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Global Mineral Resource Assessment

Sandstone Copper Assessment of the Teniz Basin, Kazakhstan

Scientific Investigations Report 2010–5090–R

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

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U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:
Cossette, P.M., Bookstrom, A.A., Hayes, T.S., Robinson, G.R., Jr., Wallis, J.C., and Zientek, M.L., 2014, Sandstone copper assessment of the Teniz Basin, Kazakhstan: U.S. Geological Survey Scientific Investigations Report 2010–5090–R, 42 p., and spatial data, *http://dx.doi.org/10.3133/sir20105090R*.

ISSN 2328-0328 (online)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, troy (troy oz)	31.103	gram (g)
ounce, troy (troy oz)	0.0000311	megagram (Mg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03215	ounce, troy (troy oz)
megagram (Mg)	32,151	ounce, troy (troy oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
	Other conversions used in this report	
metric ton (t)	1	megagram (Mg)
troy ounce per short ton	34.2857	gram per metric ton (g/t)
percent	10,000	parts per million (ppm) or grams per metric ton (g/t)
percent metal	0.01 × metal grade, percent × ore tonnage, metric tons	metric tons of metal

Acronyms and Abbreviations Used

°C	degree Celsius
COMECON	Council for Mutual Economic Assistance, an economic organization (from 1949 to 1991) of Eastern Bloc countries, under the leadership of the Soviet Union
g/t	grams per metric ton
GIS	geographic information system
k	thousand
km	kilometer
km^2	square kilometer
kt	thousand metric tons
m	meter
Ma	millions of years before the present
Moz	million ounces
Mt	million metric tons
PGE	platinum-group element(s)
ppm	parts per million
SSIB	small-scale digital international boundaries
t	metric ton (tonne) or megagram (Mg)
USGS	United States Geological Survey

Chemical Symbols Used

Ag	silver
Cu	copper

Sandstone Copper Assessment of the Teniz Basin, Kazakhstan

By Pamela M. Cossette[1], Arthur A. Bookstrom[1], Timothy S. Hayes[2], Gilpin R. Robinson, Jr.[3], John C. Wallis[1], and Michael L. Zientek[1]

Abstract

The U.S. Geological Survey (USGS) conducts national and global resource assessments (mineral, energy, water, and biological) to provide data and scientific analyses to support decision making. Three-part mineral resource assessments result in informed, unbiased, quantitative, and probabilistic estimates of undiscovered mineral resources and deposits. In particular, mineral assessment results inform decisions concerning land-use and mineral-resource development. A probabilistic mineral resource assessment of the sandstone subtype of sediment-hosted stratabound copper deposits in the Teniz Basin, Kazakhstan, was undertaken by the USGS.

The Teniz Basin is located in Akmola Oblast, central and western Kazakhstan. With an areal extent of almost 78,000 km^2, the basin contains many sediment-hosted stratabound copper prospects, none of which are well described, and the majority of which may belong to the sandstone subtype of sediment-hosted copper deposits. There are no known locations within the Teniz Basin currently mined for copper. Within the basin, however, map units permissive for the sandstone subtype of sediment-hosted stratabound copper deposits include (from oldest to youngest): the Middle Carboniferous Kiery Suite; the Middle to Upper Carboniferous Vladimirov Suite (a stratigraphic equivalent of the Dzhezkazgan Suite, Chu-Sarysu Basin); and the Upper Carboniferous or lowest Permian Kayraktin Suite. The multicolored sedimentary rocks of the Vladimirov Suite, in which 14 potentially ore-bearing horizons of gray beds have been recorded, have the greatest potential for undiscovered, sandstone subtype, sediment-hosted stratabound copper deposits.

A quantitative mineral resource assessment has been completed that (1) delineates one 49,714 km^2 tract permissive for undiscovered, sandstone subtype, sediment-hosted stratabound copper deposits, and (2) provides probabilistic estimates of numbers of undiscovered deposits and probable amounts of copper resource contained in those deposits. The permissive tract delineated in this assessment encompasses no previously known sandstone subtype, sediment-hosted stratabound copper deposits. However, this assessment estimates (with 30 percent probability) that a mean of nine undiscovered sandstone subtype copper deposits may be present in the Teniz Basin and could contain a mean total of 8.9 million metric tons of copper and 7,500 metric tons of silver.

Introduction

In response to the growing demand for information on the global mineral-resource base, the U.S. Geological Survey (USGS) conducted a global assessment of undiscovered copper resources (Briskey and others, 2001; Zientek and Hammarstrom, 2008). This assessment focuses on the two deposit types that host most of the world's known copper—porphyry copper deposits and sediment-hosted stratabound copper deposits (Singer, 1995). As part of the global assessment, this study assesses undiscovered resources associated with the sandstone subtype of sediment-hosted stratabound copper deposits in the middle to upper Paleozoic Teniz Basin, Kazakhstan.

Global resource assessments address two questions: (1) where are undiscovered resources likely to exist, and (2) how much undiscovered resource may be present? Mineral potential maps show where undiscovered resources may be present and the amount of undiscovered resource is reported as a probability distribution of in-place, undiscovered metal. This report summarizes the regional geologic setting and stratigraphy of the Teniz Basin and the distribution of sediment-hosted stratabound copper prospects. One tract, permissive for sandstone subtype, sediment-hosted copper, is delineated based upon the results of (1) a comprehensive literature review; (2) GIS data processing, evaluation, and analysis; (3) a regional geologic data synthesis; and (4) expert estimation of the probability of undiscovered, sandstone subtype, sediment-hosted stratabound copper deposits in the basin. Appendix A summarizes the principal information sources used in this assessment. Appendix B provides grade

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and tonnage model information used in resource estimation. Appendix C describes geographic information system (GIS) data files for the permissive tract and prospects. Appendix D provides biographical information about assessment team members. Finally, a glossary of terminology used in mineral assessments is provided in appendix E.

Permissive tracts are based on geology, irrespective of current land-use conditions. Therefore, tracts may include lands that already have been developed for other uses, or have been withdrawn from mineral development as protected areas. The tracts are compiled to be displayed at a scale of 1:1,000,000. Even though higher resolution information may have been used in the compilations, this information is intended for use at scales no larger than 1:1,000,000.

Assessment Methodology

Geologists, engineers, and miners have long recognized that mineral deposits can be classified into groups or types on the basis of common features and associations. A mineral deposit type is associated with distinctive geologic settings that can be recognized on geologic maps, cross sections, and stratigraphic columns. In addition, each mineral deposit type has characteristic geometries, grade and tonnage distributions, and rock and mineral properties that determine the potential value of the deposit, sampling density required to delimit the resource, and ore mining and processing methods. These deposit-type parameters collectively exert specific physical effects on the environment, whether through natural weathering processes or mining and can influence the decision-making process regarding feasibility. Mineral resource assessment methodology uses mineral deposit models to discriminate areas with mineral potential from those that are barren, and places value on the resources that may be present.

This study uses the three-part assessment form described by Singer (1993) and Singer and Menzie (2010) to estimate location and probable amounts of undiscovered resources for the sandstone subtype of sediment-hosted stratabound copper. Undiscovered resources include mineralized material whose location, grade, quality, and quantity are unknown or incompletely characterized, either in partially-characterized sites or completely unknown mineral deposits.

Location.—Using the geologic environment summarized in descriptive deposit models, areas in which geology permits the existence of a specific deposit type are selected and delineated. The delineated area, or permissive tract, represents the surface projection of a volume of the Earth's crust corresponding to a geologic environment described by the deposit model; consequently, assessment depth selection is essential to tract definition. In this study, we assess undiscovered resources to a depth of 2 km (kilometers) below the Earth's surface.

Probable amounts.—Assessments are based on analogy: undiscovered resources of a particular type are assumed to be comparable to those that have been discovered elsewhere in the world. The amount of undiscovered resource is derived from (1) grade and tonnage models for known deposits of the same type, in geologically similar settings, and (2) an estimate of a fixed, but unknown, number of undiscovered deposits that exist in delineated tracts. Grade and tonnage models are based on average grade and frequency distributions of tonnage in well-explored deposits. The distribution of undiscovered deposits is estimated by expert panels at several probability percentiles. From these estimates, a probability distribution for undiscovered deposits is obtained using an algorithm provided by Root and others (1992). Monte Carlo simulation is then used to combine grade and tonnage models with the probability distribution of undiscovered deposits to obtain probability distributions for undiscovered metals in each tract (Root and others, 1996; Duval, 2012; Bawiec and Spanski, 2012). Simulation results are then presented in summary tables and graphs. This quantitative mineral resource assessment can subsequently be evaluated by applying economic filters and cash flow models for economic and policy analysis: the results can be applied to mineral supply, economic, environmental, and land-use planning. Economic evaluations, however, are not part of this report.

Mineral inventories are the formal quantification of naturally occurring mineral materials, estimated by a variety of empirically or theoretically based procedures (Sinclair and Blackwell, 2002). 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 knowledge (Committee for Mineral Reserves International Reporting Standards, 2006). The term "mineral reserve" is restricted to the economically mineable part of a mineral resource.

In this report, we restrict usage of the word "deposit" to those sites that (1) formed by the same genetic process (same deposit type), (2) may have economic potential, (3) have a mineral inventory defined by a sampling density appropriate for the deposit type, and (4) are well explored (most mineralized rock at the site is included in a mineral inventory). Because no copper-mineralized sites within the study area satisfy all of these requirements, "deposits" are considered absent in the Teniz Basin. Consequently, sites that do not have have a published mineral inventory or are incompletely explored are referred to as "prospects" in this report. "Significant prospects" are those sites that are consistently documented in various data sources and may be referred to as "small deposits," even though tonnage and grade is not reported.

Sediment-Hosted Stratabound Copper Deposits

Sediment-hosted stratabound copper mineralization consists of fine-grained copper sulfide and copper-iron-sulfide minerals that occur as stratabound to stratiform disseminations in siliciclastic or dolomitic sedimentary rocks (Zientek, Hayes, and Hammarstrom, 2013). Ore minerals occur as cements and replacements, and less commonly as veinlets. Sulfide mineral concentrations conform closely, but not exactly, with stratification of host rocks. Ore zones typically comprise chalcocite and bornite. Deposits are commonly characterized by lateral zoning of ore minerals along and across bedding, from pyrite to chalcopyrite to bornite to chalcocite to hematite. Deposits are hosted in black, gray, green, or white (chemically reduced) sedimentary strata within or above a thick section of red (oxidized) beds.

Two genetic concepts on the origin of sediment-hosted stratabound copper deposits have been discussed in the scientific literature: (1) syngenesis, in which ore minerals developed simultaneously with sediment deposition, and (2) diagenesis, in which copper mineralization occurred after sediment deposition, from processes occurring at relatively low temperatures and pressures during compaction and lithification. The syngenetic theory was first proposed in the 18th century (Lehmann, 1756) followed by papers from Scheiderhölm (1932) and Garlick (1961) that led to model acceptance in the 1960s; papers promoting this concept were published into the late 20th century. The diagenetic model arose out of work published by White and Wright (1954), Bartholomé (1964), Rentzsch (1965), and Rydzewski (1969). For decades, the model debate went unresolved because there were no basic scientific data on age, formation temperatures, or ore fluid compositions for sediment-hosted stratabound copper deposits (Jowett, 1991). The diagenetic model of ore formation is now widely accepted and forms the basis for assessment work in this report. Jowett (1991) and Hitzman and others (2005) summarize the evolution of ideas on genesis of sediment-hosted stratabound copper deposits.

The regional and stratigraphic association of stratabound copper ores with evaporites and red bed deposits, described by Davidson (1965), Rose (1976), and Kirkham (1989), provides evidence for the composition of ore-forming fluid and factors controlling deposit distribution. Sediment-hosted stratabound copper mineralizing processes are limited to sedimentary or metasedimentary formations younger than 2,300 Ma, when free oxygen first appeared in Earth's atmosphere (Bekker and others, 2004; Canfield, 2005; Hitzman and others, 2010) and the earliest red beds formed (Chandler, 1988; Bekker and others, 2004). Red beds can form in a variety of environments, but sediment-hosted stratabound copper deposits are most commonly associated with those deposited in arid climates. These include sediments that were originally deposited in aeolian dunes, sabkhas, playas, and sand sheets, with lesser associations in host rocks deposited by alluvial fans, and ephemeral rivers. Intracontinental rift basins that formed within 20–30 degrees of the equator are ideal settings for sediment-hosted stratabound copper deposits (Kirkham, 1989), but transtensional basins and intermontane basins also contain sediment-hosted stratabound copper deposits.

Field and laboratory evidence indicates that sediment-hosted stratabound copper mineral deposits formed from late diagenetic fluids generated during the compaction and lithification of sedimentary basins containing successions of red beds (Hitzman and others, 2005; 2010). On the basis of ore and gangue mineral zoning and alteration, mineral paragenesis, fluid inclusion studies, and stable isotope geochemistry, metal-bearing fluids are relatively low-temperature (75–220 °C), hematite-stable (oxidized), sulfate- and chloride-rich, subsurface sedimentary brines.

Host lithology, and the nature of organic material in the rock, are used to distinguish three subtypes of sediment-hosted stratabound copper deposits: (1) reduced facies, (2) sandstone copper, and (3) red bed (Cox and others, 2003; Zientek, Hayes, and Hammarstrom, 2013). Host rocks for reduced-facies subtype sediment-hosted stratabound copper deposits include laterally-extensive black shale, dark-gray to black siltstone, dark-gray dolosiltstone, gray shale, or locally green shale or siltstone—all of which contain solid organic material. Host rocks for sandstone copper are typically well-sorted, siliciclastic sandstones from a variety of deltaic topset environments. Petroleum-bearing fluid inclusions and dead oil that coat detrital grains, stain authigenic minerals, and locally form cements, indicate that the mineralized strata may have hosted petroleum accumulations. For many sandstone copper deposits, these accumulations may have been sour gas (Zientek, Hayes, and Hammarstrom, 2013). Host rocks for red bed subtype deposits are fluvial sandstone, commonly conglomeratic, and contain carbonized vascular plant fragments. The ability to distinguish between subtypes is important for resource assessment studies because red bed subtype deposits are usually too small to be mined economically, whereas sandstone subtype deposits are important sources of copper[4], supplying 5 percent of the world's copper (Zientek, Hayes, and Hammarstrom, 2013). The primary cause of base-metal sulfide precipitation for reduced-facies or red bed deposits is the reduction of sulfate in brine by organic material; in sandstone copper deposits, it is direct sulfide precipitation by hydrogen sulfide (Zientek, Hayes, and Hammarstrom, 2013).

[4]Taylor and others (2013) state that global production of copper is largely derived from porphyry and sediment-hosted copper deposits (57 and 23 percent, respectively). In 2011, global copper production was almost 313 Mt of which almost 71 Mt was derived from Sandstone copper and Sandstone copper—Roan arenite subtypes (Taylor and others, 2013).

Previous Work

Detailed geologic mapping and mineral exploration studies were conducted in Kazakhstan, after the Second World War, by the Dzhezkazgan Exploratory-Geologic Expedition (Popov, 1962). Areas with mineral-resource potential were mapped at scales ranging from 1:50,000 to 1:10,000. Maps at a scale of 1:200,000 were later compiled to illustrate the regional geology and to provide basis for a prognostic assessment of mineral potential. In the Teniz Basin area, 1:200,000-scale geologic and minerals maps published between 1957 and 1970 are based on field work conducted between 1951 and 1962. The minerals maps show stream sediment survey results and location and relative size of mineral occurrences. A few English-language publications that specifically describe sediment-hosted copper mineralization in this area were published between 1960 and 1974 (Popov, 1962; Bogdanov and Feoktistov, 1972; Seyfullin and others, 1974). Those publications refer to an extensive Russian scientific literature that was not available for this study. We did, however, have access to an English-translated overview of stratabound copper deposits of the USSR (Bogdanov and others, 1973).

References to resource potential of the Teniz Basin can be found in Bogdanov and Feoktistov (1972), Syusyura and others (2010), and Information and Analysis Center of Geology and Mineral Resources of the Republic of Kazakhstan, (2008). Bogdanov and Feoktistov (1972) suggest that the potential for undiscovered copper in the southern part of the basin is quite high and show a mineral potential map with areas that have factors favorable for mineralization (their figure 6).

