.

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

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
1	1	3	3	3	1.5	0.93	61.0	9	11	890	0.012

Selected simulation results are reported in table F3. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. F7) and show the cumulative probability of a given tonnage of any metal or mineralized rock.

Table F3. Results of Monte Carlo simulations of undiscovered resources in tract 002rfnbCu1001–Ore shale, Zambia.

[Cu, copper; Ag, silver; t, metric tons; Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	0	16,000	880,000	15,000,000	24,000,000	5,100,000	0.23	0.07
Ag (t)	0	0	0	5,500	21,000	7,100	0.09	0.52
Rock (Mt)	0	1	55	740	1,200	280	0.24	0.07

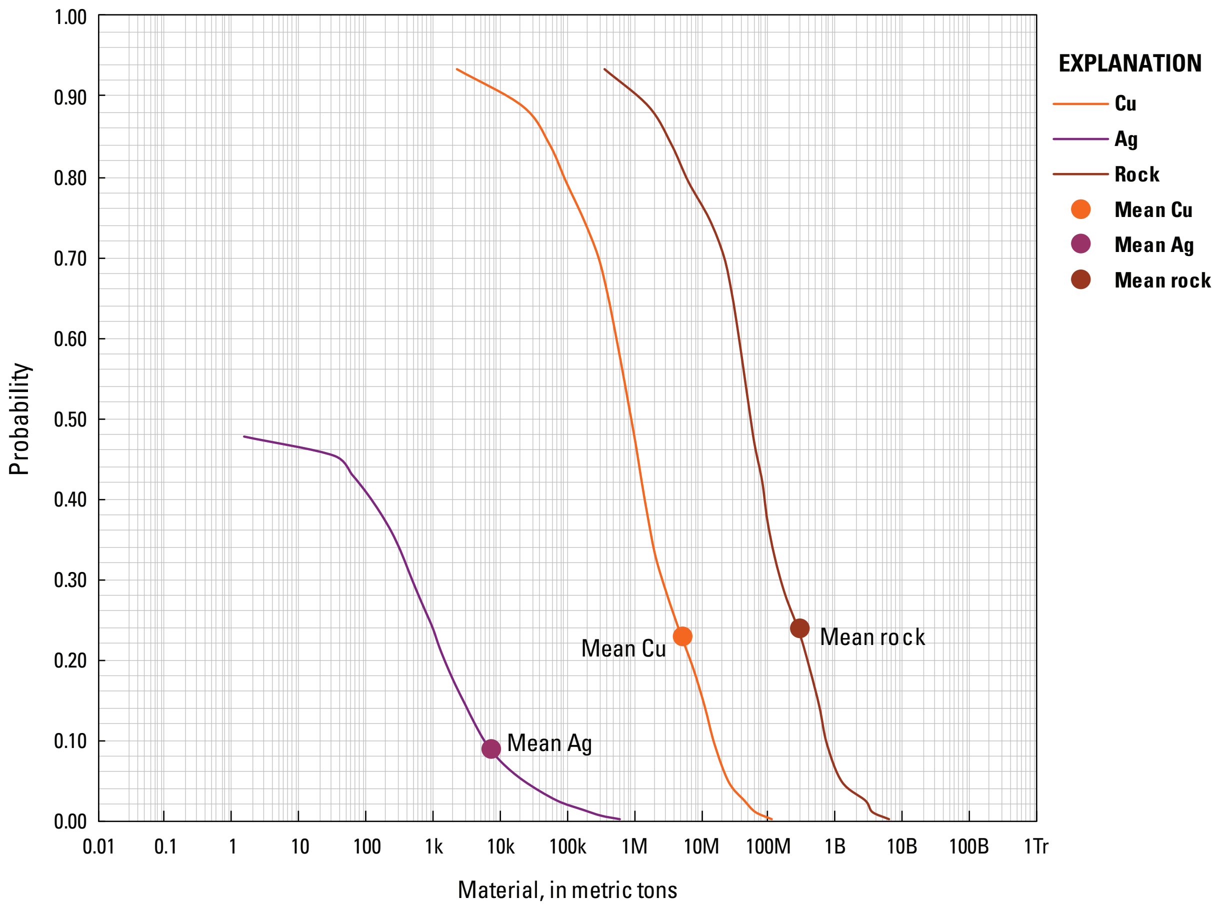


Figure F7. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 002rfnbCu1001, Ore shale, Democratic Republic of the Congo and Zambia. k=thousands, M=millions, B=billions, Tr=trillions.

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Appendix G. Sediment-Hosted Stratabound Copper Assessment for Tract 002ssCu1002, Roan Arenite—Zambia

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Deposit Type Assessed

Deposit type: Sediment-hosted stratabound copper

Descriptive model: Sediment-hosted stratabound copper, sandstone copper type (Cox, 2003; Hayes and others, in press; Zientek, Hayes, and Hammarstrom, 2013)

Grade and tonnage model: Sediment-hosted stratabound copper, sandstone copper-Roan arenite (Zientek, Hayes, and Taylor, 2013)

Table G1 summarizes selected assessment results.

Table G1. Summary of selected resource assessment results for tract 002ssCu1002–Roan arenite, Zambia.

Date of assessment	Assessment depth (kilometers)	Tract area (km^2)	Known copper resources (metric tons)	Mean estimate of undiscovered copper resources (metric tons)	Median estimate of undiscovered copper resources (metric tons)
January 2010	2	13,100	16,000,000	8,400,000	6,400,000

Location

From north to south, the tract extends from south of Lubumbashi, Democratic Republic of the Congo (DRC) to Kambwe, Zambia. The eastern limit of the tract is near Ndola, Zambia; the western limit is near Kangondi, Zambia.

Geologic Feature Assessed

Siliciclastic rocks within the Lower Roan Subgroup in the Katanga Basin near the Kafue Anticline and adjacent basement-cored domes.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

[10]Private Consultant, Duncraig, Perth, Western Australia.

Delineation of the Permissive Tract

Geologic Criteria

The assessment unit used to delineate the Roan arenite tract (002ssCu1002) includes the siliciclastic sedimentary rocks of the Lower Roan Subgroup near the Kafue Anticline and adjacent basement-cored domes that are within about 200 m of the Ore Shale member (fig. G1; Selley and others, 2005). These rocks host about 20 sandstone-hosted copper deposits in the Zambian Copperbelt.

Sandstone-hosted copper deposits occur in siliciclastic rocks that both underlie and overlie the Ore Shale member. The deposits are localized at sites where mobile hydrocarbons or sour gas could accumulate (Selley and others, 2005). Stratigraphic sections and drill information such as those in figure G2 could be used to identify potential structural or stratigraphic traps in the siliciclastic rocks of the Lower Roan Subgroup; however, this information generally was not available.

The permissive tract is delineated by estimating the location of the volume of rock containing siliciclastic rocks in the Lower Roan Subgroup to a depth of 2 km and projecting it to the surface (fig. G3). A basal section of siliciclastic rocks is characteristic of the Roan Group in the Katanga Basin (such as the R.A.T. Subgroup in the Congolese part of the Zambian Copperbelt; Cailteux and others, 2005). The Roan arenite tract (002ssCu1002) focuses only within the basal siliciclastic rocks in the Lower Roan Subgroup near the Kafue Anticline and adjacent domes where the presence of sandstone copper deposits and occurrences provides direct evidence for the movement of copper-bearing hydrothermal fluids that interacted with a reductant (likely hydrocarbons or sour gas).

Tract delineation is based on two 1:500,000-scale (De Swardt and Drysdall, 1963; Musée royal de l'Afrique centrale, 2008) and twelve 1:100,000-scale geologic maps (Moore, 1964, 1968a,b; Stillman, 1965a,b; Smith, 1965; Hickman, 1992; Keppie, 1994; Garrard, 1994; Cairney and Kerr, 1997; Marjonen, 2000; Smith and Kerr, 2000), structural data from these maps, and two cross sections (African Eagle Resources plc, 2009; Simposya and Hart, 2008). The largest-scale map and highest resolution data available were used for permissive tract delineation in each quadrangle. The 1:100,000-scale maps were used to construct slightly more than half of the permissive tract. Information from Musée royal de l'Afrique centrale (2008) was used for the areas around and north of the Konkola and Luita Domes; that from De Swardt and Drysdall (1963) was used for all the remaining areas in Zambia.