Syusyura and others (2010) published a data compilation useful for understanding copper potential in the Teniz Basin. The data include a digital geologic map at a scale of 1:1,500,000, a database of mineral localities, results from seismic surveys, and a copper forecast map. The copper forecast map in Syusyura and others (2010) shows prognostic areas categorized according to potential, priority, and need for additional study. The Teniz Basin is one of six areas that have prognostic resources associated with cupriferous sandstone in Kazakhstan (Information and Analysis Center of Geology and Mineral Resources of the Republic of Kazakhstan, 2008).

We suspect that most copper exploration activities were conducted in the 1950s because the distribution of mineral locations shown on the 1:1,000,000-scale minerals map (Marochkin and others, 1994) is virtually the same as that shown on the 1:200,000-scale (1950s) maps. Internet searches for recent exploration activity within the Teniz Basin failed to identify any commercial interest or activity. Google Earth imagery shows no evidence for construction of new roads, drill pads, or trenches at mineral localities since that time. Evenly-spaced exploration trenches were seen in images near Kenen and Kiyminskoe, but the ground disturbance is not recent.

The Teniz Basin has also been explored for oil and gas. Seismic data were collected in two periods of exploration: 1952–1954 and 1975–1982. In all, 865 line km of common depth point and 7,000 line km of analog reflection seismic data were collected in the basin (Oil & Gas Journal, 1992; Syusyura and others, 2010). In the late 1970s and early 1980s, 20 holes with depths ranging from 200 to 3,000 m were drilled to test stratigraphy (Oil & Gas Journal, 1995; Syusyura and others, 2010). In one hole, methane flowed for about 30 hours from a Middle[5] Carboniferous interval penetrated at 812 m (Oil & Gas Journal, 1995).

Geologic Overview of the Teniz Basin

Regional Geologic Setting

The Paleozoic Teniz and Chu-Sarysu Basins owe their origin to the interaction of three continental blocks—Siberia, Tarim-North China, and Kazakhstan—during development of the Altaid Orogen (Wilhem and others, 2012; Blackbourn and Thomson, 2010). The basins formed along the western margin of the Paleozoic Kazakhstan Continent described by Wilhelm and others, (2012) (fig. 1). Pre-Silurian amalgamation of the Kazakhstan Continent in eastern Gondwana resulted from collision and accretion of several microcontinents and island arc-type terranes. Assembly of the continent was virtually complete by the Early Silurian, by which time an inferred suture zone, that may underlie both the Chu-Sarysu and Teniz Basins, had closed (Allen and others, 2001; Windley and others, 2007; Smirnov, 2008; Wilhelm and others, 2012). Following its amalgamation, the continent was mostly emergent during the Silurian and Early Devonian, as indicated by continental deposits and subaerial, mafic volcanic rocks that underlie the Teniz and Chu-Sarysu Basins (fig. 2).

During the Late Devonian, clastic sediment deposition ceased and was succeeded by carbonate deposition in an extensive marine platform along the western and southern margins of the Kazakhstan Continent. This passive margin formed by back-arc opening related to development of the Kazakh-Mongol continental arcs along the eastern side of the Kazakhstan Continent. Epicontinental shallow marine basins, which would become the Teniz and Chu-Sarysu Basins, developed at this time (Wilhelm and others, 2012).

[5]We have chosen to preserve Russian age terminology to describe Series and Epoch time intervals referenced in this report. For example, whereas USGS would use middle Carboniferous Kirey Suite, the original Russian literature and translation of that literature uses Middle Carboniferous Kirey Suite. For ease of use of references cited, we have chosen to preserve the Russian style.

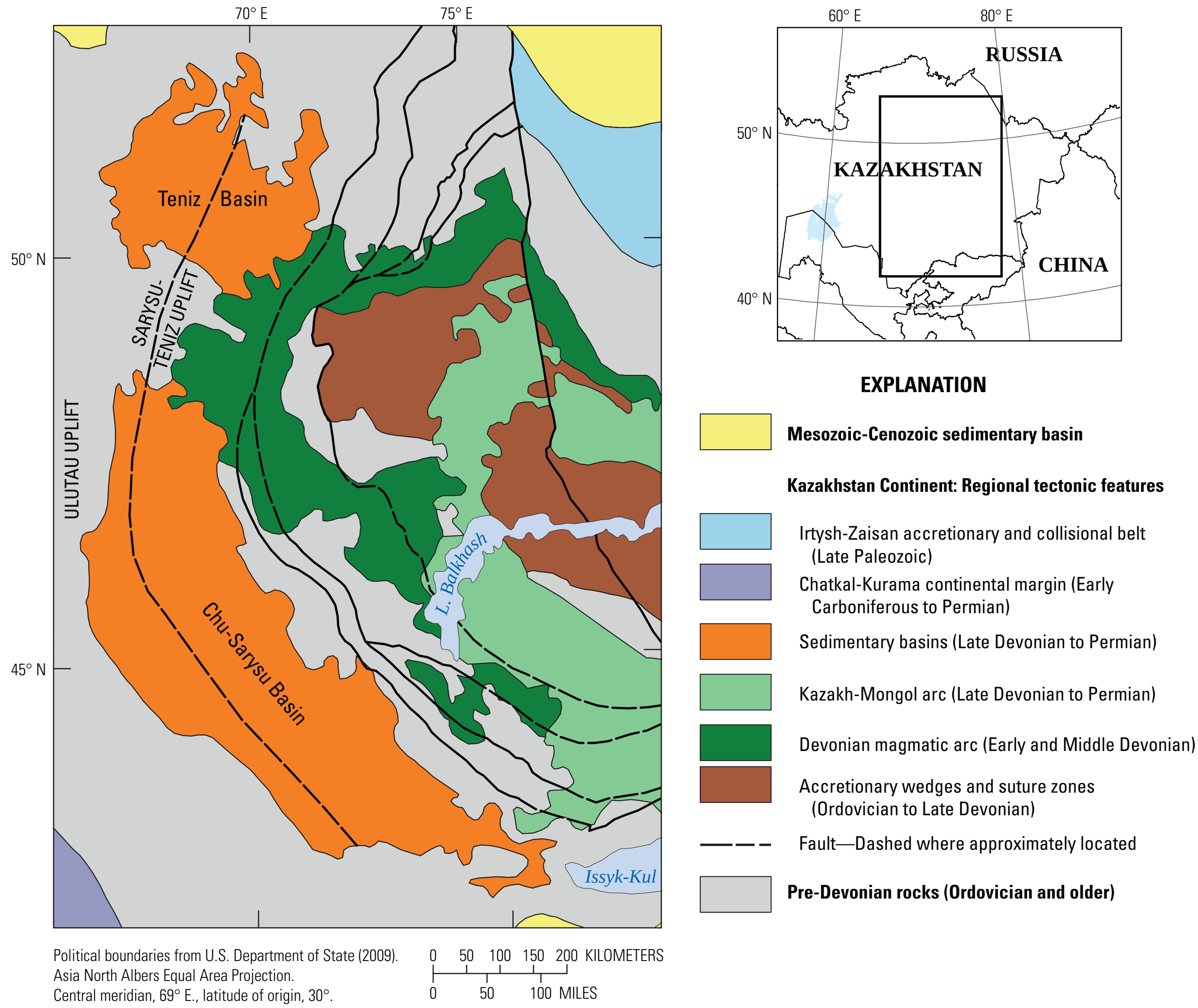

Figure 1. Map showing the regional geologic setting of the Teniz Basin, Kazakhstan (modified from Windley and others, 2007).

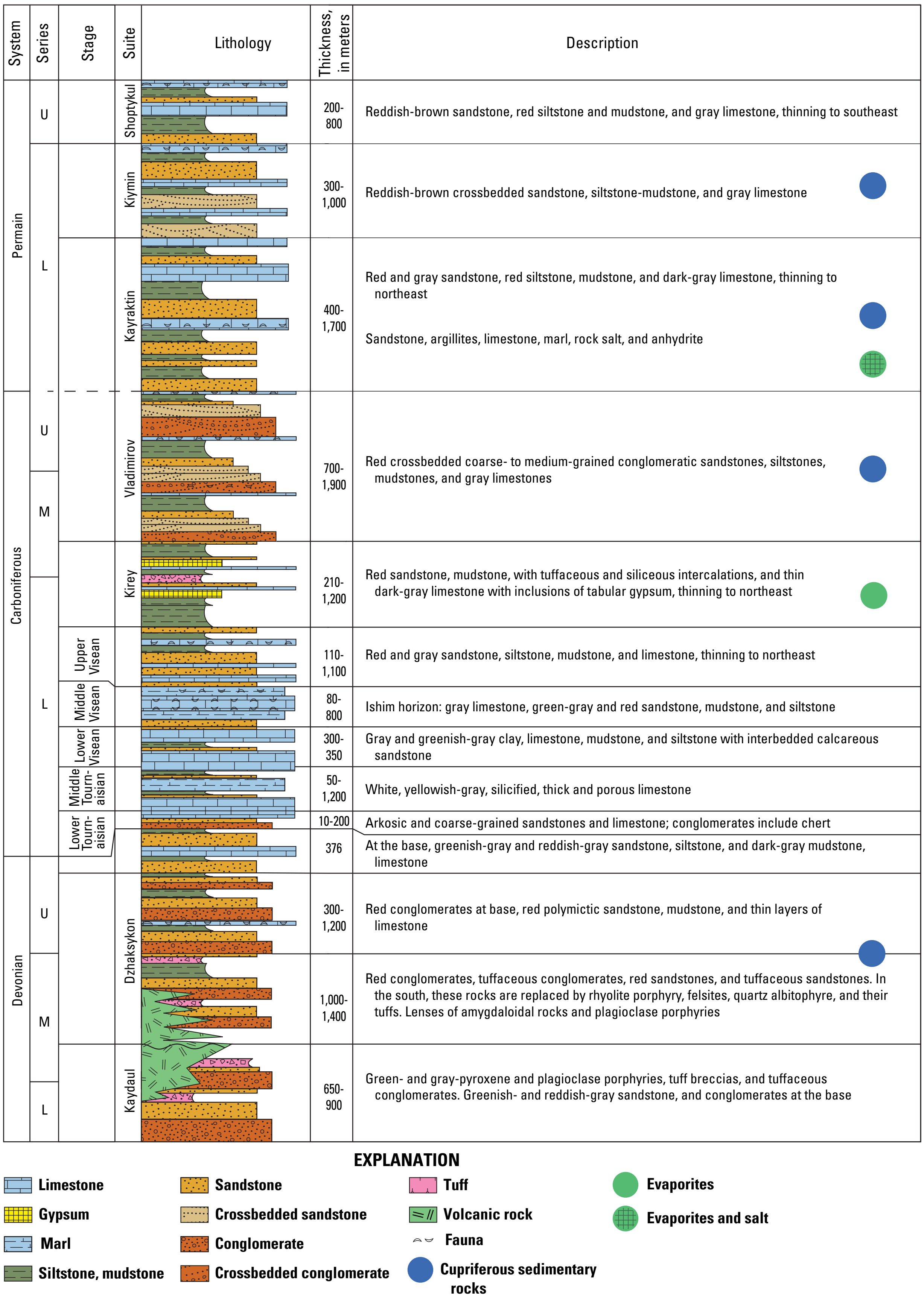

Figure 2. Generalized stratigraphic column, western Teniz Basin, Kazakhstan.

Siberia, Tarim-North China, and Kazakhstan blocks continued to interact throughout the middle and late Paleozoic. Devonian marine-sedimentary and volcanic rocks, that form the base of the Teniz and Chu-Sarysu Basins, are overlain by continental deposits that record uplift resulting from closure of the Turkestan and Uralian Oceans and the continental collision between Baltica and the Kazakhstan Continent. The new plate arrangement led to oroclinal bending and large-scale rotation of Kazakhstan during the Carboniferous. An east-west oriented, deep water trough that crossed the northern carbonate shelf was inverted, creating the Sarysu-Teniz uplift zone that now separates the Teniz and Chu-Sarysu Basins (Blackbourn and Thomson, 2010).

Stratigraphy, Depositional Environments, Tectonics and Structural Setting

A generalized stratigraphic column for the western half of the Teniz Basin (fig. 2) was compiled using information from 1:200,000-scale geologic maps (Mazarovich, 1958a; Minervin, 1961a; Mikhailov and Litvinovish, 1963; Babi'chev and others, 1970a). Our translations of Russian unit descriptions are given in table 1. This column is compared to a section for the eastern edge of the Teniz Basin, Zharysbay area (Syusyura and others, 2010) and the Chu-Sarysu Basin (Box and others, 2012) in figure 3.

Stratigraphy of the Teniz Basin indicates that the depositional setting evolved from continental to marine, and back to continental. The oldest rocks (deposited over crystalline basement) in the basin, Lower and Middle Devonian volcanogenic-sedimentary deposits, are overlain by red conglomerates and sandstones of the Middle to Upper Devonian Dzhaksykon Suite that were deposited soon after amalgamation of the Kazakhstan Continent. The overlying Tournaisian to Visean (Middle Mississippian) carbonates and mudstones are marine in origin and are part of a large carbonate shelf that formed on the passive margin of the Kazakhstan Continent. These, in turn, are conformably overlain by red bed deposits beginning with the Middle Carboniferous Kirey Suite and culminating with the Upper Permian Shoptykol Suite. The sequence of rocks that constitute the copper mineralized section are bracketed by the Upper Devonian Dzhaksykon Suite and the Upper Permian Shoptykul Suite. Total thickness of the upper Paleozoic red bed units ranges from 200 m to 4,000 m (Bogdanov, 1960). The Middle Carboniferous continental red beds were deposited in response to marine regression and regional uplift during convergence of the Kazakhstan Continent and Baltica. The Teniz Basin subsequently evolved into an evaporative, lacustrine basin that was subject to fluctuating water levels (Bogdanov, 1960).

These generalizations are consistent with fossils described on 1:200,000-scale geologic maps (Mazorovich, 1958a; Minervin, 1961a; Mikhailov and Litvinovish, 1963; Babi'chev and others, 1970a). Marine brachiopods and gastropods are associated with the Lower Carboniferous carbonate units. Fossils of ostracods, fish, reptiles, and terrestrial plants are described from the Middle Carboniferous to Permian clastic rocks. The prominent aquatic fossil in Upper Carboniferous and Permian rocks, *Darwinula* sp., is commonly associated with freshwater habitats, but modern species of *Darwinula* sp. have a cosmopolitan distribution (Sohn, 1987) and can tolerate a wide range of salinities. Therefore the presence of *Darwinula* sp. does not preclude the probability that the body of water that occupied the Teniz Basin remained saline throughout the close of the Carboniferous until at least the Middle Permian.

Convergence of the Kazakhstan Continent and Baltica during the late Paleozoic folded sedimentary rocks in both the Chu-Sarysu and Teniz Basins. In the Chu-Sarysu Basin, strata are deformed by two, nearly-orthogonal trends of upright folds: an east-northeasterly-trending set (F1, fig. 4) and a set with northerly trends (F2, fig. 4) and the Teniz Basin strata are similarly deformed (Allen and others, 2001; Alexeiev and others, 2009; Syusyura and others, 2010; Box and others, 2012). Isodepth maps of a reflecting horizon identified in seismic surveys suggest at least two episodes of folding occurred within the Teniz Basin. Seismic profiles show significant reflectors at the base of Tournaisian strata (T_1), lower and middle Visean strata (T_2), and the Vladimirov Suite (T_3) (fig. 5). The isodepth map for the T_1 reflector (Syusyura and others, 2010) was used to map traces of fold axes (fig. 5). Geologic maps of basin margins and structure contour maps demonstrate that two fold trends affect upper Paleozoic strata throughout the basin and that wavelengths of both intersecting fold sets are approximately 10–15 km with subhorizontal fold axes and steep axial planes. Complex basin and dome fold patterns result from the interaction of northeast-to east-oriented folds with near-orthogonal north-south folds.

Table 1. Translations of Russian map unit descriptions from 1:200,000-scale geologic maps from the western part of the Teniz Basin, Kazakhstan.

[Map unit, thickness, and principal lithologies with age based on Babi′chev and others (1970a), Mazarovich (1958a), Mikhailov (1963), and Minervin (1961a). m, meters]

Map Sheet M-42_II			Map Sheet M-42_III			Map Sheet M-42_XIV			Map Sheet M-42_XV		
Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description
P_2shp	500	Shoptykul Suite (Upper Permian). Reddish-brown sandstone, siltstone and mudstone with calcareous concretions, and gray limestone (500 m).	P_2shp	750–850	Shoptykul Suite (Upper Permian). Red mudstones; siltstones; gray, porphyritic fine grained sandstone; and limestone (750–850 m). Fauna.				P_2?	200–300	Shoptykul Suite (Upper Permian). Brown and greenish-brown sandstone and gray limestone and siltstone (200–300 m).
P_1km	800–1,000	Kiymin Suite (Lower Permian). Reddish-brown, crossbedded sandstone, siltstone and mudstone, and gray limestone (800–1,000 m).	P_1km	800–1,000	Kiymin Suite (Lower Permian). Multicolored sandstone, siltstone, mudstone, and gray limestone (800–1,000 m).	P_1km	300–400	Kiymin Suite (Lower Permian). Red siltstone and gray limestone interbedded with green siltstone (300–400 m).	P_1	800–1,000	Kiymin Suite (Lower Permian). Red mudstone and siltstone, crossbedded sandstone and thin beds of gray limestone and concretions. Gray sandstone and mudstone. Scales and prints of fish, pelecypods, ostracods (800–1,000 m).
C_3kr	400–800	Kayraktin Suite (Lower Permian). Sandstone, limestone, and mudstone, commonly gray (400–800 m). Skeletal remains and fish scales.	P_1kr	900–1,350	Kayraktin Suite (Lower Permian). Gray sandstone, siltstone, mudstone, dark-gray limestone (900–1,350 m).	C_3kr	1,700	Kayraktin Suite (Lower Permian). Greenish-gray sandstone and siltstone, gray pelitic limestone. Red sandstone and siltstone at the base (1,700 m).	C_3	1,300–1,700	Kayraktin Suite (Lower Permian). The upper section consists of alternating greenish-gray mudstone, siltstone, dense dark-gray limestone, and calcareous sandstones. The lower part consists of alternating greenish-gray mudstone, siltstone, coarse-grained sandstones and limestones. Layers of red siltstone (1,300–1,700 m).

Table 1. Translations of Russian map unit descriptions from 1:200,000-scale geologic maps from the western part of the Teniz Basin, Kazakhstan.—Continued

[Map unit, thickness, and principal lithologies with age based on Babi′chev and others (1970a), Mazarovich (1958a), Mikhailov (1963), and Minervin (1961a). m, meters]

Map Sheet M-42_II			Map Sheet M-42_III			Map Sheet M-42_XIV			Map Sheet M-42_XV		
Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description
C_2v_1	1,100	Vladimirov Suite (Middle Carboniferous). Brownish-purple and cherry-red sandstones, pebbly conglomerates, and gray limestone. Chert lens at the base (1,100 m). Plant remains.	$C_{2-3}vl$	700–1,900	Vladimirov Suite (Middle to Upper Carboniferous). Red-, rarely gray- conglomeratic sandstone, siltstone, mudstone, and gray limestone (700–1,900 m). Flora.	C_2v_1	900–1,500	Vladimirov Suite (Middle to Upper Carboniferous). Red sandstone and siltstone with lenses of conglomerate. Red conglomerates at the base (900–1,500 m).	C_2	1,200–1,400	Vladimirov Suite (Middle to Upper Carboniferous). Red crossbedded coarse- to medium-grained conglomeratic sandstones; few siltstones with rare interbeds of limestone (1,200–1,400 m).
			$C_1n–C_2kr$	210	Kirey Suite (Lower to Middle Carboniferous). Red-colored sandstones, mudstones, with tuffaceous and siliceous intercalations (210 m).	C_1n_2	750–1,200	Violet-gray and variegated sandstone and siltstone (Lower Carboniferous). Chert in uppermost part of unit. Base consists of greenish-gray sandstone and gray pelitic limestone (750–1,200 m).	C_1n_2	900	Kirey Suite (Lower to Middle Carboniferous). Predominantly red siltstone, sandstone, mudstone interbedded with thin dark-gray limestone with inclusions of tabular gypsum (900 m).
C_1v_3-n	200–250	Upper Visean rocks (Lower Carboniferous). Gray sandstone, mudstone, siltstone, and sandy limestone (200–250 m).	C_1v_3-n	110–330	Upper Visean rocks (Lower Carboniferous). Gray sandstone, siltstone, mudstone, and limestone (110–330 m). Fauna.	$C_1v_3+n_1$	400–800	Upper Visean rocks (Lower Carboniferous). Greenish-gray sandstone and siltstone, gray bioclastic and pelitic limestone. Dark-red siltstone, mudstone, and sandstone at the base (400–800 m).	C_1v_3-n1	650–1,100	Upper Visean rocks (Lower Carboniferous). Coal-bearing formation Dark-gray and green mudstones, siltstones and sandstones with thin interlayers and lenses of carbon[soot] and coal. Subordinate red sandstone and siltstone interbeds at the top of the unit (650–1,100 m).

Table 1. Translations of Russian map unit descriptions from 1:200,000-scale geologic maps from the western part of the Teniz Basin, Kazakhstan.—Continued

[Map unit, thickness, and principal lithologies with age based on Babi′chev and others (1970a), Mazarovich (1958a), Mikhailov (1963), and Minervin (1961a). m, meters]

Map Sheet M-42_II			Map Sheet M-42_III			Map Sheet M-42_XIV			Map Sheet M-42_XV		
Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description
C_1v_{1+2}	80	Visean rocks (Lower Carboniferous). Limestone, sandy limestone, and calcareous sandstone (80 m).	C_1v_{1+2}	40–270	Visean rocks (Lower Carboniferous). Ishim and undivided Yagovkinskii horizons. Gray limestone, sandstone, siltstone, mudstone (40–270 m). Fauna.	C_1v_{1+2}	350–800	Visean rocks (Lower Carboniferous). Gray limestone, green-gray sandstone and siltstone. Unit grades from limestone in the north to sandstone in the south Limestone at the base of the unit (350–800 m).	C_1v_2	500–550	Visean rocks (Lower Carboniferous). Limestones, sandstones, siltstones; gray- to dark-gray mudstone. The uppermost part consists of red sandstone, siltstone, and mudstone (500–550 m).
									C_1v_1	300–350	Lower Visean rocks (Lower Carboniferous). Gray and greenish-gray clay, limestone, mudstone, siltstone with interbedded calcareous sandstone (300–350 m).
C_1t_2	50	Middle Tournaisian rocks (Lower Carboniferous). Conglomerates, siliceous limestone, and marl (50 m).	C_1t_2*rs*	20–90	Middle Tournaisian rocks (Lower Carboniferous). Rusakov horizon Brownish-gray limestone, sandstone layers (20–90 m).	C_1t_2	300–1,200	Middle Tournaisian rocks (Lower Carboniferous). Silicified, fine-grained, bioclastic limestone interbedded with marls and light-gray sandstone At the base, dolomites, sandstones, and dolomitized, pelitic limestones (300–1,200 m).	C_1t_2	450–800	Middle Tournaisian rocks (Lower Carboniferous). White, yellowish-gray, silicified, thick and porous limestone. To the east are terrigenous, clastic sediments; mudstones, siltstones and sandstones with thin interbedded limestones (450–800 m).
			C_1t_1	10–200	Lower Tournaisian rocks (Lower Carboniferous). Multicolored arkosic sandstones, coarse-grained sandstones, pebbly conglomerates; basal conglomerates include chert (10–200 m).	C_1t_1	200	Lower Tournaisian rocks (Lower Carboniferous). Limestone; chert at the base (200 m).	C_1t_1	120	Lower Tournaisian rocks (Lower Carboniferous). Limestone and dolomitized limestone with gray lenses and nodules of chert (120 m).
						D_3fm	305–550	Dolomitized limestone and dolomite (Upper Devonian). At the base, greenish-gray and reddish-gray sandstone; siltstone and dark-gray mudstone (305–550 m).	D_3fm	200–450	Dolomites, dolomitized limestones (Upper Devonian). Gray limestone and thick dark-gray laminates. Yellow-gray arkosic sandstones at the base (200–450 m).

Table 1. Translations of Russian map unit descriptions from 1:200,000-scale geologic maps from the western part of the Teniz Basin, Kazakhstan.—Continued

[Map unit, thickness, and principal lithologies with age based on Babi′chev and others (1970a), Mazarovich (1958a), Mikhailov (1963), and Minervin (1961a). m, meters]

Map Sheet M-42_II			Map Sheet M-42_III		
Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description
D_3fr	1,200	Dzhaksykon series (Upper Devonian). Red conglomerates. Sandstone, mudstone and thin layers of limestone (1,200 m). Plant remains.	D_2gv–D_3fr	300–400	Variegated sandstones, coarse-grained sandstones, conglomerates, and siltstones (Middle to Upper Devonian; 300–400 m).
D_2–D_3fr	300–1,200	Dzhaksykon series (Middle to Upper Devonian). Amygdaloidal rock, basaltic and andesitic porphyry, diabase,and agglomerates; replaced along strike by red conglomerates, sandstones, and siltstones (300–1,200 m).			
			D_{1}-$_{2}$*kd* ?	650–700	Kaydaul Suite (Lower to Middle Devonian). Purple and violet-gray andesite, basaltic andesite, andesite-dacite porphyry (650–700 m).

Map Sheet M-42_XIV			Map Sheet M-42_XV		
Unit label	Thickness (m)	Description	Unit label	Thickness (m)	Description
D_3frs	300–1,050	Upper unit, red sequence (Upper Devonian). Conglomerates, sandstones, siltstones, argillites. Conglomerates at the base. Cherry-red siltstones and mudstones at the top (300–1,050 m).	D_3frs	400–450	Red-polymictic sandstones, coarse-grained sandstones, and conglomerates (Upper Devonian; 400–450 m).
D_2–D_3fri	100–1,400	Sedimentary-extrusive sequence (Middle to Upper Devonian). Red conglomerates, tuffaceous conglomerates, sandstones, and tuffaceous sandstones. In the south, these rocks are replaced by rhyolite porphyry, felsites, quartz albitophyre, and their tuffs. Lenses of amygdaloidal rocks and plagioclase porphyries (100–1,400 m).	D_2–D_3fri	600–800	Red-brown albitophyre and quartz porphyries, porphyry and tuffs (Middle to Upper Devonian). Red sandstones and conglomerates (600–800 m).
D_{1-2}	900	Green- and gray-pyroxene and plagioclase porphyries, tuff breccias, and tuffaceous conglomerates (Lower to Middle Devonian). Greenish- and reddish gray sandstone and conglomerates at the base (900 m).			

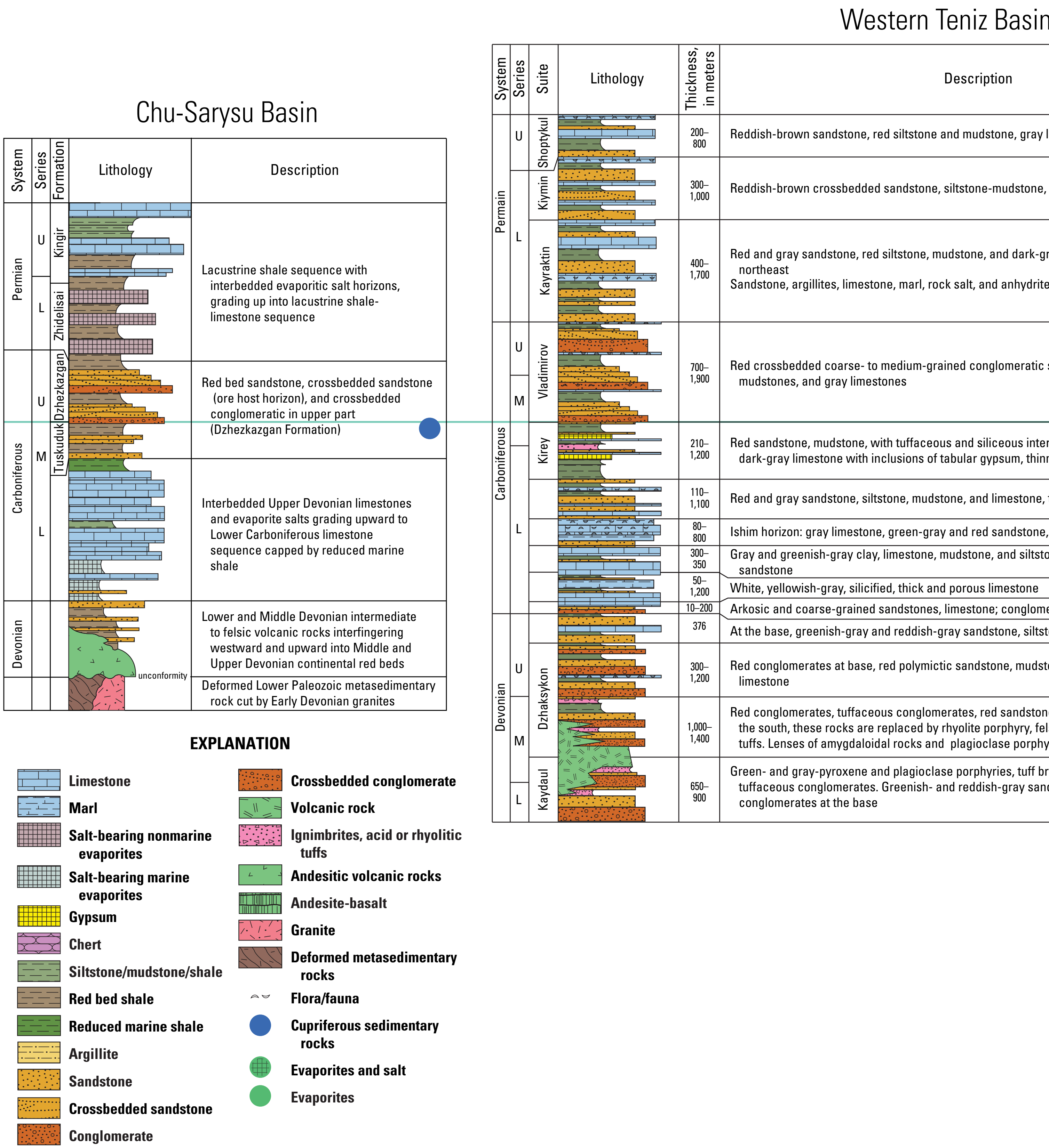

Figure 3. Correlation chart for the Chu-Sarysu Basin (Box and others, 2012), the western Teniz Basin, and the Zharysbay area, eastern Teniz Basin, Kazakhstan (Syusyura and others, 2010). Stratigraphic columns are correlated at the base of the Vladimirov and Dzhezkazgan Formations (indicated by horizontal green lines) which are several upward-fining clastic sequences above Lower Carboniferous platform carbonates.