Surface exposure of the Roan Group was digitized into polygons in ArcGIS from these rectified 1:100,000-scale maps. The structural style is dominated by upright to inclined, high-amplitude folds. Lower contacts of the Roan Group with underlying Kibaran basement gneiss were strictly followed because these older units are nonpermissive for the occurrence of deposits. However, basaltic sills that intrude the Roan Group were included within the tract because their geometry conforms with Roan strata. Downdip projections along fold limbs to a depth of 2 km were based on more than 250 strike and dip measurements and analysis of rock geometry based on map patterns. A simple trigonometric calculation [2 km/tangent(dip°)] allowed for the projection of the downdip extension of the permissive unit to the surface. Topographic relief in the region is low enough to allow for straightforward interpretations of unmapped kilometer-scale folds and domes, which typify this area. Parasitic folds on the meter scale throughout the region were regarded as too small to influence tract boundaries and were ignored in the analyses. Where strikes and dips were unavailable, apparent thickness of the mapped units was used to estimate the dip. Cross sections from two mines were used to confirm fold geometry and depth to the Roan Group (African Eagle Resources plc, 2009; Simposya and Hart, 2008). Tract boundaries were adjusted slightly to encompass known ore bodies and deposit locations; adjustment amounts were on the order of the cartographic resolution of map linework (fig. G3).

Known Deposits

Mineral deposits within siliciclastic rocks in the Lower Roan Subgroup near the Kafue Anticline contain about 16 million metric tons of copper, or about 10 percent of the total endowment of the Zambian Copperbelt (appendix D). After applying a spatial rule of 500 m to aggregate sites for modeling, 20 deposits can be defined within this tract. Among these, all are significant (having more than 50 thousand metric tons of contained copper); Mufulira is a giant deposit (having more than 2 million metric tons of contained copper; figs. G4 and G5).

The Mufulira copper deposit is within the Lower Roan Subgroup that is exposed along the eastern side of the Kafue Anticline in Zambia (Van Eden, 1974; Annels, 1979; Garlick, 1981; Fleischer, 1976; Selley and others, 2005). The Lower Roan Subgroup overlies Precambrian basement, which forms a number of hills. In the mine area, the Lower Roan is informally divided into Footwall, Ore, and Hangingwall Formations, based on the presence or absence of copper-iron sulfide minerals. The stratigraphy of the upper part of the Footwall Formation and the Ore Formation is characterized by three upward-fining units that have conglomeratic sandstone at their bases, followed upsection by sandstone (quartzite), and culminating with argillite (shale) and dolomite at the top (fig. G4).

An ore body is associated with each of the fining-upward units, with the C ore body in the lowest unit and the A ore body in the highest (figs. G4 and G5). Each ore body consists of multiple mineralized beds. The ore bodies are stacked and vertically coincident. The top of each ore body coincides with an abrupt transition to low-permeability dolomitic or argillaceous strata that form the stratigraphic top of each fining-upward unit. Lateral footwall and lateral boundaries of the ore bodies do not correspond to lithological changes.

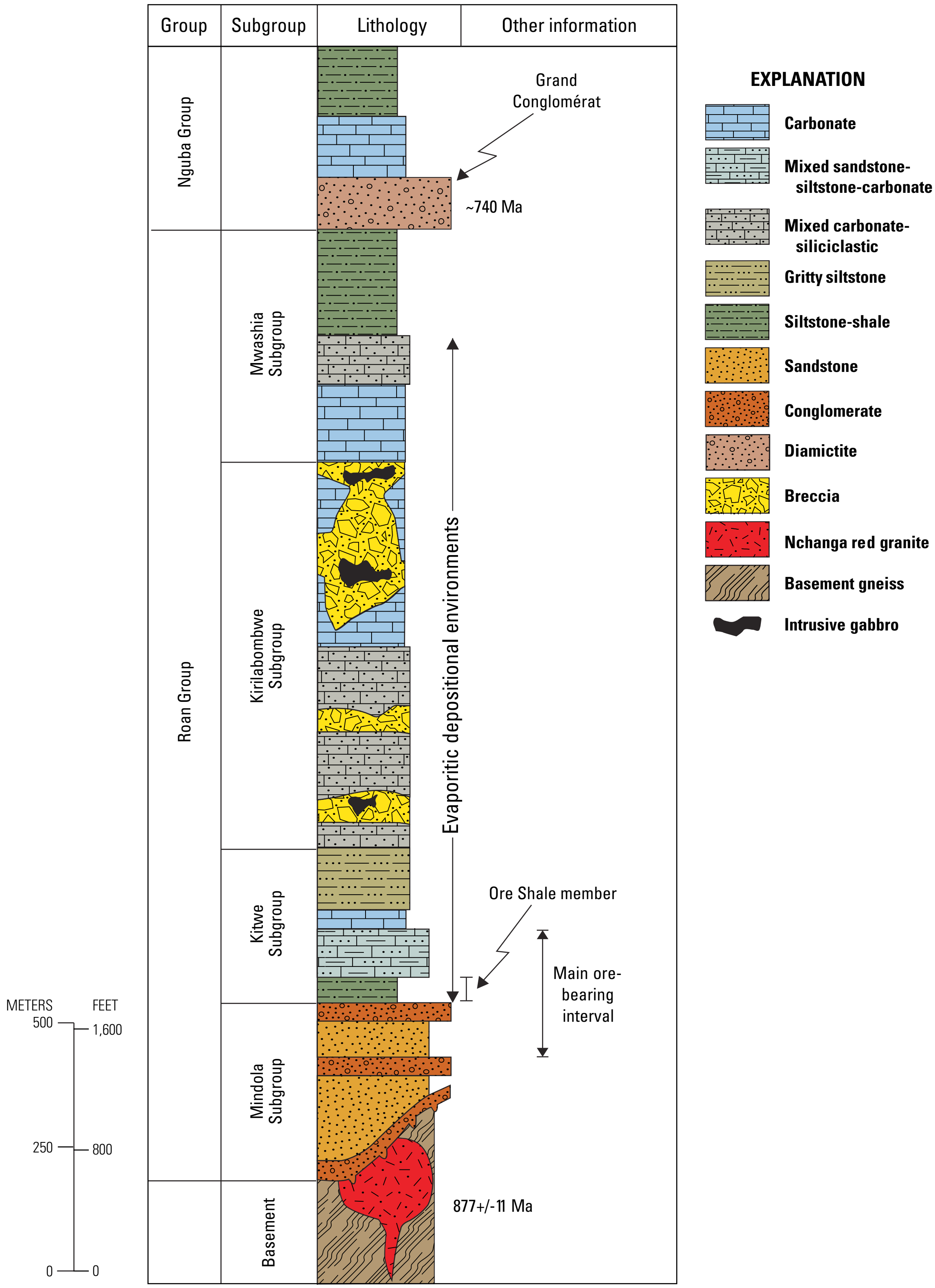

Figure G1. Stratigraphic column of the Roan Group exposed in the Zambian portion of the Central African Copperbelt showing the stratigraphic interval that hosts sediment-hosted stratabound mineralization. Modified from Selley and others (2005).