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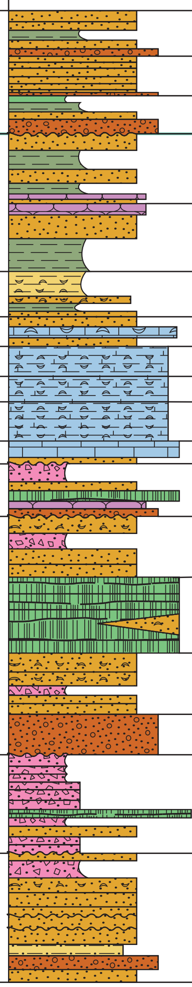
Zharysbay area, eastern Teniz Basin



System	Series	Suite	Lithology	Thickness, in meters	Description
Permian	L	Vladimirov		300	Upper subformation: conglomerates, sandstones, and siltstones
				260	Middle subformation: red sandstones, arkosic siltstones, and conglomerate lenses
	U			250	Lower subformation: conglomerates, siltstones, and layer of rhyolitic tuffs
Carboniferous	M	Kirey		460	Upper subformation: sandstones, siltstones, and layer of sandstones with magnetite
				450	Lower subformation: siltstones, tuffs, tuff-sandstones, sandstones, and cherts
	L			300	Gray sandstones, carbonaceous siltstones, and argillites with Pelecypoda fauna and flora
				200	Gray sandstones, siltstones, and limestones with fauna
				200	Ishim horizon: silicified marls, and calcareous sandstones with rich fauna
				170	Rusakov horizon: variegated marls with fauna
				260	Gray marls, and limestones with fauna
Devonian	U			150	Dark-gray pelitomorphic limestone with fauna, conglomerates, and sandstones
				>350	Conglomerates, cherts, andesite-basalts, sandstones, rhyolitic tuffs, and conglomerate lenses
	M			400	Yellow sandstones, fine detrital tuffs of rhyolitic porphyries, and siltstones with flora
				500	Gray, green-gray andesite-basalts, and sandstone lenses with flora
				400	Gray, yellow sandstones, and siltstones with flora
				300	Cobble conglomerates and sandstones
	L			>650	Ignimbrites, acid tuffs, and layers of black basalts
Silurian	L			2,000–2,100	Green sandstone with layers of dark-red siltstones and argillites, and conglomerates; thickness compressed for clarity

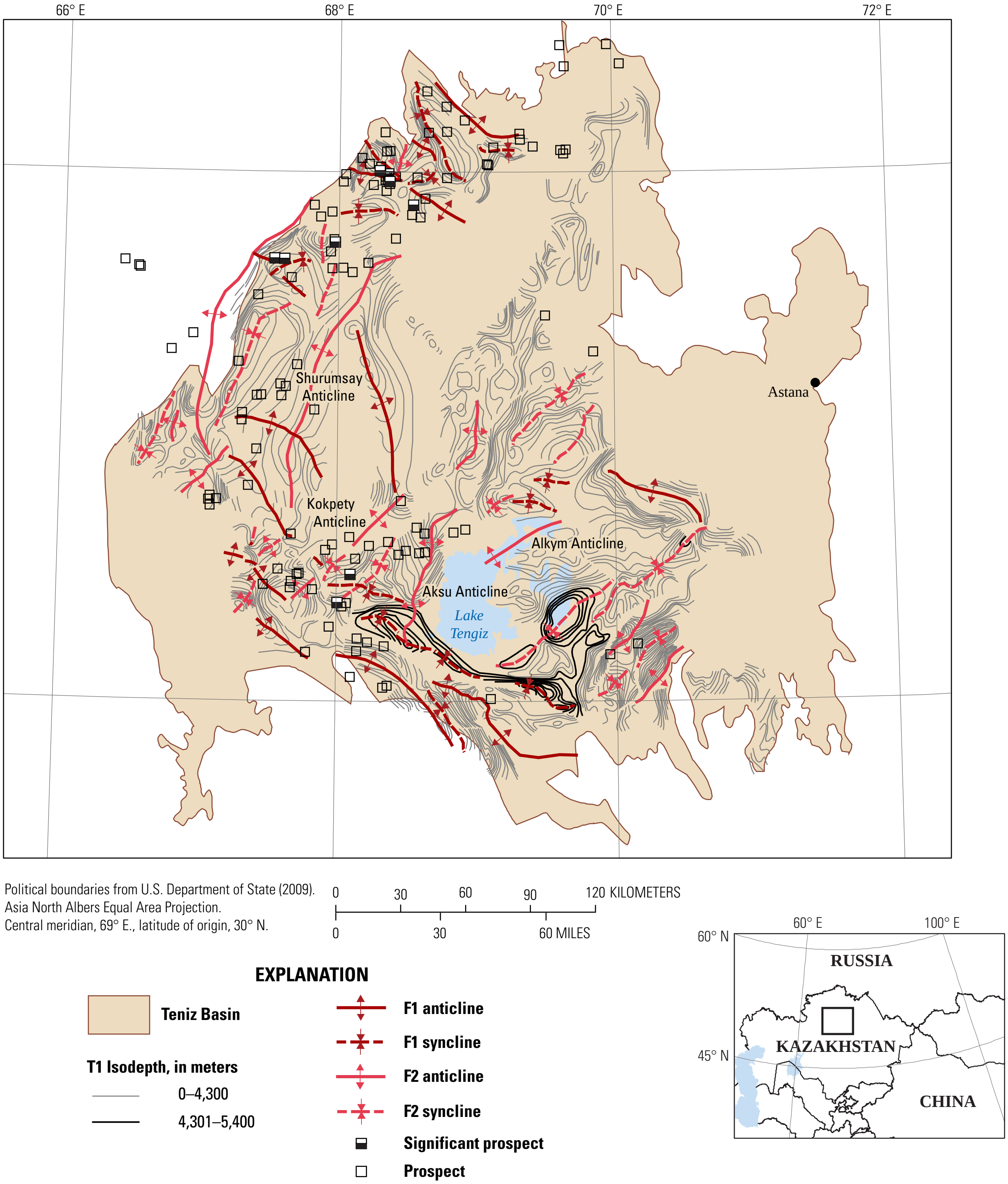


Figure 4. Map showing contours of the T_1 reflecting horizon (Syusyura and others, 2010), traces of fold axes, and sediment-hosted stratabound copper prospects in the Teniz Basin, Kazakhstan. The extent of the Teniz Basin is from Fugro Robertson, Ltd. (2008).

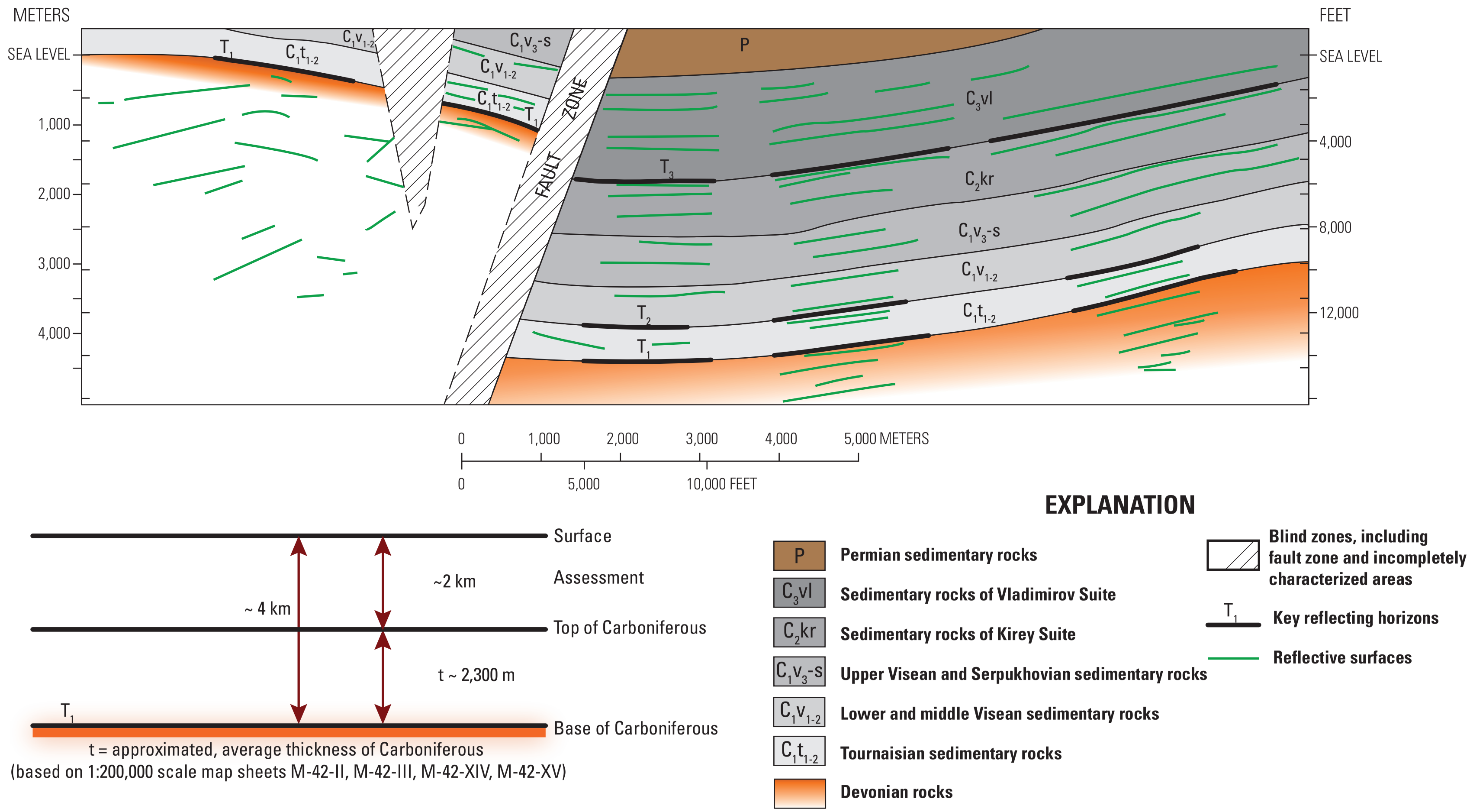


Figure 5. Interpreted seismic section from the Teniz Basin, Kazakhstan (Syusyura and others, 2010) and sketch showing how T_1 reflection horizon at top of Devonian rocks (that form the basin floor) is used to constrain permissive tract extent.

Delineation of Permissive Tracts

Ore deposits represent the ultimate focal points of much larger-scale systems of energy and mass flow, and mineral system models are used to systematically organize our ideas about ore deposit genesis in the context of larger Earth systems. In order to map areas where undiscovered deposits may occur, we first need evidence that an ore-forming system was present. Next, we must identify spatial positions where an ore-forming system is predicted to have formed undiscovered deposits.

Variations of the source-transport-trap paradigm are used to define both petroleum and mineral systems (Magoon and Dow, 1994; Wyborn and others, 1994; Magoon and Schmoker, 2000). Petroleum exploration and assessment uses a system that considers the following elements and processes essential to petroleum accumulation: source rocks, maturation of source rocks to generate oil, oil migration (transport), and reservoir rocks that trap and seal hydrocarbons (Magoon and Dow, 1994). Similarly, given the late diagenetic ore theory, formation of sediment-hosted stratabound copper deposits in sedimentary basins requires a metals source, a fluid that extracts and moves metals away from source rocks, a pathway that allows movement of ore-bearing fluids, and a physical and redox chemical trap that fixes metals in an ore body (Taylor, 2000; Hitzman and others, 2005; Hayes and others, 2012). Essentially, the same elements, processes, and timing required to create a total petroleum system (Magoon and Schmoker, 2000) are also required of an ore system to form sediment-hosted stratabound copper deposits. The timing of processes that control fluid generation, migration, accumulation, and preservation is critical. If a single element or process is missing or occurs out of order, viable accumulations of copper cannot form.

In this USGS global mineral resource assessment, areas with potential for sediment-hosted stratabound copper deposits are mapped if they possess the following geological characteristics: (1) aquifer facies red bed rocks juxtaposed against strata that contain reductants (typically organic material and earliest diagenetic pyrite); (2) a basin history indicative of rock burial and diagenesis (depths of 1–5 km at temperatures ranging from 70 to 220 °C); and (3) evidence that copper-enriched solutions were present in the basin. Maps, cross sections, and stratigraphic sections are used to map hydrologically-conductive sequences of rock with stratigraphic relationships consistent with sandstone subtype facies. Copper-mineralized rock, burial history, and copper in subsurface waters all indicate copper enrichment of solutions occurred.

Middle and Upper Carboniferous and Permian sedimentary rocks within the greater extent of the Teniz Basin have attributes favorable for hosting sandstone subtype and red bed type deposits (figs. 2 and 6) and to a lesser extent, reduced-facies copper deposits. The lowermost red bed unit, the Lower and Middle Carboniferous Kirey Suite (210–1,200 m thick), consists of red sandstone, mudstone, with tuffaceous and siliceous interbeds, and thin dark-gray limestone. Tabular gypsum crystals are found in some limestone beds. This suite is overlain by the Middle to Upper Carboniferous Vladimirov Suite (700–1,900 m thick), which consists of several upward-fining sequences made up of red crossbedded conglomeratic sandstone, siltstone, and mudstone capped by thin layers of gray limestone (fig. 2). The Lower Permian Kayraktin Suite is characterized by alternating layers of reddish-brown sandstone, siltstone, mudstone, and gray limestone. Rock salt and anhydrite are reported in the Kayraktin Suite (Marochkin and others, 1994). The Kayraktin Suite ranges in thickness from 400 m in the northwest part of the basin to 1,700 m in the southeast. The overlying Lower Permian Kiymin Suite (300–1,000 m thick) generally consists of reddish-brown sandstones, green siltstone, mudstone, and gray limestone. The uppermost unit, the Upper Permian Shoptykul Suite (200–800 m thick), includes red-brown to brownish-green sandstone, gray limestone, and siltstone.

In the Teniz Basin, aquifer-facies red bed rocks include conglomeratic sandstones of the Vladimirov Suite that were deposited in fluvial or shallow-water marine depositional environments. In sandstone subtype copper deposits, reduced rocks are former aquifer and reservoir facies red bed rocks that were exposed to petroleum. Reduction of ferric iron phases by reaction with petroleum resulted in bleaching of the former red beds to white, light-gray, or pastel green. Fourteen potentially ore-bearing intervals of gray beds (inferred by us to be bleached red beds) have been recorded in the Vladimirov Suite (Bogdanov and Feoktistov, 1972). Sandstones in the upper part of the underlying Kirey Suite and the lower part of the overlying Kayraktin Suite are also permissive host rocks. Rocks of the Vladimirov Suite likely underwent burial diagenesis at appropriate depths and temperatures because these strata are overlain by 900–3,500 m of younger Permian sedimentary rocks. Finally, the widespread distribution of copper prospects and occurrences in Carboniferous and Permian rocks throughout the basin provides direct evidence for the presence of copper-enriched subsurface water.

A permissive tract was delineated for the Teniz Basin based on the distribution of the Kirey, Vladimirov, and Kayraktin Suites as shown on geologic and isodepth maps compiled by Syusyura and others (2010). To further constrain permissive tract extent, we resolved where the top of the Vladimirov Suite occurred more than 2 km below the surface (the depth limit for this assessment). By adding the approximate thickness of Carboniferous strata (2,300 m) to the assessment depth (2,000 m), we were able to use the T1 isodepth map (base of Carboniferous) to construct the permissive tract by excluding areas where the T1 reflector is deeper than 4,300 m. A volume of rock satisfying these criteria was defined and vertically projected to the surface to define the bounds of the permissive tract.

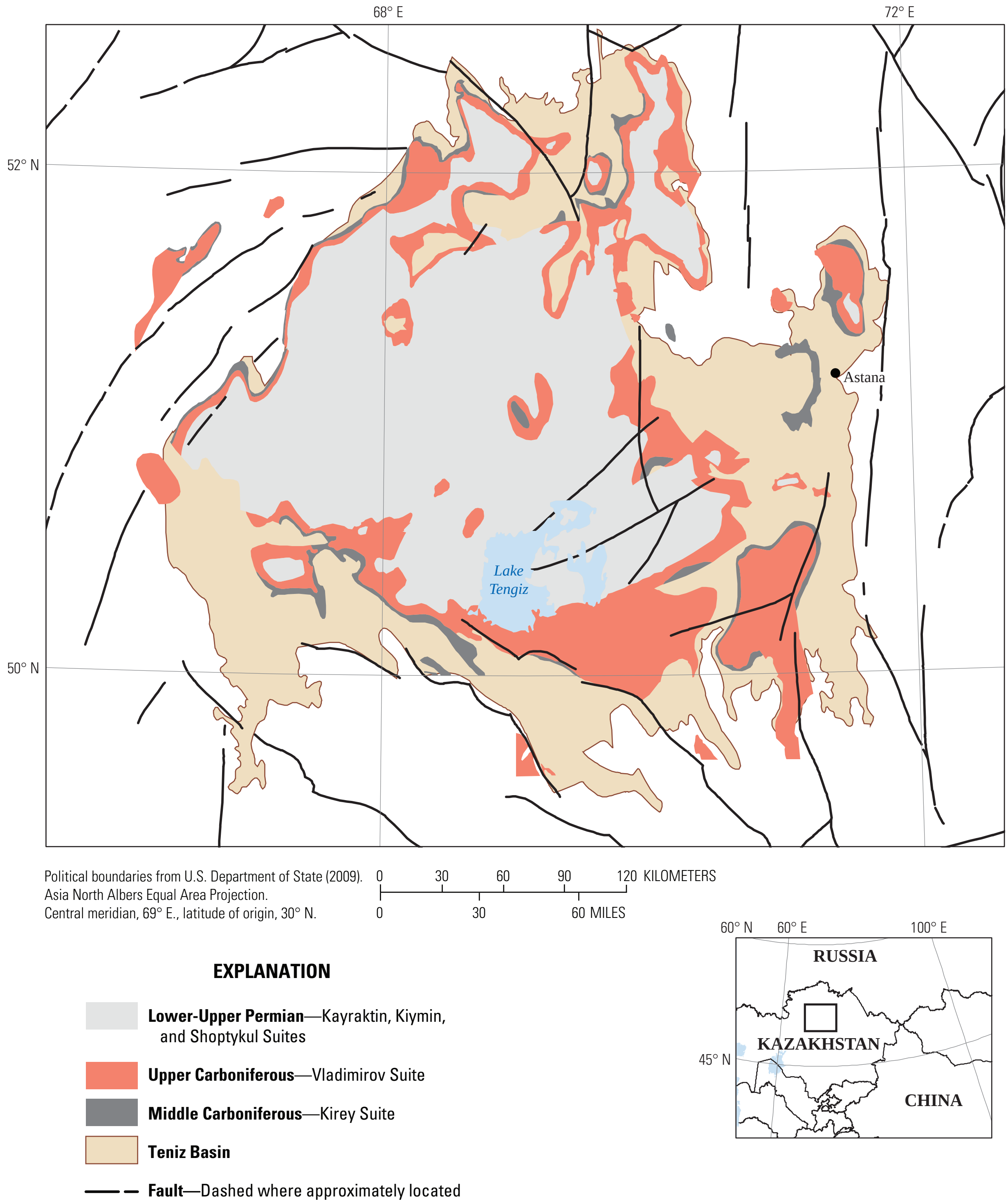


Figure 6. Geologic map showing the extent of the Teniz Basin, Kazakhstan and the bedrock distribution of Carboniferous and Permian rock units (modified from Syusyura and others, 2010).