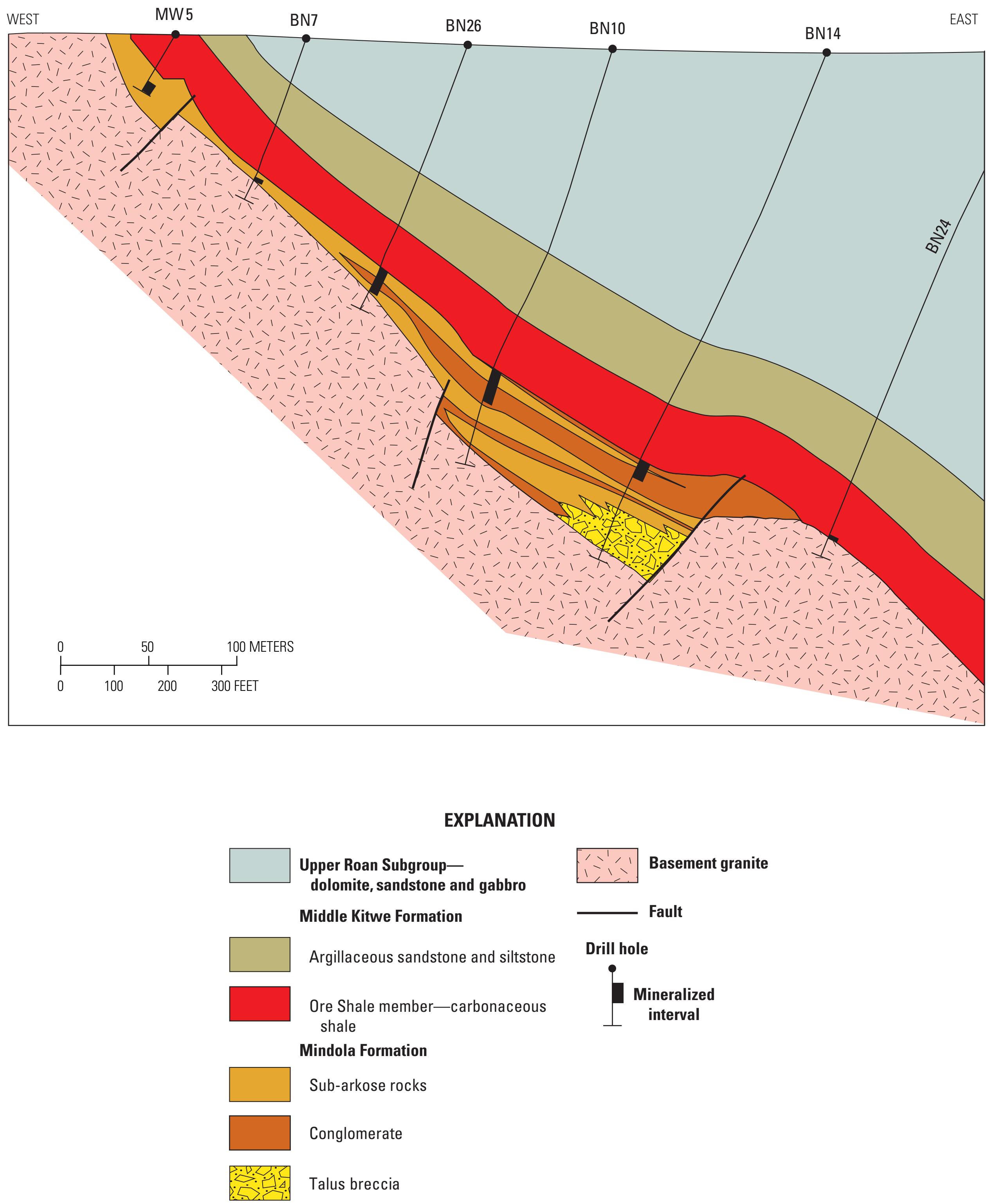

Figure G2. Geologic cross section through the Mwambashi B deposit, Zambia, showing a thick section of the Mindola Formation in a half-graben and transgression of the overlying Ore Shale member. Modified from Selley and others (2005).

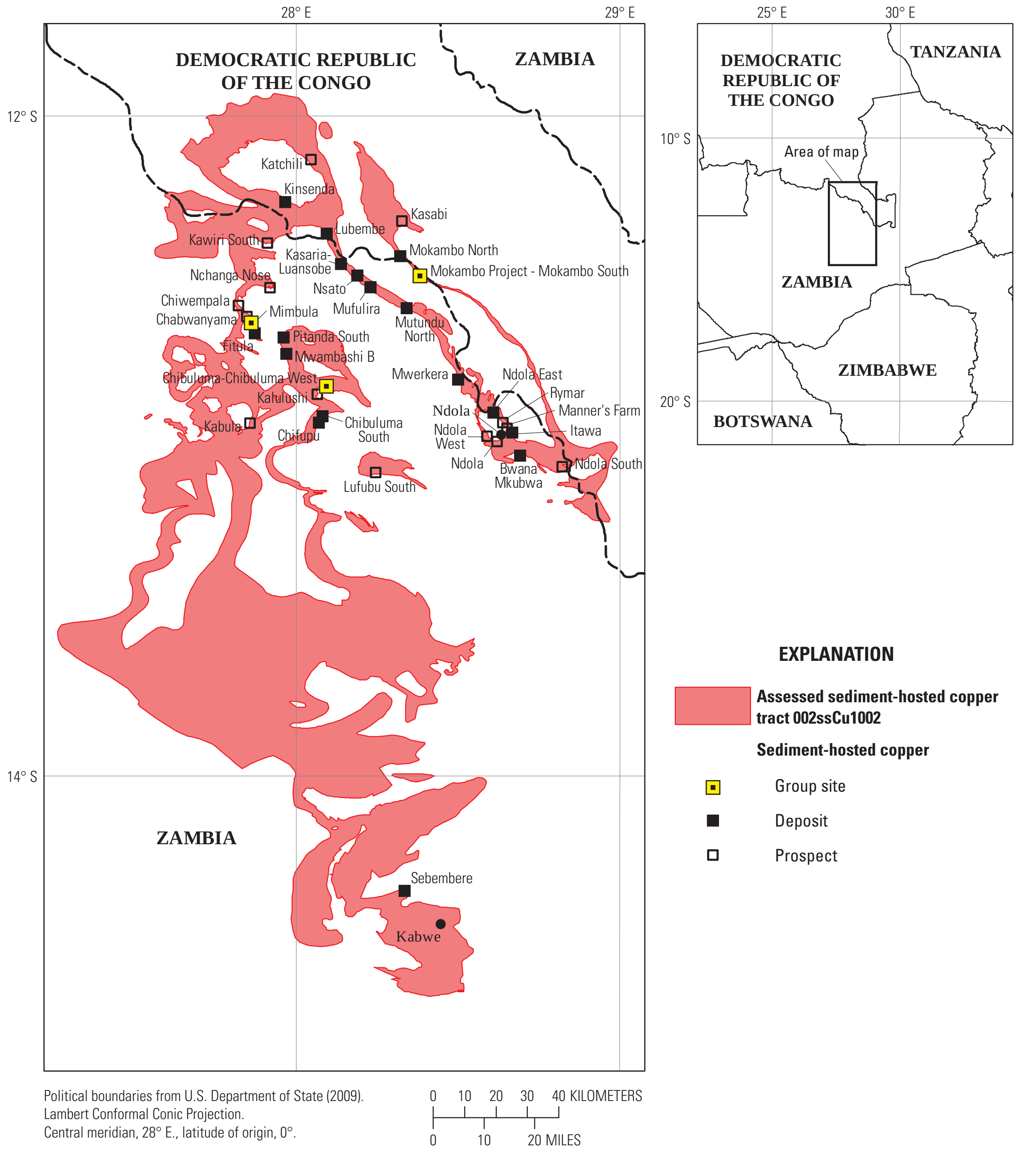

Figure G3. Map showing tract location, known sediment-hosted stratabound copper deposits and prospects for tract 002ssCu1002, Roan arenite, Democratic Republic of the Congo and Zambia.

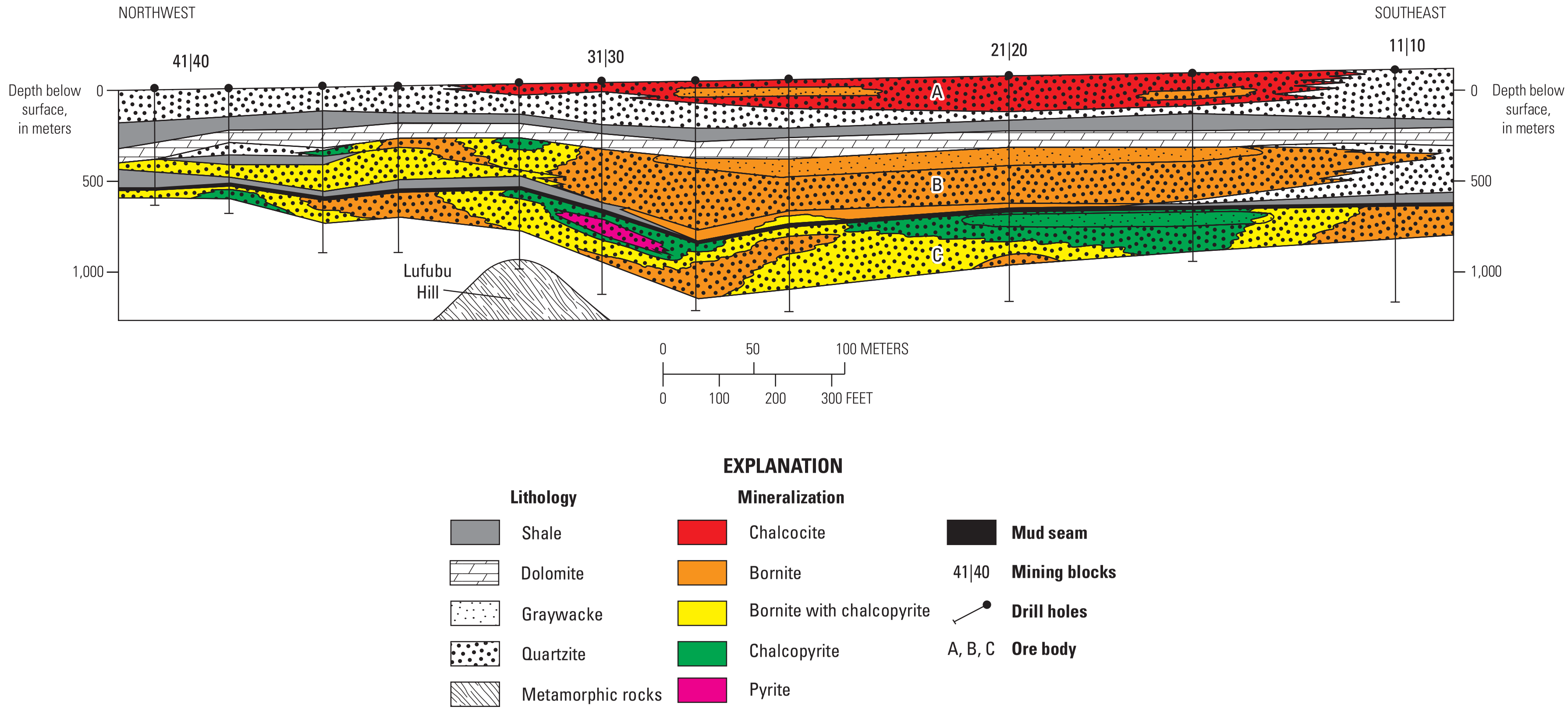

Figure G4. Geologic section through the Mufulira deposit, Zambia, showing the relation of mineralization to sedimentary layering. Modified from Brandt and others (1961).