Sandstone Copper Deposits and Prospects

No sites with reported mineral inventory or past production are known in the study area; therefore, no mineralized areas qualify as “deposits,” and all mineralized sites are referred to as “prospects.” B. Syusyura (2008) states that most of the hundred or so small copper occurrences in the Teniz Basin are associated with gray sandstones and siltstones that contain coalified plant remains. On that basis, one could assume that all copper occurrences are of the red bed subtype of Lindsey and Cox (2003). However, a few site descriptions suggest the possibility that some or many of the copper occurrences are of the sandstone subtype. Without specific information regarding organic material in the rocks, we use depositional environment to classify sites according to deposit type. Occurrences in the Kiymin and Shoptykul Suites are classified as red bed subtype because information in stratigraphic columns and unit descriptions is consistent with an alluvial-fluvial-lacustrine depositional environment in which mineralization is likely confined to sand lenses that have restricted lateral extents. In contrast, occurrences in the Kiery, Vladimirov, and Kayraktin Suites are assigned to the sandstone subtype.

Only three intervals in the Middle Carboniferous and Permian stratigraphic sections host prospects (Bogdanov and others, 1973). The first interval is situated in the basal, upper section of the Vladimirov Suite and consists of cupriferous, greenish-gray, thin-bedded silty sandstones. The second interval is confined to sedimentary rocks of the lower section of the Kayraktin Suite. Copper sulfide disseminations are found in dark-gray argillites and clay slates interbedded with marls, and also in greenish-gray silty sandstones. The third interval occurs in the middle section of the Kayraktin Suite. In all of the copper-bearing intervals, the ore bodies have a lenticular shape, are arranged en echelon, and thin along-strike and down-dip (Bogdanov and others, 1973). The main sulfide minerals are bornite and chalcocite. Galena, chalcopyrite, and tennantite-tetrahedrite occur rarely. Finely-dispersed ores predominate. Copper sulfides occasionally are found in veins of calcite, but are generally absent in barite, celestine, and gypsum veinlets. Malachite and azurite are widespread in the oxidized zone.

Only six mineralized sites in the basin have geologic descriptions and four are summarized here. The Dzhezkazgan Geologic Research Expedition Exploratory found two small ore bodies with ore grade mineralization in the Tersakkan area of the southern Teniz Basin (Bogdanov and Feoktistov, 1972); we believe they are sites known subsequently as Kenen and Kopkazgan (B. Syusyura, 2008, written comm.; Seltmann and others, 2009). Both occurrences are located in the core of the Kokpekty anticline (fig. 5). The Kenen prospect, in rocks near the base of the Kayraktin Suite, has three fragmented ore bodies in a reduced, gray sandstone that is rhythmically interbedded with red-colored silty mudstones. The ore body does not exceed 1 m in thickness and has an average grade of about 0.5 percent copper. Mineralization at the Kopkazgan prospect is found in gray rocks that constitute the upper part of the Vladimirov Suite. Ore-bearing intervals are 0.75–7.3 m thick and can be traced 500–900 m along-strike and up to 200 m down-dip. Copper grades range from 0.88 to 1.75 percent. Organic material associated with these deposits was not described.

Copper mineralization at two other sites, Borisovskoe and Kiyminskoe, is localized by carbonized plant remains (Bogdanov and others, 1973), indicating they are best categorized as red bed type deposits of Lindsey and Cox (2003) or the Urals (lacustrine-alluvial) type of Bogdanov and others (1973). Copper mineralization at the Borisovskoe occurrence in the Vladimirov Suite is concentrated in a 10-m-thick unit consisting of interbedded gray and greenish-gray sandstones and argillites. Intense malachite mineralization is confined to interlayers rich in carbonized plant remains. The primary sulfide mineral in this deposit is chalcopyrite (Bogdanov and others, 1973). The Kiyminskoe occurrence is associated with red beds of the Lower Permian Kiymin Suite where copper mineralization is confined to two horizons that are nearly 200 m apart stratigraphically. The lower ore interval is 0.4–1.5 m thick and consists of greenish-gray fine-grained sandstones with films of malachite. The sandstones form lenses that extend 35–95 m along strike. Fossil impressions of *Calamites* are a common characteristic of the host rock. The upper ore interval is a 1–8 m thick interval of greenish-gray, fine-grained sandstones and argillites. Copper mineralization is confined to several discrete sandstone lenses measuring 1–5 m thick. Malachite and azurite are concentrated in thin interlayers that are enriched with accumulations of carbonized plant remains (Bogdanov and others, 1973).

Development of the Prospects Database

Multiple data sources about mineralized areas were used to develop a prospects database. The number of points and quality of attribution varied among them. The 1:200,000-scale maps of mineral resources of USSR, Ulutau-Kokchetav series (Mikhailov, 1951, 1963; Mazarovich, 1958b; Minervin, 1961b; Vavic and Rosen, 1963; Babi′chev and others, 1970b) are the primary sources used for subsequent compilations, in particular the 1:1,000,000-scale map of mineral resources for the Tselinograd-Akmola sheet (Marochkin and others, 1994); the 1:1,500,000-scale compilation of geologic and minerals information for central Asia (Seltmann and others, 2009); and a 1:1,500,000-scale compilation published by Syusyura and others (2010). Previous national or global compilations contained only 10–16 records for the Teniz Basin (Rundkvist, 2001; Kirkham and others, 1994, 2008; Cox and others, 2003). No datasets provided tonnage or grade data; however, sites were categorized as a deposit, mineral occurrence, or mineral point in five datasets (table 2). Site names were available in three compilations. Locations for a same-named feature were not consistent among datasets and differed by more than 10 km in the worst cases.

We compiled a database of about 120 prospects among the various datasets. If a spatially coherent cluster of sites was judged to represent the same feature, then the location considered most reliable was the one shown on the 1:200,000-scale mineral deposit maps (fig. 7). Consistent attributes were transferred to our database and were supplemented with information from geologic maps and Google Earth imagery. Prospects are shown in relation to the permissive tract for the Teniz Basin on figure 8.

Sites consistently referred to as “deposits” in previous compilations are coded as “significant prospects” in our compilation (table 3). In each source dataset, localities coded as deposits were categorized as small. We suspect grade and tonnage must have been estimated for these sites in order for them to be categorized by size but have been unsuccessful in finding data for these sites.

Table 2. Categorization of sediment-hosted stratabound copper occurrence in data sources used to compile a prospects database for this assessment.

[Counts are for those points that fall within the extent of the permissive tract. Sources for Ulutau-Kokchetav Series minerals maps are Babi′chev and others (1970b); Mazarovich (1958b); Mikhailov (1951, 1963); Minervin (1961a,b); Vavic and Rosen (1963); –, no data]

Source (scale)	Ulutau-Kokchetav series minerals maps[1] (1:200,000)	Marochkin and others (1994)[2] (1:1,000,000)	Syusyura and others (2010)[3] (1:1,500,000)	Seltmann and others (2009)[4] (1:1,500,000)	Rundkvist (2001)[5] (1:2,500,000)
Deposit					
Small deposit	–	3	3	3	3
Non-industrial	3	–	–	–	–
Prospect					
Mineral occurrence	43	28	83	72	7
Mineralization point	–	48	–	19	–

[1]1:200,000-scale maps: Kenen, Altynkazgan, Kiyminskoe.

[2]Marochkin and others (1994): Kenen, Kiyminskoe, Borisovskoe.

[3]Syusyura and others (2010): Kenen, Kopkazgan, Proletarskoe.

[4]Seltmann and others (2009): Kopkazgan, Altynkazgan, Kieilin.

[5]Rundkvist (2001): Kopkazgan-Kenen, Kiyminskoe, Spasskoe.

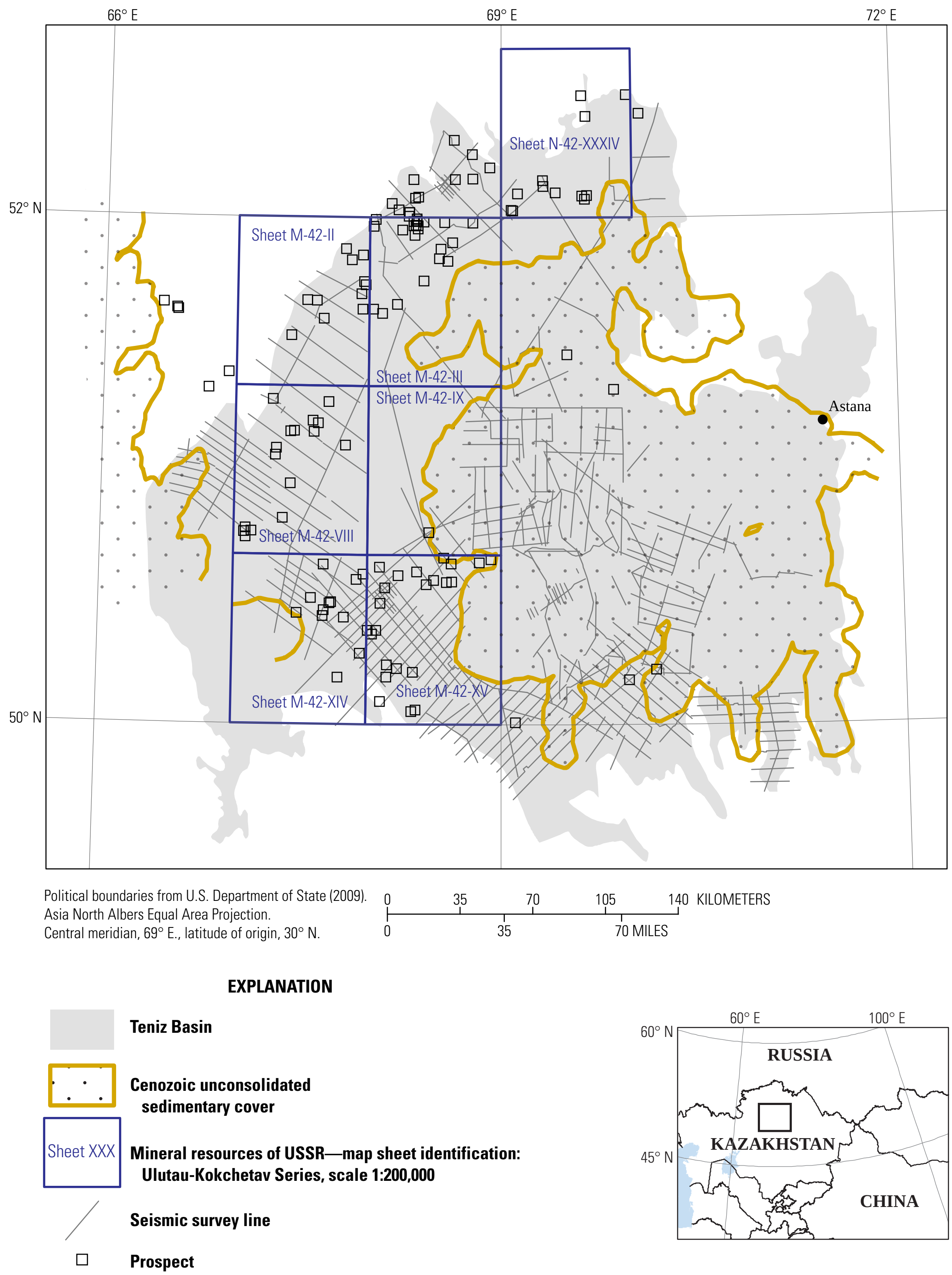


Figure 7. Map showing location of 1:200,000-scale geological and mineral resource map sheets used in this study relative to extent of Teniz Basin, Kazakhstan (Fugro Robertson, Ltd., 2008), extent of Cenozoic cover (Syusyura and others, 2010), location of prospects, and seismic survey lines (Syusyura and others, 2010).

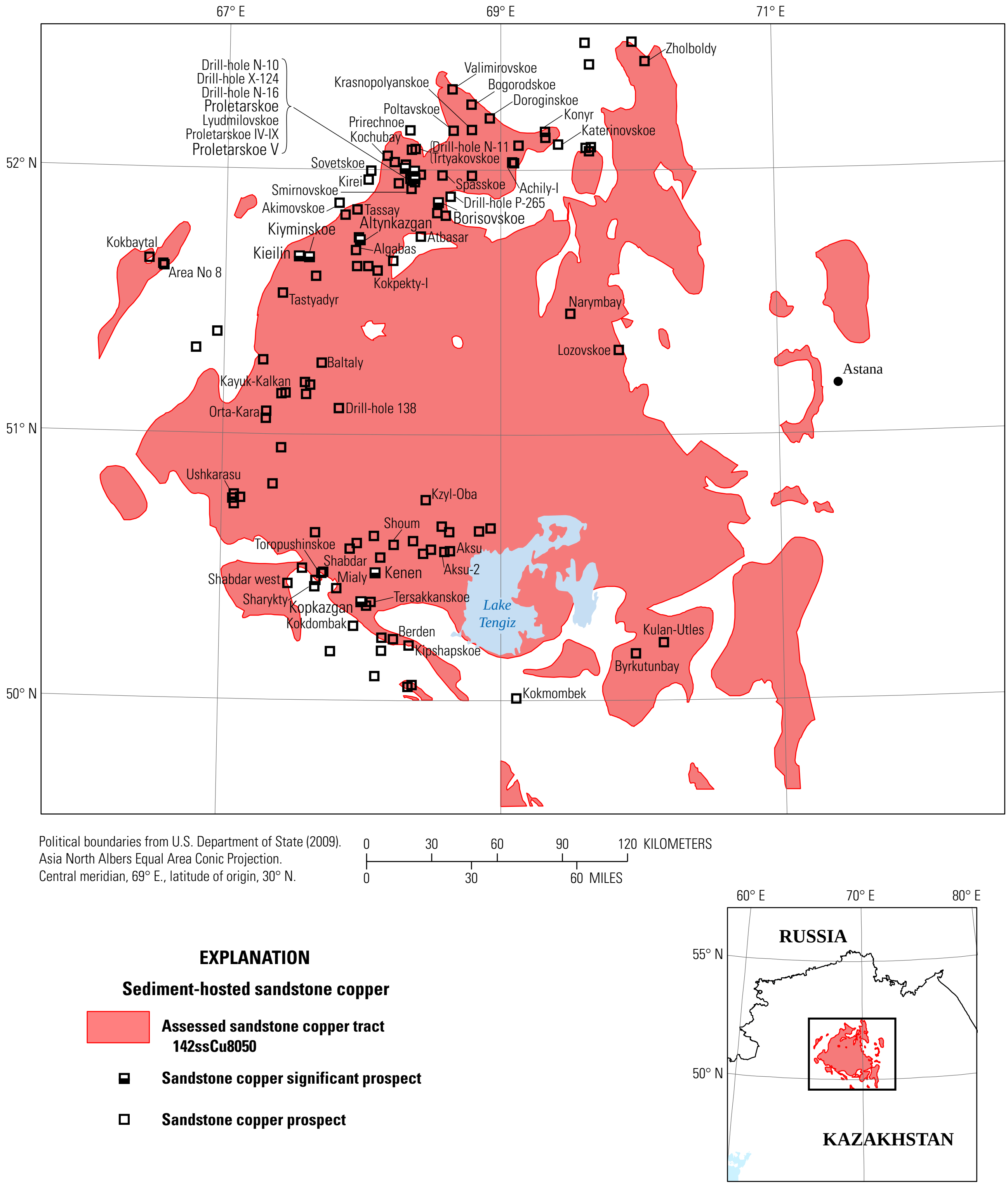


Figure 8. Map showing location of permissive tract 142ssCu8050 (TZ-1) and known prospects, Teniz Basin, Kazakhstan. Detailed descriptive information is available in both the GIS database and in tables 2 and 3.

Table 3. Significant Upper Carboniferous and Lower Permian sandstone copper prospects, Teniz Basin, Kazakhstan.

Name	Latitude (N)	Longitude (E)	Geologic map unit at point location outcrop	Reference
Unnamed	51.9948	68.3585	Vladimirov Suite	Babiʹchev and others (1970b)
Altynkazgan	51.7333	67.9726	Kayraktin Suite	Mikhailov and Litvinovich (1963), Bogdanov and others (1973), Seltmann and others (2009)
Borisovskoe	51.8758	68.541	Vladimirov Suite	Babiʹchev and others (1970b), Bogdanov and others (1973)
Kenen	50.4776	68.1014	Vladimirov Suite	Mazarovich (1958b), Bogdanov and others (1973), Marochkin and others (1994), Rundkvist (2001), Syusyura and others (2010), Bogdanov and Feoktistov (1972), Seyfullin and others (1974), Kirkham and others, 2008)
Kieilin	51.6705	67.5291	Kayraktin Suite	Mikhailov and Litvinovich (1963)
Kiyminskoe	51.6687	67.6036	Kayraktin Suite	Mikhailov and Litvinovich (1963), Rundkvist (2001), Marochkin and others (1994)
Kopkazgan	50.3702	68.0068	Vladimirov Suite	Mazarovich (1958b), Bogdanov and Feoktistov (1972), Seyfullin and others (1974), Seltmann and others (2009), Kirkham and others (2008), Syusyura and others (2010), Bogdanov and others (1973)
Proletarskoe	52.0054	68.2955	Vladimirov Suite	Syusyura and others (2010)
Proletarskoe V	51.9662	68.3663	Vladimirov Suite	Babiʹchev and others (1970b)

Grade and Tonnage Model for Sandstone Copper Deposits

Because grade and tonnage data are not available for prospects in the Teniz Basin area, a global grade and tonnage for 70 sandstone subtype copper deposits is used in this assessment (appendix B). Mean and median values for ore tonnage are 77 and 10 million metric tons, respectively (fig. 9). Mean and median copper grades are 1.4 and 1.2 percent. Distributions of ore tonnage, copper grade, and contained copper are all positively skewed and consistent with a lognormal model. Cobalt and silver are important coproducts of some sediment-hosted stratabound copper deposits, but concentration data are missing for 96 and 73 percent, respectively, of the cobalt and silver deposits used for the global database. Log-transformed values of copper and cobalt grades do not show significant correlation with log-transformed values of tonnage.

Estimate of the Number of Undiscovered Deposits

All components and processes necessary for sediment-hosted stratabound copper ore system formation are present in the Teniz Basin. Red bed sediments or mafic volcanic rocks, such as the Early and Middle Devonian volcanic sequence that floors the basin, could be copper sources in the basin. Oxidized brines, derived from evaporitic rocks interbedded with the red beds, are capable of leaching and transporting metals from red bed sediments and volcanic rocks because of their high oxidation state and high anion concentration. Residual brines, formed through dewatering in response to sediment loading, and capable of dissolving and transporting copper in solution, may have become chloride- and sulfate-enriched by moving through the thick Permian Kayraktin and the Lower to Middle Carboniferous Kirey Suites (southern part of basin) in which tabular gypsum (anhydrite) minerals have been reported (Zharkov, 1988) (table 1). Widespread mineral occurrences indicate that formation waters redistributed copper within the basin. Hydrocarbon accumulation in the aquifer facies rocks, at the time of copper mineralization, is possible. Potential petroleum source rocks include Lower Carboniferous bituminous carbonate units and Lower Carboniferous coal-bearing units found near the southern margin of the basin (Oil & Gas Journal, 1995; Kushev, 1963). The 14 horizons of gray beds (red beds bleached by migrating hydrocarbons) in the Valdimirov Suite resemble, in appearance and position, gray beds in the Chu-Sarysu Basin that are important ore hosts (Box and others, 2012). A methane show, from a Middle Carboniferous interval penetrated in a stratigraphic test hole, indicates that rocks in the basin locally developed hydrocarbon accumulations (Oil & Gas Journal, 1995).

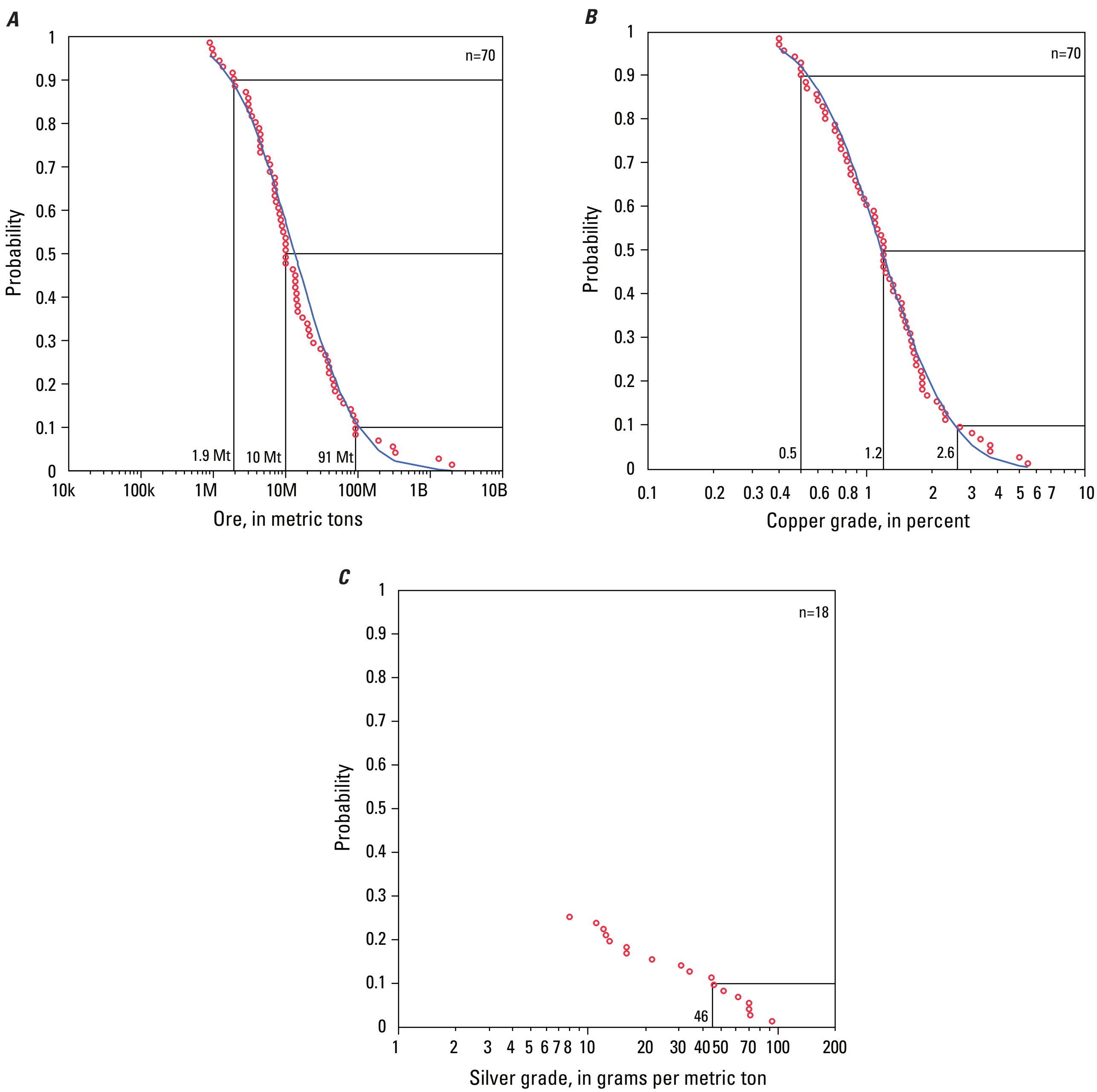


Figure 9. Cumulative frequency plots of ore tonnage (*A*), copper grade (*B*), and silver grade (*C*), for 70 sediment-hosted sandstone copper deposits. Percentiles (10th, 50th, and 90th) of measured values are labeled along the x-axis. Each red circle is a data point for a deposit; the blue curve is the calculated lognormal distribution based on the population parameters of the data. Values for tonnage and grade for the 90th, 50th, and 10th probability values of the distribution are illustrated by extending a horizontal line from the vertical axis to the data curve, then drawing a vertical line to the horizontal axis. The value for the point where the vertical line intersects the horizontal axis is labeled. k=thousands, M=millions, Mt=million metric tons, B=billions.

The association of known prospects and occurrences with anticlines and fault-related features suggests that structural traps, where petroleum may have accumulated, also controlled ore formation. The entire Kazakhstan area was under constant tectonic adjustment throughout the Paleozoic, as evident by the extensive suturing, faulting, folding, and refolding (Allen and others, 2001; Filippova and others, 2001). Any one or combination of deformation events could have initiated the flow of oxidizing brines, provided pathways for brines and reductants, and formed structural traps for copper mineralization.

Structures associated with known prospects and occurrences highlight the most prospective areas and help delineate areas with higher sediment-hosted stratabound copper mineral potential in the permissive tract. For example, fold structure traces and axes on a map we created from isodepth maps (fig. 4) correspond to, and sometimes follow trend with, copper prognostic areas defined in mapping by Syusyura and others (2010) (fig. 10). Seismic surveys show that similar structural features are present in the eastern part of the basin, where they are covered by younger sediments. Additional geophysical studies of the eastern Teniz Basin would facilitate evaluation of this underexplored area.

Undiscovered Deposit Estimate

In October, 2011, an expert panel (appendix D) met to estimate the number of undiscovered, sandstone subtype, sediment-hosted stratabound copper deposits in the permissive tract. After discussing the geology of the area and the deposit model, assessment team members made individual, subjective estimates of the minimum number of sandstone subtype copper deposits that 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 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 present in a permissive tract.

Each person made initial estimates without sharing results; then, results were compiled and discussed. This discussion almost always reveals information or insight not held by all panelists. Once team consensus was achieved, individual results were adjusted (table 4) and a consensus estimate was established for the simulation process (table 5; fig. 11). The consensus undiscovered deposit estimate reflects both the uncertainty and favorability of the tract (Singer, 1993; Singer and Menzie, 2010).

Final team estimates of undiscovered deposits are summarized in table 5, along with statistics that describe mean expected numbers of undiscovered deposits, the standard deviation and coefficient of variation associated with the estimate, and the number of known deposits. The assessment predicts a mean of nine undiscovered sandstone subtype copper deposits in the Teniz Basin.

Estimate Rationale

The tract has nine identified significant prospects (table 3). Many of them are called small deposits in mineral occurrence compilations (tables 2 and 3) and we infer that a mineral inventory has been determined for some of them. Because we do not have grade and tonnage information, we consider them to be undiscovered deposits, and assign a high level of confidence to that designation. Four sites are described as small deposits in several of the mineral occurrence datasets; this information constrained the estimate to three deposits at the 90th percentile. The number of structures that could localize undiscovered deposits, the lack of exploration at depth in the western part of the basin, and the complete lack of exploration under shallow cover in the eastern part of the basin (fig. 7) led the team to estimate 20 deposits at the 10th percentile.

Quantitative Assessment Simulation Results

Probable amounts of undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered sandstone-copper deposits with the sediment-hosted copper, sandstone subtype model (Zientek, Hayes, and Taylor, 2013) using the EMINERS program (Root and others, 1992; Duval, 2012). Simulation results are reported at selected quantile levels, along with the mean expected amount of metal, the probability of the mean, and the probability of no metal. The amount of metal reported at each quantile represents the least amount of metal expected. Results of the Monte Carlo simulation are presented with a cumulative frequency plot and histogram (figs. 12 and 13). The cumulative frequency plots show estimated resource amounts associated with cumulative probabilities of occurrence, as well as the mean, for copper and total mineralized rock tonnage.

Discussion

This probabilistic assessment of undiscovered sandstone subtype of sediment-hosted stratabound copper deposits in the Teniz Basin indicates that a modest amount of undiscovered resource may be present (table 6). The mean estimate of undiscovered copper resources in the study area is 8.9 million metric tons. By comparison, the Chu-Sarysu Basin has identified 27.6 million metric tons of copper resources, with a mean estimate of 60.5 million metric tons of undiscovered copper (Box and others, 2012).

Assessment results are consistent with previous evaluations of copper resource potential in the Teniz Basin.

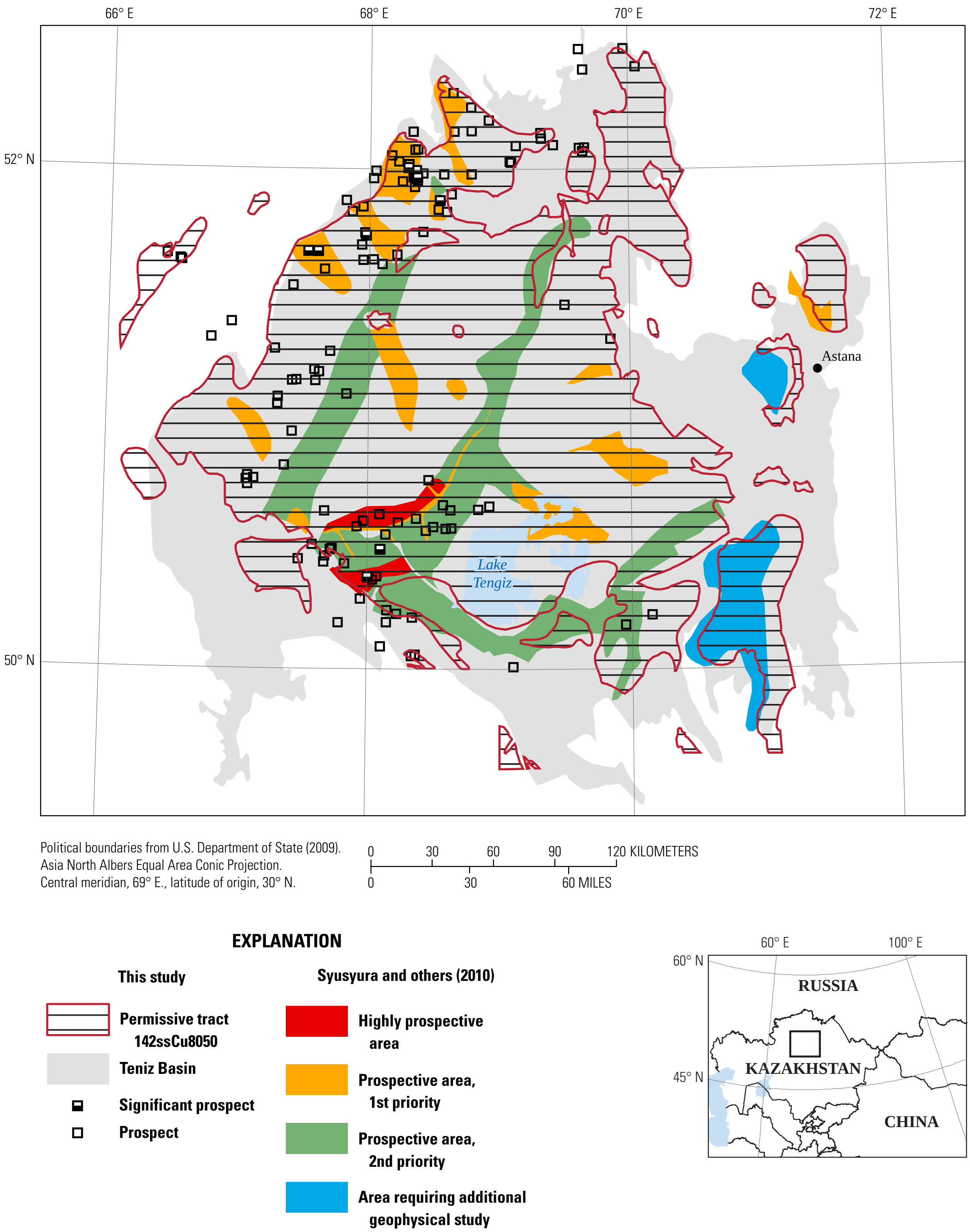


Figure 10. Map showing tract 142ssCu8050 (TZ-1) and prospects in relation to prospective areas as defined by Syusyura and others (2010). Extent of the Teniz Basin is from Fugro Robertson, Ltd. (2008).