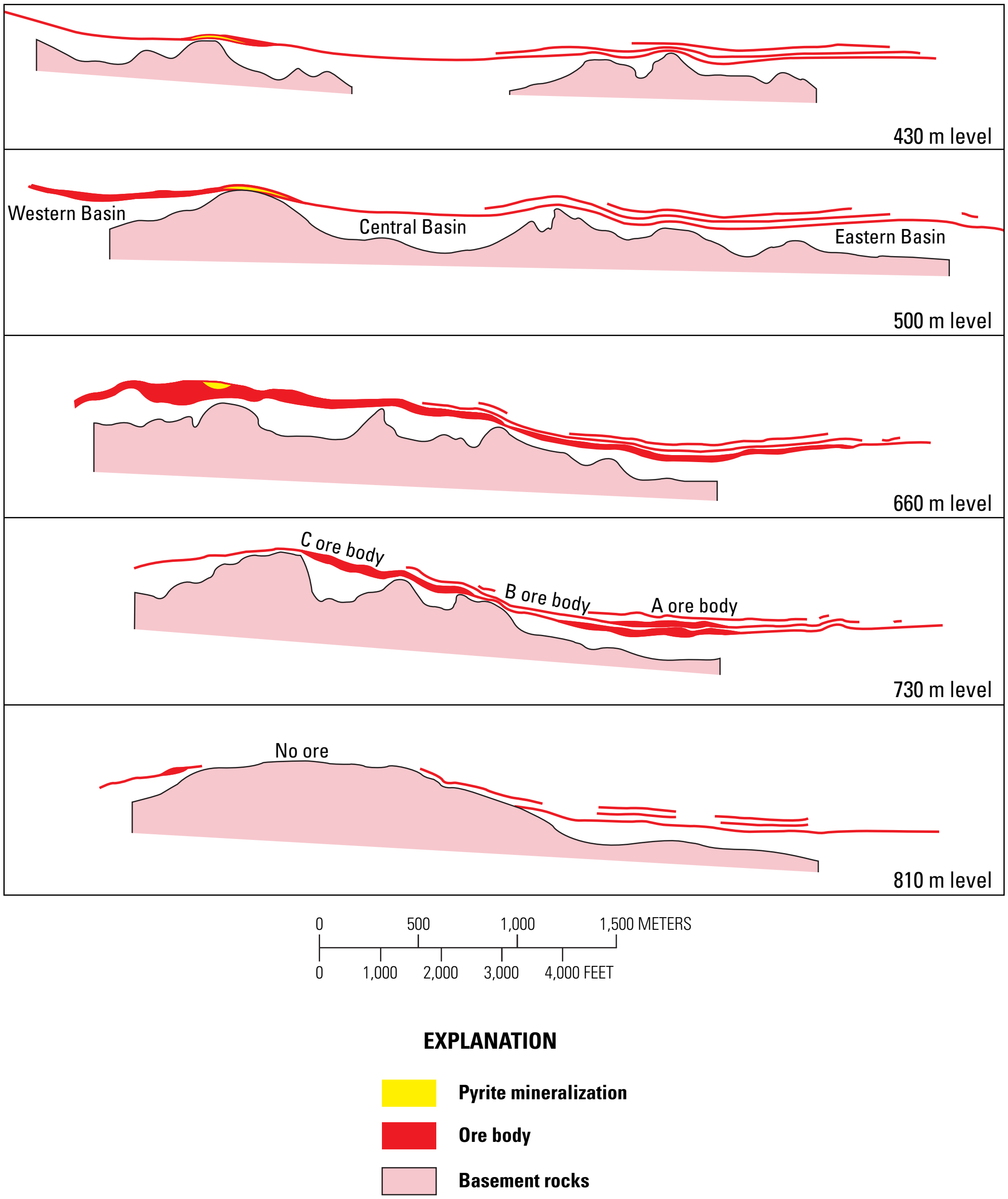

Figure G5. Geological maps of level plans of the Mufulira deposit, Zambia, showing how the three ore bodies vary downdip in relation to basement rocks. Level names reflect depth below the surface. Modified from Fleischer (1976).

Copper mineralization is coincident with lenses of arenite that are enriched in carbonaceous matter relative to nearby strata (called graywacke on fig. G4). The carbonaceous lenses are also vertically stacked, and occur within the central and upper parts of the masses of mineralized rocks. The carbonaceous zones transgress bedding and are postdepositional, that is, they formed after the deposition of the graywacke. Laterally, the mineralized rock passes from the carbonaceous lenses through gray sericitic quartzite into barren pink quartzite and arkose. Barren interbeds within the ore formations and barren "ore" horizons adjacent to the Mufulira deposit have as much as 30 percent anhydrite. In contrast, the mineralized ore beds contain interstitial dolomite with little or no anhydrite.

Annels (1979) proposed that the carbonaceous matter was introduced as mobile hydrocarbons into arenite reservoirs; reservoir-seal relationships found in hydrocarbon systems can explain the remarkable vertical stacking of the sandstone-type copper deposits and the confinement of patterns of mineral zoning within each cyclic unit at Mufulira (Selley and others, 2005). Each cyclic unit formed separate and isolated reservoirs into which hydrocarbons accumulated. The reservoirs were also isolated at the time copper-enriched fluids interacted with the hydrocarbons. Each reservoir has its own pattern of mineral zones. Pre-ore stage evaporitic anhydrite likely provided an in-place source of sulfur. Migration of oxidized, copper-bearing brines and thermochemical reduction of in-place sulfate within hydrocarbon reservoirs likely resulted in precipitation of the copper sulfide minerals. Multiple, vertically stacked ore bodies are characteristic of other sandstone-type copper deposits where the distribution of mobile hydrocarbons may have controlled sulfide accumulation (Box and others, 2013).

Prospects, Mineral Occurrences, and Related Deposit Types

Fourteen copper occurrences in siliciclastic rocks have been described from the Roan arenite tract and 12 can be classified as sandstone-type stratabound copper prospects (appendix D). All of the copper occurrences are in the northern part of the tract, where known deposits spatially occur within the mapped distribution of the Ore Shale member. However, 9 sites having copper mineralization in the Roan Group are described from the southern part of the tract that cannot definitively be classified as sandstone-type stratabound copper prospects; they are simply shown as a location with copper: B&T, Kabwe, Kashitu, Lukali No 4, Masaka, MO 365, Mufukushi MO 702, Puku, and Rhoda's Luck (Cairney and Kerr, 1997; De Swardt and Drysdall, 1963; Moore, 1964; Keppie, 1994; Verbeek and others, 2005). Little or no information is available for these southernmost occurrences, with the exception of Sebembere, which is a sandstone-type stratabound copper deposit. The Romanian State company "Geomin" investigated this site from 1970 to 1973. According to an ICS Copper Systems press release (Chisholm, 2008), "A geological report on the property prepared by Geomin shows a historic estimate of 16.3 million tons with an average grade of 1.61% copper." The report further states that "with additional drilling….it is considered that the potential could be raised up to 19–20 million tons with a copper content of more than 1.8%." The report also advises that this "deposit estimate does not include the mineralization in the oxidation zone of the deposit." A report published by Zambian Consolidated Copper Mines (ZCCM) in August 1992 on the Sebembere Syncline stated "there is abundant reason to believe that drilling to investigate the lateral and downdip extensions to the known body would result in a significant increase in the indicated tonnage" (Chisholm, 2008).

Exploration History

Major leaseholders include African Eagle Resources plc; Caledonia Mining Corp.; Coffey Mining (SA) pty ltd; Equinox Minerals Ltd; First Quantum Minerals Ltd; and Teal Exploration and Mining Ltd (fig. G6). Even though the Zambian Copperbelt has a mature exploration status, additional discoveries can be made by applying modern target generation techniques, systematic use of conventional exploration methods, and drilling (Lomberg and Thamm, 2009). In the area south of Chingola, a mature mining area, geochemistry surveys for copper and cobalt identified four high priority anomalies that may be related to sandstone copper mineralization in the Lower Roan Subgroup (Williams and others, 2005). In an area having known occurrences but no deposits, Mukuba Resources used versatile time domain electromagnetic (VTEM) and soil geochemistry to define multiple exploration targets in parts of the Lower Roan Subgroup that crop out around the Kabuche Dome (Porada and Berhorst, 2000; Lomberg and Thamm, 2009).

Sources of Information

Principal sources of information used by the assessment team for delineation of the Roan arenite tract (002ssCu1002) are listed in appendix C.

Grade and Tonnage Model Selection

A grade and tonnage model constructed using Roan arenite-hosted deposits is used to model the undiscovered metal contents of undiscovered deposits in the Roan Group in Zambia (Zientek, Hayes, and Taylor, 2013).

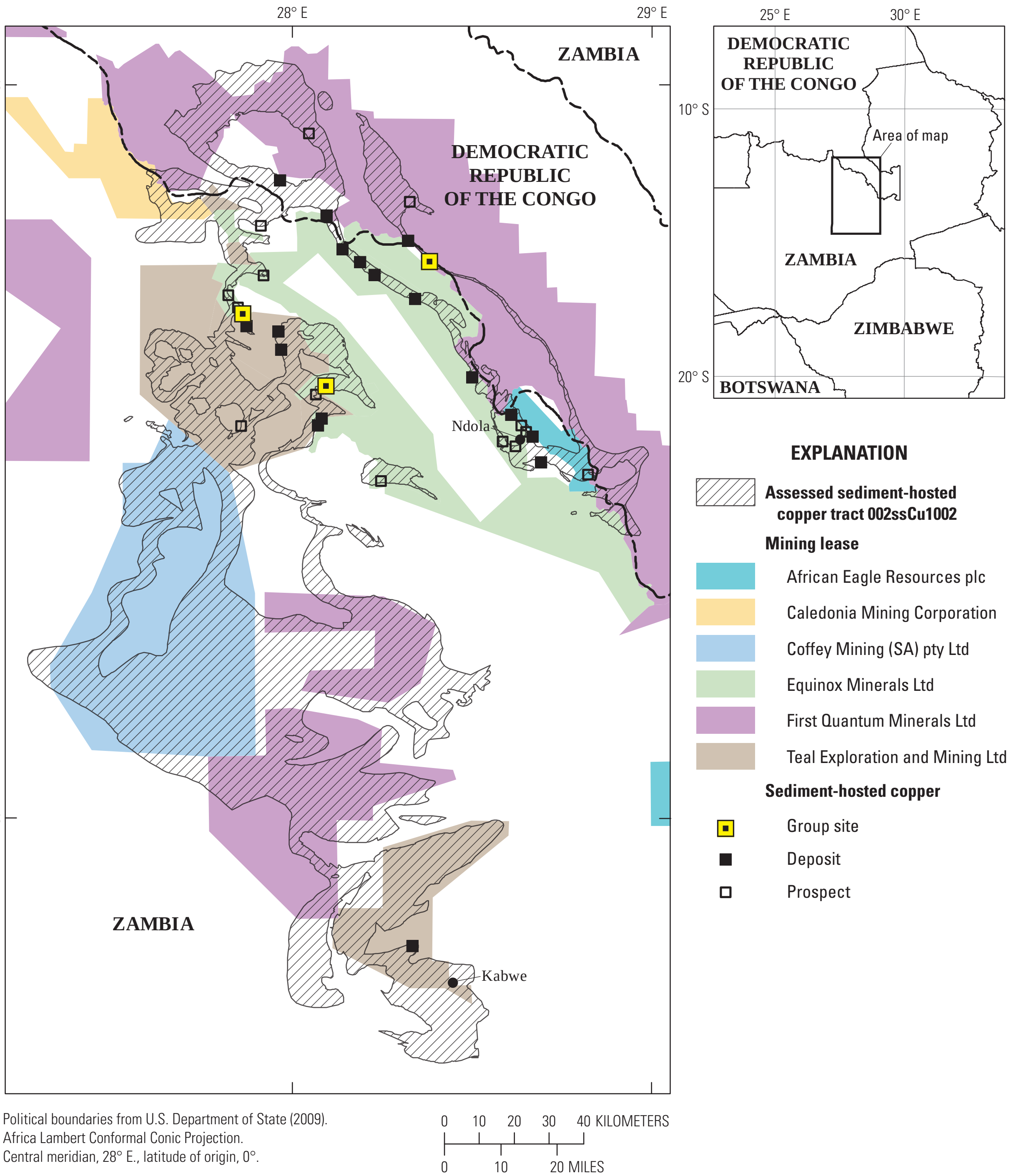

Figure G6. Map showing mineral exploration and mining leases and concessions in relation to the Roan arenite permissive tract, Zambia. Lease and concession boundaries from various company reports.

Estimate of the Number of Undiscovered Deposits

Rationale for the Estimate

Spatial geometry of the sandstone-hosted copper deposits in the Zambian Copperbelt—limited lateral continuity, relatively small vertical projection of ore bodies, and separation of deposits—allows for application of the three-part form of assessment to estimate the endowment of undiscovered mineral resources. Without detailed information that would allow specific targets to be identified, the assessment panel used the relative frequencies of known deposits and occurrences to constrain their estimates of undiscovered deposits (appendix D). Exploration has identified about 20 deposits and 14 occurrences within the tract. One assessment panel member is conducting exploration in the area and indicated that five sites have unannounced, drilled-defined mineral inventories that are consistent with the grade and tonnage model used for the assessment. Exploration conducted in the region has focused on finding mineralization that is near the surface. Areas below a depth of approximately 1 km have not been explored and the assessment panel thought this domain has similar potential as the rocks near the surface. Therefore, the panel decided that the estimate at the 10th percentile should be similar to the number of deposits that already have been discovered. Consensus estimates used in the simulation process are given in table G2.

Quantitative Assessment Simulation Results

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered sediment-hosted stratabound copper deposits with the CACB arenite-subtype model (this report) using the Economic Mineral Resource Simulator (EMINERS) program (Root and others, 1992; Bawiec and Spanski, 2012; Duval, 2012). Selected simulation results are reported in table G3. Results of the Monte Carlo simulation are presented as a cumulative frequency plot (fig. G7) and show the cumulative probability of a given tonnage of any metal or mineralized rock.

Table G2. Undiscovered deposit estimates, deposit numbers, tract area, and deposit density for tract 002ssCu1002–Roan arenite, Zambia.

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

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}		
5	8	20	20	20	10	5.80	56.0	20	30	13,100	0.0023

Table G3. Results of Monte Carlo simulations of undiscovered resources in tract 002ssCu1002–Roan arenite, Zambia.

[Cu, copper; t, metric tons; Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Cu (t)	770,000	1,400,000	6,400,000	19,000,000	23,000,000	8,400,000	0.39	0.02
Rock (Mt)	39	68	320	820	990	390	0.42	0.02