Table 4. Estimates by individual assessment team members of the number of undiscovered sandstone copper deposits in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan.

[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_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%
3	7	15	15	15	8	4.4	56
3	7	12	12	12	7.1	3.3	47
2	4	8	10	10	4.6	2.7	58
3	5	20	20	20	8.7	6.5	75
5	8	20	20	20	10	5.8	56

Table 5. Consensus estimate of the number of undiscovered sandstone copper deposits in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan.

[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; N_{und}, *s*, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics				
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	*s*	C_v%	N_{known}	N_{total}
3	6	20	20	20	9.1	6.4	71.0	0	9.1

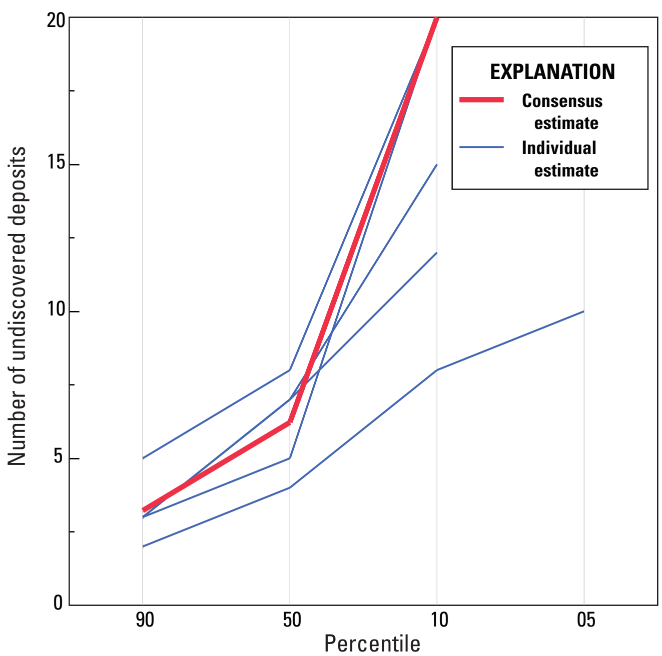


Figure 11. Graph comparing individual and consensus estimates of number of undiscovered sandstone copper deposits in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan.

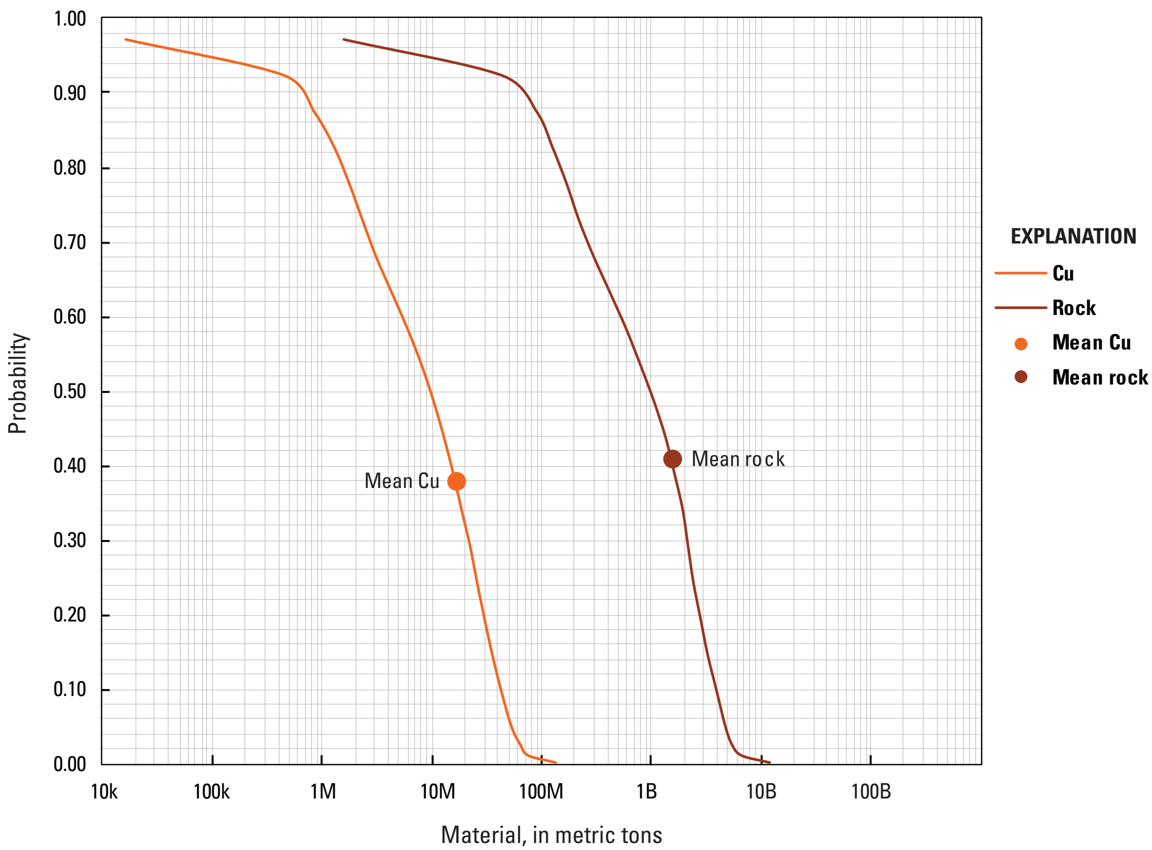


Figure 12. Cumulative frequency plot showing the results of a Monte Carlo computer simulation of undiscovered sandstone copper resources in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan. k=thousands, M=millions, B=billions.

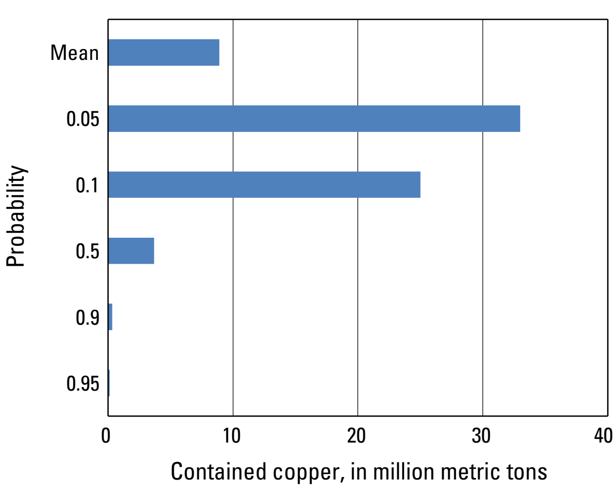


Figure 13. Histogram showing the results of a Monte Carlo computer simulation of undiscovered sandstone copper resources in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan.

Table 6. Results of Monte Carlo simulations of undiscovered resources in sandstone copper deposits in tract 142ssCu8050 (TZ-1), Teniz Basin, Kazakhstan.

[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)	130,000	330,000	3,700,000	25,000,000	33,000,000	8,900,000	0.31	0.03
Ag (t)	0	0	2,300	20,000	33,000	7,500	0.27	0.19
Rock (Mt)	10	29	320	2,200	2,800	780	0.34	0.03

Previous prognostic resource estimates (P_1+P_2) for the Teniz copper ore cluster proposed 500,000 metric tons of copper (Information and Analysis Center of Geology and Mineral Resources of the Republic of Kazakhstan, 2008). This agency follows the resource and reserve classification system used in the former Soviet Union and other COMECON countries, in which prognostic resources are divided into two categories, P_1 and P_2 (Diatchkov, 1994; Jakubiak and Smakowski, 1994; Henley and Young, 2009). Prognostic resources are inferred from indirect indications of mineralization (such as geochemical or geophysical anomalies), mineral occurrences, or isolated sampling and are equivalent to undiscovered resources in the classification of mineral resources used by the USGS (U.S. Bureau of Mines and U.S. Geological Survey, 1976). Resources under the P_1 category may be adjacent to and extend beyond the limits of drill-indicated resources and can be considered more certain. Resources under the P_2 category represent possible mineral structures in known mineral deposit or ore-bearing regions and are more conjectural than those in the P_1 category (Diatchkov, 1994). Our estimate of contained copper at the 90th percentile, 330,000 metric tons, is similar to the (P_1+P_2) prognostic resource estimate for the same region as calculated by the Government of Kazakhstan.

The small resource estimate for the Teniz Basin was influenced by several factors. Firstly, development of the giant Dzhezkazgan sandstone copper deposit, and exploration for nearby deposits in the Chu-Sarysu Basin, may have impeded exploration in the Teniz Basin. Additionally, concepts of ore genesis may have restrained exploration interest in this area. The syngenetic model was invoked in early papers on mineralization in the basin and genetic concepts emphasizing the hydrothermal nature of sediment-hosted stratabound copper deposits have been accepted since the initial exploration of that area was conducted. Recent seismic surveys show many potential structural traps that could localize sandstone subtype copper deposits that were not considered targets when exploration was conducted in the 1950s. Furthermore, the far-eastern half of the basin is buried under an undetermined thickness of unconsolidated Neogene and Quaternary sedimentary cover, adding significantly to the difficulties of minerals exploration.

With the available information, it is difficult to rigorously classify known prospects as sandstone subtype or red bed-type occurrences. Descriptive information is available for only 6 of the 100 or more mineral occurrences, and the extent and results of exploration activities conducted in the middle part of the last century are virtually unknown. Future assessments of the prospectivity of this region will be significantly enhanced if this information is found. Ideally, assessments are repeated on a recurring basis, at a variety of scales, because available data change over time and different datasets can affect assessment results.

Acknowledgments

USGS colleagues Stephen Box, George Breit, Susan Hall, and Jane Hammarstrom, served as the Assessment Oversight Committee to review the preliminary assessment results. Heather Parks, Kassandra Lindsey, and Michael Landkammer helped prepare the illustrations in this report. George Breit, and Susan Hall provided helpful and timely technical reviews of the final report. Series edit by Kathleen M. Johnson.

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Appendixes A–E

Appendix A. Principal Sources of Information Used by the Assessment Team

Table A1. List of principal sources used to compile database.

Theme	Name or title	Scale	Citation
Mineral occurrences	Maps of mineral resources of USSR, Ulutau-Kokchetav Series	1:200,000	Babi′chev and others (1970); Mazarovich (1958); Mikhailov (1951, 1963); Minervin (1961); Vavic and Rosen (1963)
	Mineragenetic map of Russian Federation and adjacent states	1:2,500,000	Rundkvist (2001)
	Mineral deposits database and thematic maps of Central Asia	1:1,500,000	Seltmann and others (2009)
	Geological map of the Russian Federation, new series, sheet M-(41),42 Tselinograd (Akmola), Map of Mineral Resources	1:1,000,000	Marochkin and others (1994)
	TZ_Cu-deposits.shp	1:1,500,000	Syusyura and others (2010)
Geology	Geological-mineragenetic map of the Teniz sedimentary basin with elements of forecast for stratiform copper mineralization	1:1,500,000	Syusyura and others (2010)
	Interpretation of fold axes based on isodepth maps	1:1,000,000	This study
Geophysics	Isodepth map of T_1 reflector as interpreted from seismic surveys	1:1,500,000	Syusyura and others (2010)
Exploration	Stratigraphic and exploration borehole collar locations	1:500,000	Syusyura and others (2010)

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Appendix B. Grade and Tonnage Model for Sandstone Copper Deposits

Description

The grade and tonnage model used for this assessment is based on 70 known sandstone copper deposits (table B1) and resource estimates that were available through the end of 2011. Sites with estimated resources of less than 10,000 metric tons of contained copper are not included in the model because they may not be fully explored or of economic interest in current market conditions.

Spatial aggregation rules are applied to ensure that deposits in grade and tonnage and spatial density models correspond to deposits as geologic entities. These rules are essential to complete an assessment in which the estimated number of undiscovered deposits is consistent with the grade and tonnage model (Singer and Menzie, 2010). For this dataset, a 500-m aggregation rule was used by measuring either from the edge of a deposit polygon or between points representing deposit locations. Aggregated deposits are labeled "*" in the Site column in table B1.

For all sandstone copper deposits identified worldwide, the mean and median values for ore tonnage are 77 and 10 million metric tons, respectively. Mean and median copper grades are 1.4 and 1.2 percent copper (table A2). Distributions of ore tonnage, copper grade, and contained copper are all positively skewed and consistent with a normal model. Cobalt and silver data are missing for 96 and 73 percent of the samples, respectively. Log-transformed values of copper and cobalt grades do not show significant correlation with log-transformed values of tonnage. The grade and tonnage distributions are illustrated as cumulative frequency plots in figure 9.

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Table B1. Deposit data used to develop grade and tonnage model for sandstone copper deposits.