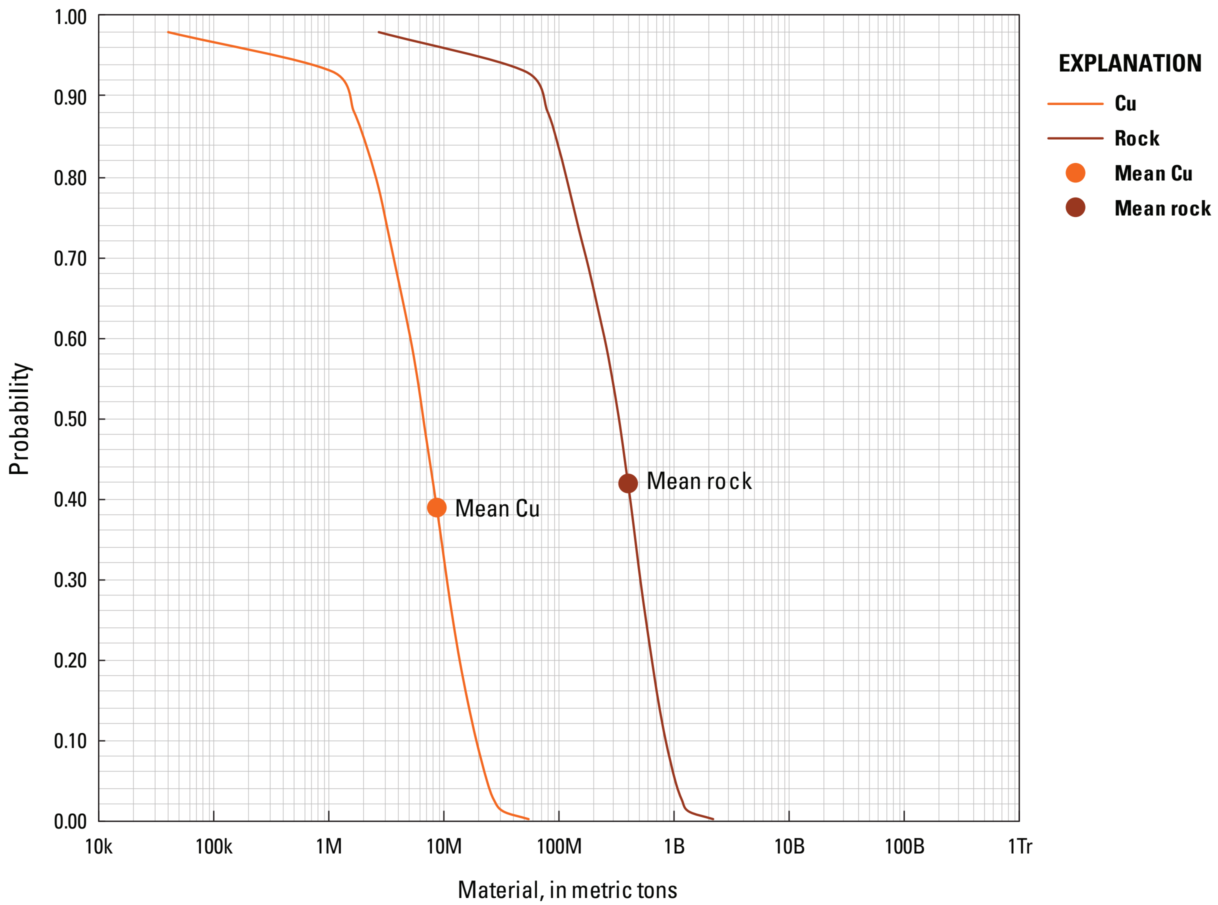

Figure G7. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered resources in tract 002ssCu1002, Roan arenite, Katanga Basin, Democratic Republic of the Congo and Zambia. k=thousands, M=millions, B=billions, Tr=trillions.

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Appendix H. Individual Estimates of Number of Undiscovered Deposits

By Michael L. Zientek[1], James D. Bliss[2], David W. Broughton[3], Michael Christie[4], Paul D. Denning[5], Timothy S. Hayes[2], Murray W. Hitzman[6], John D. Horton[5], Susan Frost-Killian[7], Douglas J. Jack[8], Sharad Master[9], Heather L. Parks[1], Cliff D. Taylor[5], Anna B. Wilson[5], Niki E. Wintzer[1], and Jon Woodhead[10]

Each member of the assessment panel made an independent estimate of the number of undiscovered deposits for each permissive tract. After the results were shared and discussed, some panel members revised their estimates. These are given in table H1, together with the final consensus estimate for each tract. The table also includes the affiliation of the estimator (academia, government, private sector) so that differences among these groups can be evaluated; the results are shown in parallel plots on figures H1 to H5.

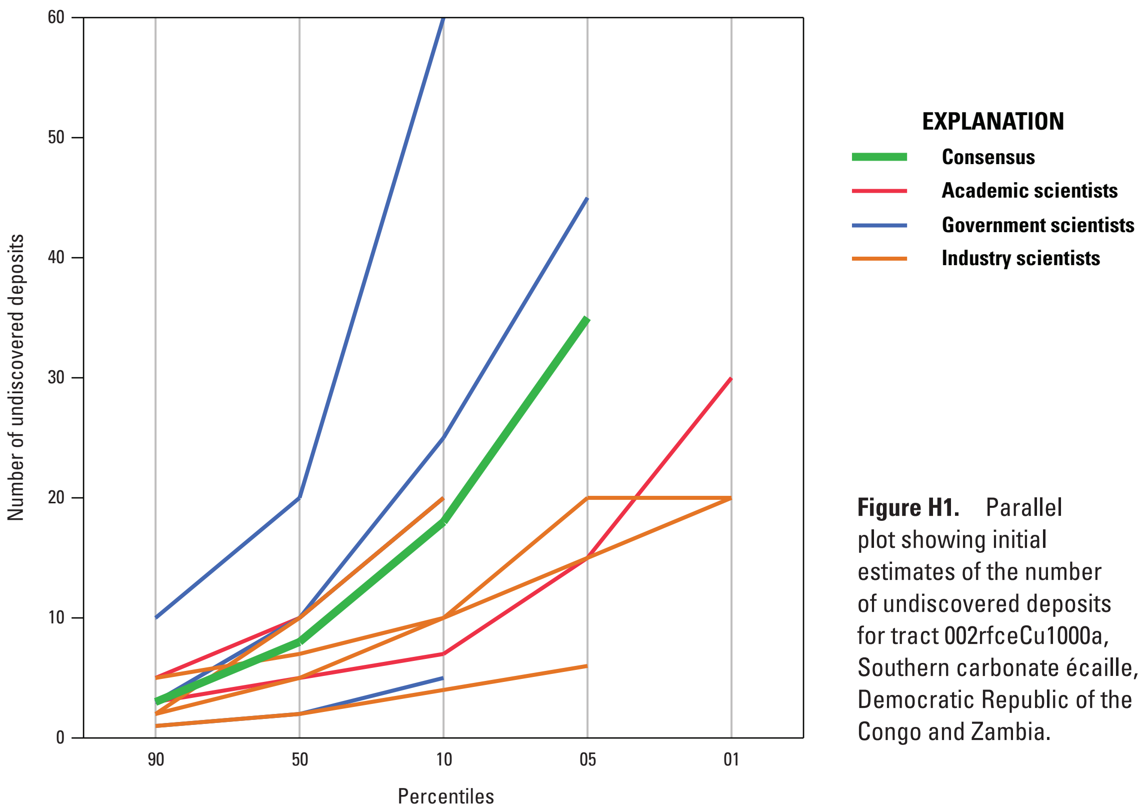


Figure H1. Parallel plot showing initial estimates of the number of undiscovered deposits for tract 002rfceCu1000a, Southern carbonate écaille, Democratic Republic of the Congo and Zambia.

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

[2]U.S. Geological Survey, Tucson, Arizona, United States.

[3]Ivanhoe Nickel and Platinum Ltd., Ottawa, Ontario, Canada.

[4]First Quantum Minerals Ltd., Perth, Western Australia.

[5]U.S. Geological Survey, Denver, Colorado, United States.

[6]Colorado School of Mines, Golden, Colorado, United States.

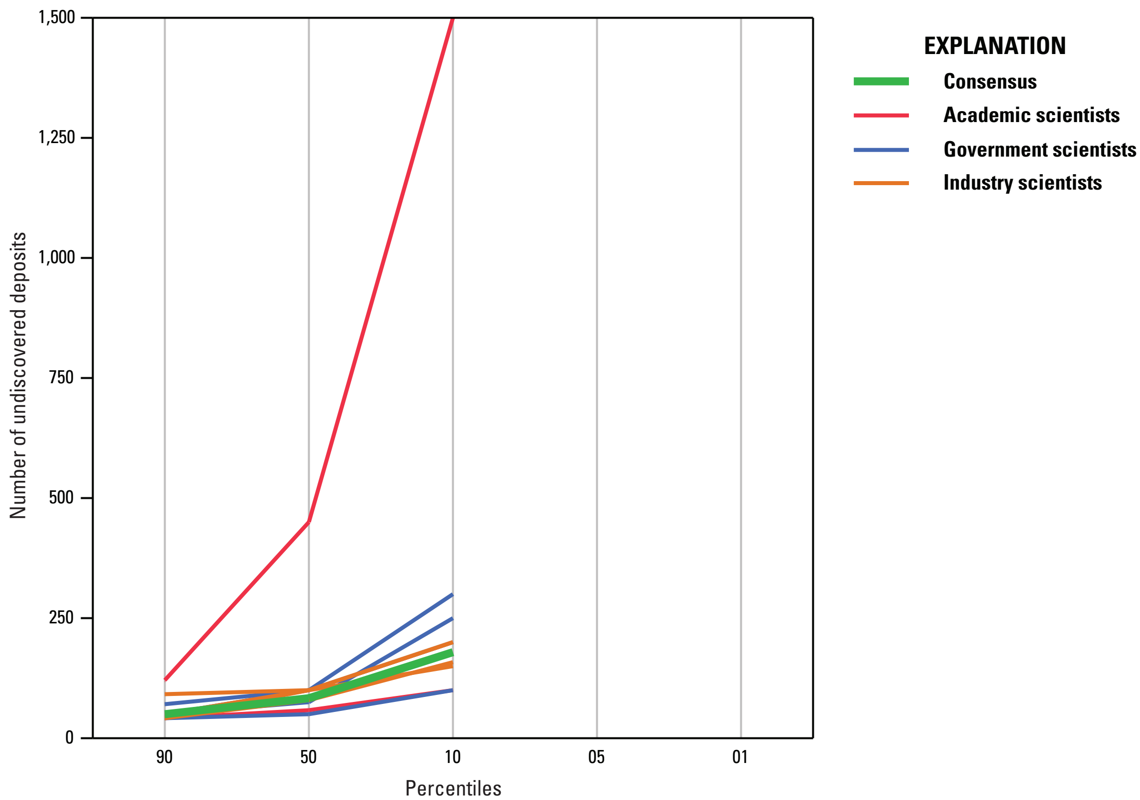
[7]South Africa Council for Geoscience, Pretoria, Republic of South Africa.

[8]First Quantum Minerals Ltd., Lubumbashi, Democratic Republic of the Congo.

[9]University of the Witwatersrand, Johannesburg, Republic of South Africa.

[10]Private Consultant, Duncraig, Perth, Western Australia.

A



B

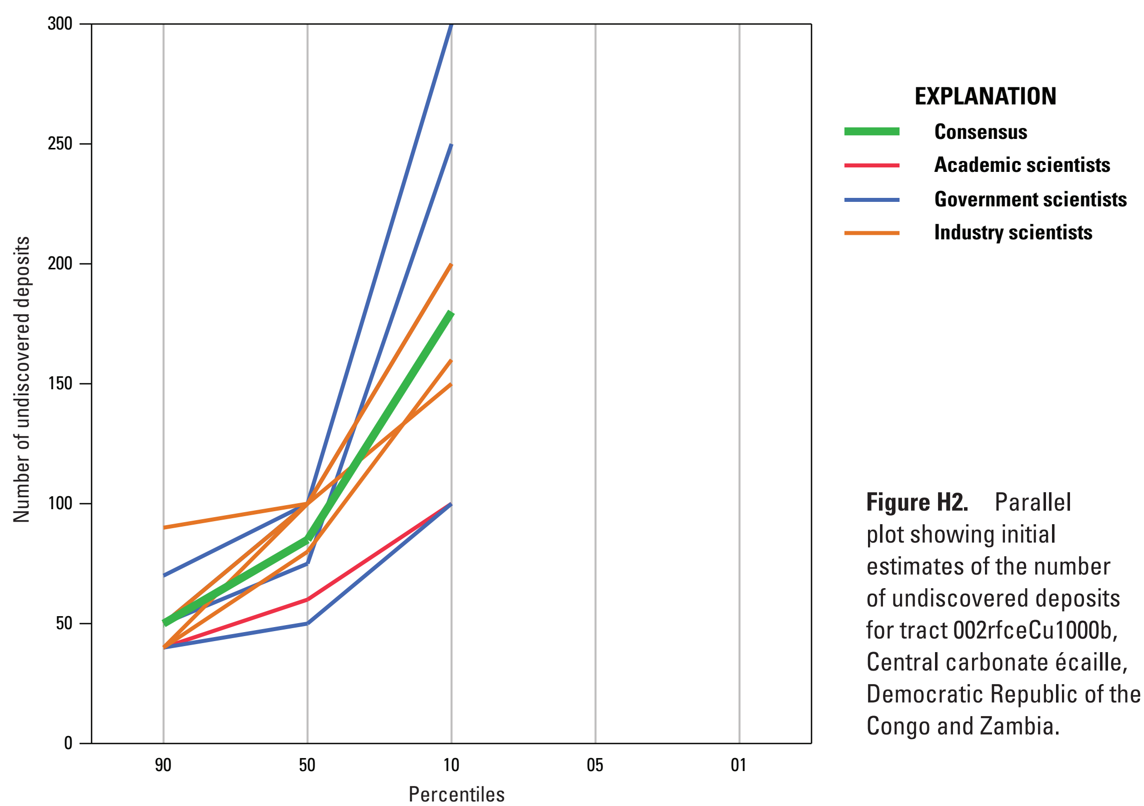


Figure H2. Parallel plot showing initial estimates of the number of undiscovered deposits for tract 002rfceCu1000b, Central carbonate écaille, Democratic Republic of the Congo and Zambia.

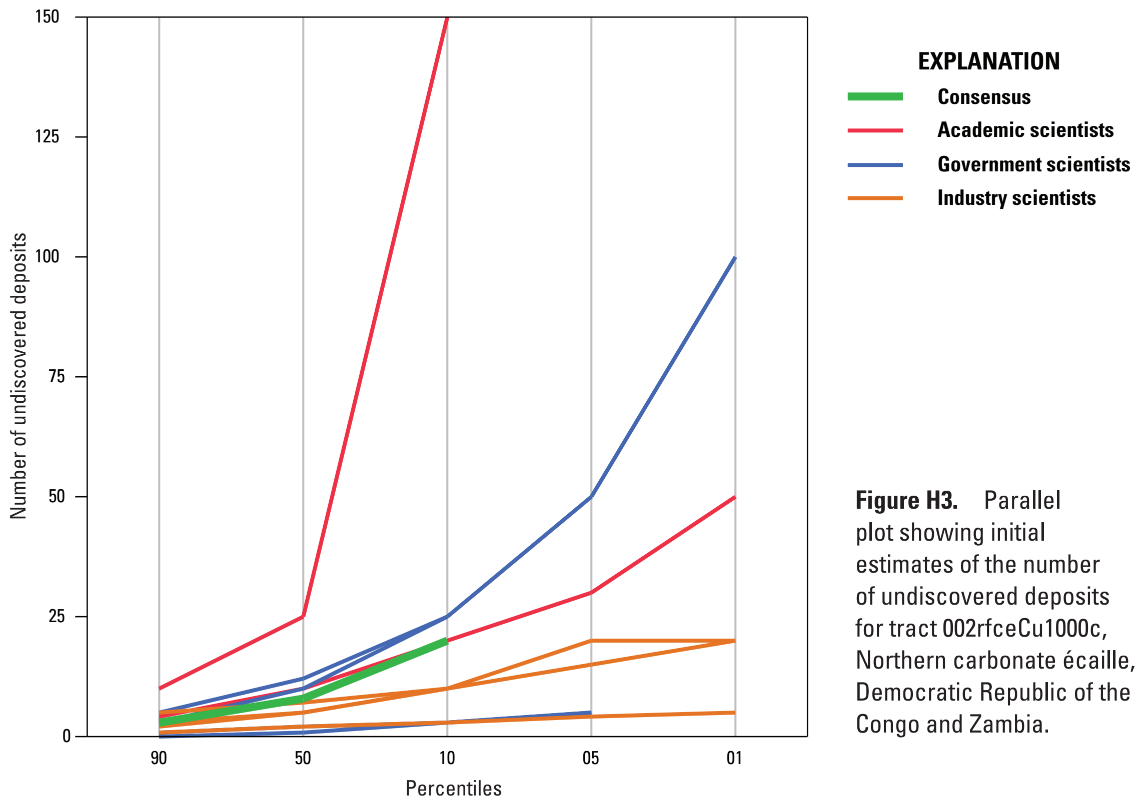


Figure H3. Parallel plot showing initial estimates of the number of undiscovered deposits for tract 002rfceCu1000c, Northern carbonate écaille, Democratic Republic of the Congo and Zambia.

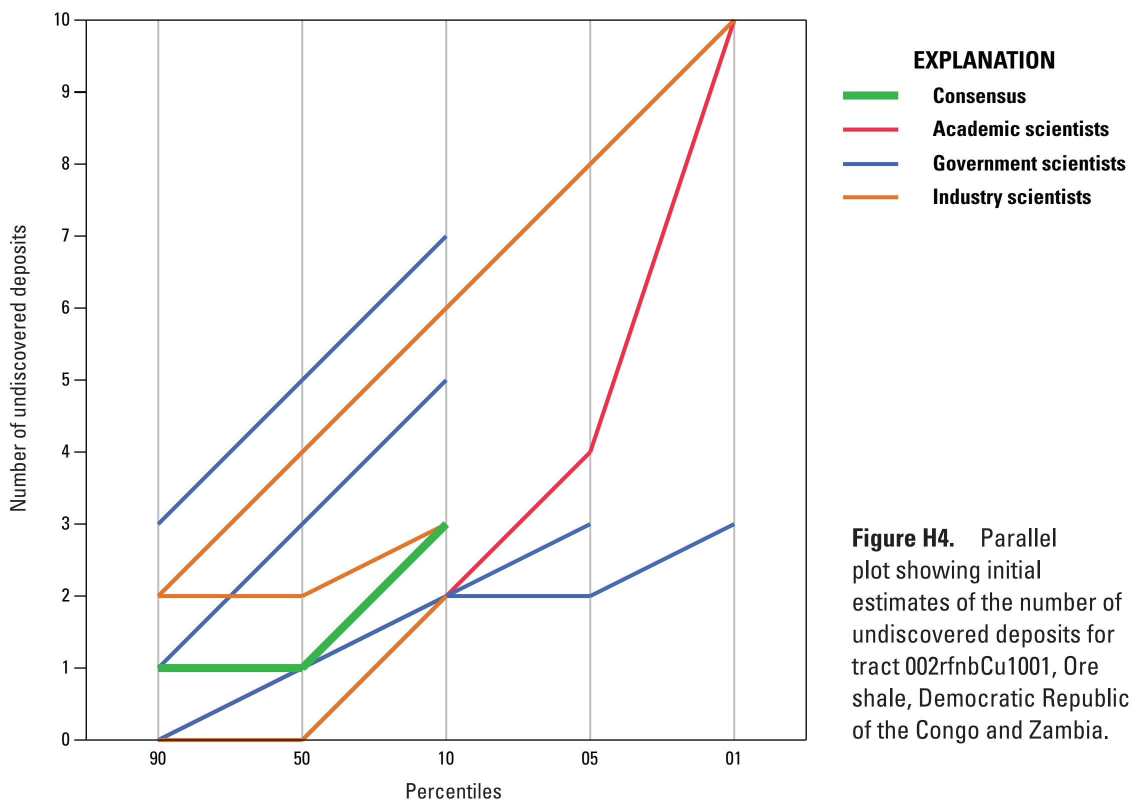


Figure H4. Parallel plot showing initial estimates of the number of undiscovered deposits for tract 002rfnbCu1001, Ore shale, Democratic Republic of the Congo and Zambia.