[t, metric tons; %, percent; g/t, grams per metric ton; *, site includes multiple deposits, aggregated using the 500-m spatial separation rule; DRC, Democratic Republic of the Congo; –, no data]

Deposit name	Site	Country	Ore (t)	Copper grade (%)	Silver grade (g/t)
Bwana Mkubwa		Zambia	8,600,000	3.34	–
Cashin		United States	7,141,000	0.53	–
Cattle Grid		Australia	7,200,000	1.90	8.0
Centennial		United States	24,415,944	0.59	–
Chejiang		China	3,022,321	1.12	–
Chibuluma South		Zambia	7,365,766	3.70	–
Chibuluma—Chibuluma West	*	Zambia	19,922,000	3.69	–
Chifupu		Zambia	1,936,000	3.05	–
Christiadore		Namibia	1,200,000	2.30	–
Copper Gulch		United States	13,608,000	0.53	51.4
Dacun		China	12,777,778	1.80	–
Datongchang		China	14,810,833	1.20	–
Dzhezkazgan		Kazakhstan	2,000,000,000	1.10	–
East Sary Oba		Kazakhstan	91,400,000	0.85	–
Fitula		Zambia	4,500,000	5.00	–
Geyiza		China	3,120,000	1.00	–
GTO		United States	4,463,000	0.84	–
Haojiahe		China	14,101,852	1.08	–
Horizon Basin		United States	10,069,920	0.60	61.7
Itauz		Kazakhstan	94,140,000	0.92	–
Itawa		Zambia	40,000,000	0.76	–
JF		United States	13,600,000	0.40	44.6

Table B1. Deposit data used to develop grade and tonnage model for sandstone copper deposits.—Continued

[t, metric tons; %, percent; g/t, grams per metric ton; *, site includes multiple deposits, aggregated using the 500-m spatial separation rule; DRC, Democratic Republic of the Congo; –, no data]

Deposit name	Site	Country	Ore (t)	Copper grade (%)	Silver grade (g/t)
Jiuquwan		China	10,076,923	1.17	–
Juramento		Argentina	44,700,000	0.80	21.8
Karshoshak		Kazakhstan	8,900,000	1.46	–
Kasaria—Luansobe		Zambia	21,500,000	2.31	–
Kinsenda		DRC	35,000,000	5.50	–
Kipshakpai		Kazakhstan	38,500,000	0.94	–
Laoqingshan		China	1,377,049	1.22	–
Liuju		China	30,860,000	1.32	–
Lubembe		DRC	47,500,000	2.20	–
Malachite Pan		Namibia	3,000,000	2.10	–
Mangula		Zimbabwe	62,000,000	1.20	12.0
Mimbula	*	Zambia	46,850,000	1.20	–
Missoula National		United States	4,500,000	0.50	34.0
Mokambo North		Zambia	3,854,000	1.70	–
Mokambo Project—Mokambo South	*	Zambia	20,900,000	1.64	–
Moudin		China	14,414,063	1.28	–
Mufulira		Zambia	332,586,652	2.66	–
Mutundu North		Zambia	4,300,000	1.44	–
Mwambashi B		Zambia	14,210,000	1.78	–
Mwerkera		Zambia	7,100,000	1.53	–
Ndola East		Zambia	40,000,000	0.76	–
Niagara		United States	17,000,000	0.47	16.0
Norah		Zimbabwe	10,000,000	1.20	–
Nsato		Zambia	8,400,000	1.61	–
Oamites		Namibia	6,100,000	1.33	12.3
Okasewa		Namibia	6,000,000	1.80	–
Pitanda South		Zambia	7,060,000	1.58	–
Qingshuihe		China	969,136	1.62	–
Repparfjord		Norway	10,000,000	0.72	70.0
Rock Creek/Montanore		United States	299,000,000	0.81	71.0
Rock Peak		United States	9,888,480	0.65	92.6
Sauzal Bonito		Argentina	2,000,000	0.50	–
Sebembere		Zambia	5,700,000	1.70	–
Sentinel		United States	4,465,000	0.40	–
Shackleton		Zimbabwe	3,400,000	1.20	–
Shimenkan		China	1,000,000	1.09	–
Silverside		Zimbabwe	900,000	1.80	–
Spar Lake		United States	80,600,000	0.63	46.0
Tordillos		Argentina	9,350,000	0.42	–
Tschudi		Namibia	57,000,000	0.72	11.0
Udokan		Russia	1,300,000,000	1.45	13.0
Unkur		Russia	90,900,000	0.75	70.8
Vermilion River		United States	13,600,000	0.50	30.8
Wadi Abu Khushaybah		Jordan	8,000,000	0.65	–
West Sary Oba		Kazakhstan	86,200,000	0.89	–
Witvlei Pos		Namibia	2,800,000	1.50	–
Zhaman—Aibat		Kazakhstan	193,000,000	1.40	16.0
Zhangjiachunshengjiping		China	1,836,735	0.98	–

Table B2. Summary statistics for sandstone copper deposits.

[Mt, million metric tons; %, percent; g/t, grams per metric ton; –, no data]

	Number of deposits	Mean	Quartile						
			5th	10th	25th	50th	75th	90th	95th
Ore (Mt)	70	77	1.1	1.9	4.5	10	39	91	310
Copper grade (%)	70	1.4	0.5	0.5	0.8	1.2	1.7	2.6	3.7
Silver grade (g/t)	18	38	8.0	11	13	32	64	73	93
Cobalt grade (%)	3	0.1	–	–	–	–	0.2	0.2	0.2
Contained copper (Mt)	70	1.0	0.016	0.018	0.054	0.12	0.41	1.0	5.5

Appendix C. Description of GIS Files and Data Package

Digital data available with this report include GIS data described below and an Excel spreadsheet containing information presented in table 1.

GIS data are:

An Esri file geodatabase—a collection of various types of GIS datasets stored in a file system folder, **TZ_ssCu_Assessment.gdb**.

Two feature datasets, *Teniz_Basin_Tract_Equal_Area* and *Teniz_Basin_sedCu_prospects*, organize two feature classes representing spatial data results of this study. *Teniz_Basin_Tract_Equal_Area* contains the permissive tract (polygon) feature class, **TZ_ssCu_Tract**, and *Teniz_Basin_sedCu_prospects* contains the prospects (points) feature class, **TZ_ssCu_Prospects**.

Two shapefiles, **TZssCuTract.shp** and **TZssCuPros.shp**, correspond to feature classes and are included for convenience in the zipped data package provided. Feature classes and corresponding shapefiles are as follows:

TZ_ssCu_Tract (TZssCuTract.shp): Attributes include tract identifiers, tract name, a brief description of the basis for tract delineation, and assessment results. Attributes are briefly defined in the metadata accompanying these data.

TZ_ssCu_Prospects (TZssCuPros.shp): Attributes include the assigned tract, alternate site names, age, mineralogy, site status, comments fields, data sources and references. Attributes are briefly defined in the metadata accompanying these data.

The two feature classes (tract and prospects) are included in an Esri map document (ArcGIS Desktop 10 Service pack 3): **TZ_GIS_SIR5090-R.mxd**.

The complete data package may be downloaded from the USGS website as zipped file **sir2010-5090R_gis.zip**.

Appendix D. Short Biographies for Members of the Assessment Team

Arthur A. Bookstrom is a research geologist with the USGS in Spokane, Washington. He received his degrees in geology from Dartmouth College, the University of Colorado, and Stanford University. He is an economic geologist with expertise on porphyry-related deposits and mineral resource assessment.

Pamela M. Cossette is a biologist, geologist, geographer, and geographic information systems (GIS) specialist with the USGS in Spokane, Washington. She received her degree in geology from Eastern Washington University.

Timothy S. Hayes is a research geologist with the USGS in Tucson, Arizona. He received his degrees in geology from the South Dakota School of Mines and Stanford University. He is an economic geologist with expertise in sediment-hosted copper deposits.

Gilpin R. Robinson, Jr., is a research geologist, geochemist, and mineral resources specialist with the USGS in Reston, Virginia, USA. He received his degrees in geology from Tufts University and Harvard University. He works on mineral resource assessment and other projects, including geologic mapping, studies of the origin and genesis of metal and industrial mineral deposits, and geochemical modeling.

John C. Wallis is a geologist and geographic information systems (GIS) specialist with the USGS in Spokane, Washington, USA. He received his degree in geology from Eastern Washington University.

Michael L. Zientek is a research geologist with the USGS in Spokane, Washington. He received his 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. He is co-chief of the USGS Global Mineral Resource Assessment Project.

Appendix E. Assessment Terminology

Terminology used in the Global Mineral Resource Assessment Project is adapted from definitions established for mineral resource assessments conducted by the U.S. Geological Survey using the 3-part form of mineral resource assessment (Singer, 1993), fundamental definitions for mineral deposit models (Cox and Singer, 1986), and definitions for a mineral resource classification established by the U.S. Bureau of Mine and U.S. Geological Survey (1976). Other definition sources for terms are noted.

Cost models Capital and operating cost equations that estimate the cost to develop a mineral deposit given its tonnage, grade, mining and milling methods, and depth. (Singer, written comm., 6/11/2007). Simplified cost models for mining and beneficiation (milling) can be used to calculate the proportion of resources contained in a deposit model that might be economically produced at stated conditions (D.W. Menzie, written commun., 2005).

Cumulative past production Total amount of all past production (U.S. Geological Survey National Mineral Resource Assessment Team, 2000).

Cumulative probability distributions for resource estimates Graphical depictions of estimated resource volumes presented with associated cumulative probabilities of occurrence. The distributions are used to derive the percent (95, 90, 50, 10, 5), and mean resource levels reported: a low case, with a 95 percent probability of that amount or more occurring (a 19 in 20 chance); a high case, with a 5 percent probability of that amount or more occurring (a 1 in 20 chance); and a mean case representing an arithmetic average of all possible outcomes weighted by their probabilities (U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995).

Cutoff grade (a) Any grade that, for any specified reason, is used to separate two courses of action, for example, to mine or to leave, to mill or to dump; also, any of a series of grades used to truncate a frequency distribution, or to separate mineralized materials into graded fractions (Taylor, 1972). (b) The lowest grade, or quality, of mineralized material that qualifies as economically mineable and available in a given deposit. May be defined on the basis of economic evaluation, or on physical or chemical attributes that define an acceptable product specification (Committee for Mineral Reserves International Reporting Standards, 2006). (Please be aware that a growing consortium of the minerals industry now uses the second, more restricted definition of this term).

Deposit density models Frequency distribution of number of deposits from the grade and tonnage model per unit of permissive control area. These models are commonly applied in a regression of number of deposits versus area permissive. These models are used to estimate the number of deposits or guide estimation. (D.A. Singer, written comm., 2007)

Descriptive mineral deposit model A set of data in a convenient form describing a group of mineral deposits having similar characteristics (U.S. Geological Survey National Mineral Resource Assessment Team, 2000). The model identifies the geologic environments in which the deposit type is a found and provides identifying characteristics of the type.

Discovered resources Total amount of identified resources and cumulative past production (U.S. Geological Survey National Mineral Resource Assessment Team, 2000).

Giant deposit A mineral deposit whose contained metal content ranks in the upper 10 percent of all known deposits. Accordingly, giant gold deposits contain at least 100 t of gold, giant silver deposits contain more than 2,400 t (77 Moz) of silver, and giant copper, zinc, and lead deposits contain at least 2, 1.7, and 1 Mt of their respective metals (Singer, 1995). Synonym: World-class deposit.

Grade and tonnage model Frequency distributions of pre-mining tonnages, and average grades of well-explored deposits of a given type, that are used to model grades and tonnages for undiscovered deposits of the same type, in geologically similar settings. Models are constructed on the basis of average grades of each commodity of possible economic interest and associated tonnage based on total production, reserves, and resources at the lowest possible cutoff grade (Singer and Berger, 2007). Mineral deposits in grade and tonnage models should be completely characterized in terms of location, tonnage, and grade.

Grade Average metal content measured as a percentage of weight of a given volume of mineralized rock. It is estimated by analyzing samples of the deposit. (D.W. Menzie, written commun., 2005).

Identified resources Resources whose location, grade, quality, and quantity are known or can be estimated from specific geologic evidence (U.S. Bureau of Mines and U.S. Geological Survey, 1976).

Metal endowment The sum of metal in all occurrences with specified characteristics, such as concentration, size, and depth (Harris, 1984).

Mineral deposit (a) 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 Singer, 1986). (b) A mass of naturally occurring mineral materials, for example, metal ores or nonmetallic minerals, usually of economic value, without regard to mode of origin (Bates and Jackson, 1987). (c) 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).

Mineral deposit type (a) Deposits sharing a relatively wide variety and large number of attributes (Cox and Singer, 1986). (b) A class representing all the recognized mineral deposits that are defined by physical and genetic factors that can be consistently differentiated from those of other classes or deposit types (Barton and others, 1995).

Mineral occurrence (a) A concentration of a mineral that is considered valuable by someone somewhere, or that is of scientific or technical interest (Cox and Singer, 1986). (b) Any ore or economic mineral in any concentration found in bedrock or as float; especially a valuable mineral in concentration sufficient to suggest further exploration (Bates and Jackson, 1987).

Mineral prospect (a) An area that is a potential site of mineral deposits, based on mineral exploration (Bates and Jackson, 1987). (b) Sometimes, an area that has been explored in a preliminary way but has not given evidence of economic value (Bates and Jackson, 1987). (c) An area to be searched by some investigative technique, for example, geophysical prospecting (Bates and Jackson, 1987). (d) A geologic or geophysical anomaly, especially one recommended for additional exploration (Bates and Jackson, 1987). (e) A mineral property whose value has not been proved by exploration (BLM, 1999).

Mineral reserve Mineral reserves are estimates of mineral as mined (allowing for losses and dilution) (Committee for Mineral Reserves International Reporting Standards, 2006).

Mineral resource (a) A concentration of naturally occurring mineral material in or on the Earth's crust in such form that economic extraction of a commodity from the concentration is currently or potentially feasible (Modified from U.S. Bureau of Mine and U.S. Geological Survey, 1976 by adding the word mineral). (b) A concentration or occurrence 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 knowledge (Committee for Mineral Reserves International Reporting Standards, 2006). (Please be aware that a growing consortium of the minerals industry now uses the second, more restricted definition of this term).

Mineralization (a) Any single mineral or combination of minerals occurring in a mass, or deposit, of economic interest. The term is intended to cover all forms in which mineralization might occur, whether by class of deposit, mode of occurrence, genesis or composition (Committee for Mineral Reserves International Reporting Standards, 2006). (b) The process or processes by which a mineral or minerals are introduced into a rock, resulting in a valuable or potentially valuable deposit (Bates and Jackson, 1987).

Mineral-resource assessment A study that estimates or evaluates the amount and (or) potential supply of mineral resources within a specific volume of the Earth's crust.

Number of undiscovered mineral deposits estimates The probability, or degree of belief, that a fixed but unknown number of deposits like those in the grade and tonnage model exist in the delineated tracts (D.W. Menzie, written commun., 2005).

Ore (a) A mineral assemblage of actual or potential economic interest (Taylor, 1972). (b) The naturally occurring material from which a mineral or minerals of interest can be extracted at a reasonable profit (Bates and Jackson, 1987).

Ore deposit (a) A mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit (Cox and Singer, 1986). (b) A mineral deposit of high enough quality to mined at a profit (BLM, 1999).

Permissive tract A geographic area delineated such that the probability of deposits of the type delineated occurring outside the boundary is negligible (that is, less than 1 in 100,000 to 1,000,000) (Singer, 1993). The delineated area represents the surface projection of a part of the Earth's crust and overlying surficial materials that corresponds to a geologic environment described in a published deposit model; consequently, depth from surface is an essential part of a tract definition. A permissive tract can be subdivided into two or more parts that have different kinds of information or possibly different numbers of undiscovered deposits.

Quantitative assessment of undiscovered resources A study that presents a numerical estimate of the amount and quality of undiscovered mineral resources present within a specific volume of the Earth's crust; because of the uncertainty inherent in assessment of unknown resource, the results are presented probabilistically.

Resource A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form that economic extraction of a commodity from the concentration is currently or potentially feasible (U.S. Bureau of Mines and U.S. Geological Survey, 1976).

Resource uncertainty Uncertainty means variability or being unknown; in mineral resource assessments it refers to possible locations of undiscovered resources and to the amounts and qualities of these resources. Location uncertainty is addressed by permissive tracts, and uncertainty of amounts and qualities is addressed by estimates of undiscovered deposits and grade and tonnage models (See Cunningham and others, 2008, for example).

Significant deposit A mineral deposit whose contained metal content ranks in the upper 99 percent of all known deposits. Accordingly, significant gold deposits contain at least 2 t of gold, significant silver deposits contain more than 85 t of silver, and significant copper, zinc, and lead deposits contain at least 50,000, 35,000, and 50,000 t of their respective metals (Long and others, 2000).

Spatial rule An operational spatial rule developed to ensure that deposits in grade and tonnage and spatial density models correspond to deposits as geologic entities (Singer and Menzie, 2010).

Supergiant deposit A mineral deposit whose contained metal content ranks in the upper 1 percent of all known deposits. Accordingly, supergiant gold deposits contain at least 1,200 t of gold, supergiant silver deposits contain more than 22,000 t of silver, and supergiant copper, zinc, and lead deposits contain at least 24, 12, and 7 Mt of their respective metals (Singer, 1995).

Tonnage Weight of a volume of mineralized rock (D.W. Menzie, written commun., 2005).

Undiscovered mineral deposit (a) A mineral deposit that may exist within a specified volume of Earth's crust (for example, 1 km or less from the surface of the ground). (b) An incompletely explored mineral occurrence or prospect that could have sufficient size and grade to be classified as a deposit. (c) A mineral deposit whose location and (or) grade, quality, and quantity of mineralized material are unknown or incompletely characterized.

Undiscovered resource (a) Resources in undiscovered mineral deposits whose existence is postulated on the basis of indirect geologic evidence (U.S. Geological Survey National Mineral Resource Assessment Team, 2000). (b) Mineralized material whose location, grade, quality, and quantity are unknown or incompletely characterized.

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Menlo Park Publishing Service Center, California
Manuscript approved for publication, June 9, 2014
Edited by Sarah E. Nagorsen and Chet Zenone
Layout and design by Sharon L. Wahlstrom

USGS

Cossette and others—**Sandstone Copper Assessment of the Teniz Basin, Kazakhstan**—Scientific Investigations Report 2010–5090–R

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20105090R