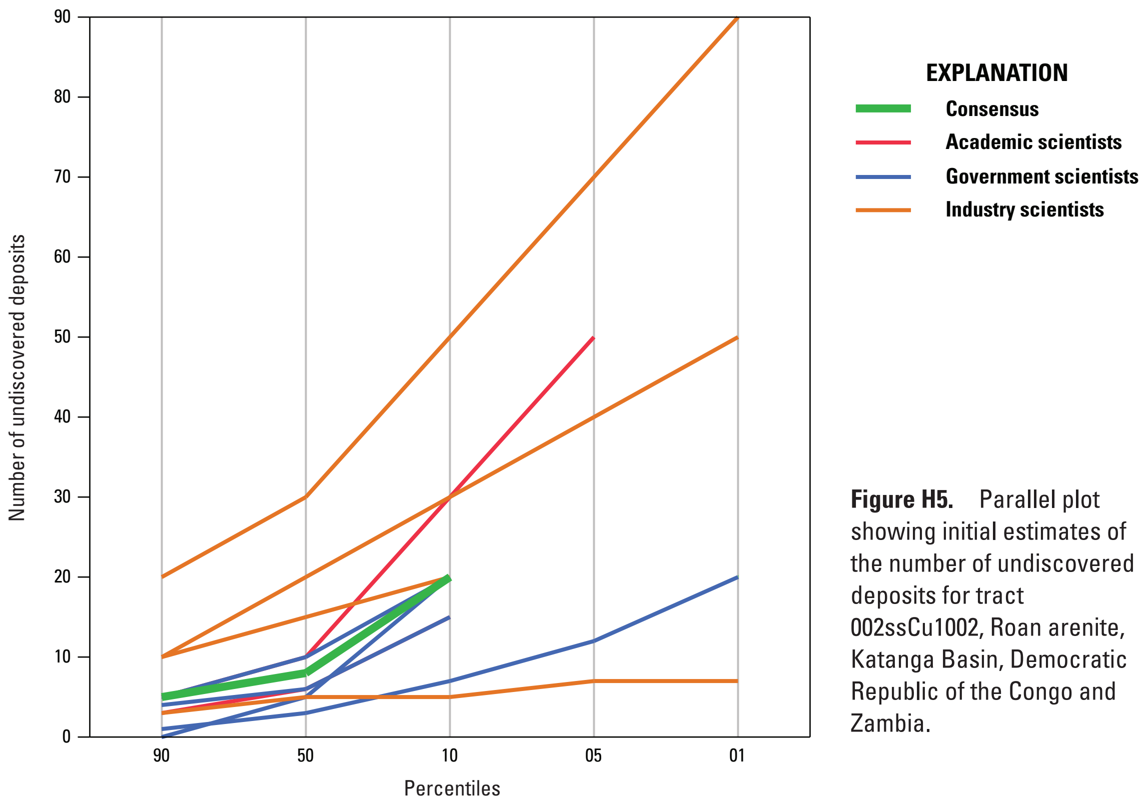


Figure H5. Parallel plot showing initial estimates of the number of undiscovered deposits for tract 002ssCu1002, Roan arenite, Katanga Basin, Democratic Republic of the Congo and Zambia.

Table H1. Individual and consensus estimates of undiscovered number of deposits, Central African Copperbelt, Democratic Republic of the Congo and Zambia.

[N_{XX}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; n.s., no score]

Estimator's affiliation	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}
Southern carbonate écaille tract						
Government	3	10	25	45	n.s.	14
Industry	2	5	10	20	20	6
Industry	5	7	10	15	20	7
Industry	2	10	20	n.s.	n.s.	10
Industry	1	2	4	6	n.s.	2
Government	3	10	20	n.s.	n.s.	11
Academia	5	10	20	n.s.	n.s.	11
Academia	3	5	7	15	30	6
Government	1	2	5	n.s.	n.s.	3
Government	10	20	60	n.s.	n.s.	28
Consensus	3	8	18	35	35	11
Central carbonate écaille tract						
Government	50	100	300	n.s.	n.s.	142
Industry	50	100	200	n.s.	n.s.	112
Industry	90	100	150	n.s.	n.s.	106
Industry	40	100	200	n.s.	n.s.	109
Industry	40	80	160	n.s.	n.s.	89
Government	50	75	250	n.s.	n.s.	117
Academia	120	450	1,500	n.s.	n.s.	658
Academia	40	60	100	n.s.	n.s.	63
Government	40	50	100	n.s.	n.s.	59
Government	70	100	200	n.s.	n.s.	116
Consensus	50	85	180	180	180	100
Northern carbonate écaille tract						
Government	1	2	3	5	n.s.	2
Industry	2	5	10	20	20	6
Industry	5	7	10	15	20	7
Industry	3	5	10	n.s.	n.s.	6
Industry	1	2	3	4	5	2
Government	3	10	25	n.s.	n.s.	12
Academia	10	25	150	n.s.	n.s.	57
Academia	4	10	20	30	50	12
Government	0	1	3	5	n.s.	1
Government	5	12	25	50	100	17
Consensus	3	8	20	20	20	10
Ore shale tract						
Government	0	1	2	3	n.s.	1
Industry	2	2	3	n.s.	n.s.	2
Industry	2	4	6	8	10	4
Industry	0	0	2	n.s.	n.s.	1
Industry	2	4	6	8	10	4
Government	3	5	7	n.s.	n.s.	5
Academia	0	1	3	n.s.	n.s.	1
Academia	0	0	2	4	10	1
Government	1	3	5	n.s.	n.s.	3
Government	1	1	2	2	3	1
Consensus	1	1	3	3	3	2

Appendix I. Panel Who Assessed Number of Undiscovered Deposits

David W. Broughton is Executive Vice President for Exploration with Ivanplats Ltd. He has written papers on the Kansanshi deposit in Zambia and the Kamoa deposit in the Democratic Republic of the Congo.

Michael Christie is Exploration Director with First Quantum Minerals Ltd. He received his M.Sc. from Camborne School of Mines (U.K.).

Susan Frost-Killian worked as a senior geoscientist with the Council for Geoscience, Pretoria, Republic of South Africa, at the time of the assessment workshop and currently is project geologist with The MSA Group. She received her M.Sc. in geology from Rhodes University (South Africa).

Timothy S. Hayes is a research geologist with the USGS in Tucson, Arizona. He received degrees in geology from the South Dakota School of Mines and Stanford University. He is an economic geologist with expertise in sediment-hosted stratabound copper deposits. Hayes has worked on sediment-hosted stratabound copper deposits in the Belt Basin of Montana; in Permian rocks in Oklahoma; and in the Ablah Group, Saudi Arabia.

Murray W. Hitzman is the Charles Fogarty Professor of Economic Geology at the Colorado School of Mines, Golden, Colorado. Hitzman has written numerous papers on sedimentary rock-hosted stratiform copper deposits. He has been involved in research on this deposit type in the African Copperbelt during the past decade and has worked with graduate students on similar deposits worldwide.

Douglas J. Jack is an exploration manager with First Quantum Minerals Ltd. He received degrees from University of the Witwatersrand (South Africa) and the University of Tasmania (Australia). He is an economic geologist and discovered the Hellyer massive sulfide deposit, Mount Read province, western Tasmania.

Sharad Master is on the faculty at the University of the Witwatersrand (South Africa). He is an economic geologist whose research interests include sediment-hosted stratabound copper deposits. He received degrees from the University of the Witswatersrand.

Cliff D. Taylor is a research geologist with the USGS in Denver, Colorado. He received a doctorate in geology from the Colorado School of Mines. He is an economic geologist with expertise in volcanogenic massive sulfide deposits.

Jon Woodhead worked as a private consultant at the time of the workshop and currently is principal geologist for Condor Consulting. He received a Master's degree from the University of the Witwatersrand and a doctorate from the Colorado School of Mines on the geology and geophysics of the Zambian Copperbelt

Michael L. Zientek is a research geologist with the USGS in Spokane, Washington. He received degrees in geology from the University of Texas and Stanford University. He is an economic geologist with expertise in magmatic ore deposits and mineral resource assessment.

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