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Undiscovered porphyry copper resources in the Urals—A probabilistic mineral resource assessment

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ABSTRACT

A probabilistic mineral resource assessment of metal resources in undiscovered porphyry copper deposits of the Ural Mountains in Russia and Kazakhstan was done using a quantitative form of mineral resource assessment. Permissive tracts were delineated on the basis of mapped and inferred subsurface distributions of igneous rocks assigned to tectonic zones that include magmatic arcs where the occurrence of porphyry copper deposits within 1 km of the Earth's surface are possible. These permissive tracts outline four north-south trending volcano-plutonic belts in major structural zones of the Urals. From west to east, these include permissive lithologies for porphyry copper deposits associated with Paleozoic subduction-related island-arc complexes preserved in the Tagil and Magnitogorsk arcs, Paleozoic island-arc fragments and associated tonalite-granodiorite intrusions in the East Uralian zone, and Carboniferous continental-margin arcs developed on the Kazakh craton in the Transuralian zone. The tracts range from about 50,000 to 130,000 km^2 in area. The Urals host 8 known porphyry copper deposits with total identified resources of about 6.4 million metric tons of copper, at least 20 additional porphyry copper prospect areas, and numerous copper-bearing skarns and copper occurrences.

Probabilistic estimates predict a mean of 22 undiscovered porphyry copper deposits within the four permissive tracts delineated in the Urals. Combining estimates with established grade and tonnage models predicts a mean of 82 million metric tons of undiscovered copper. Application of an economic filter suggests that about half of that amount could be economically recoverable based on assumed depth distributions, availability of infrastructure, recovery rates, current metals prices, and investment environment.

1. Introduction

1.1. Porphyry copper deposits in the Urals

The Ural Mountains expose one of the world's best preserved Paleozoic metallogenic belts. The 2000-km-long mobile belt that separates the eastern European and western Siberian cratons hosts ore deposits formed in island-arc, continental-margin arc, and syn- and post-collisional geodynamic settings that record a complex history of subduction, accretion, arc-continent collisions, and ocean basin closures. Magmatism associated with these events produced world-class VMS deposits, magmatic chromite deposits, PGE-Fe-Ti deposits associated with mafic and ultramafic rocks, massive magnetite deposits, and porphyry copper deposits (Herrington et al., 2005b). Although the copper in the Urals region is mainly produced from volcanogenic massive sulfide (VMS) deposits, recent discoveries suggest that it may also be an important porphyry copper province. In addition to copper, the porphyry deposits in the Urals are likely a significant source of molybdenum and gold.

Paleozoic porphyry copper deposits and prospects occur throughout the eastern Urals in a series of north-south trending fault-bounded tectonic zones. These zones lie between the Main Uralian Fault on the west and the Transuralian zone and West Siberian Basin on the east (Fig. 1). The potential for undiscovered resources associated with porphyry copper deposits in the Urals was assessed by (1) outlining geographic areas

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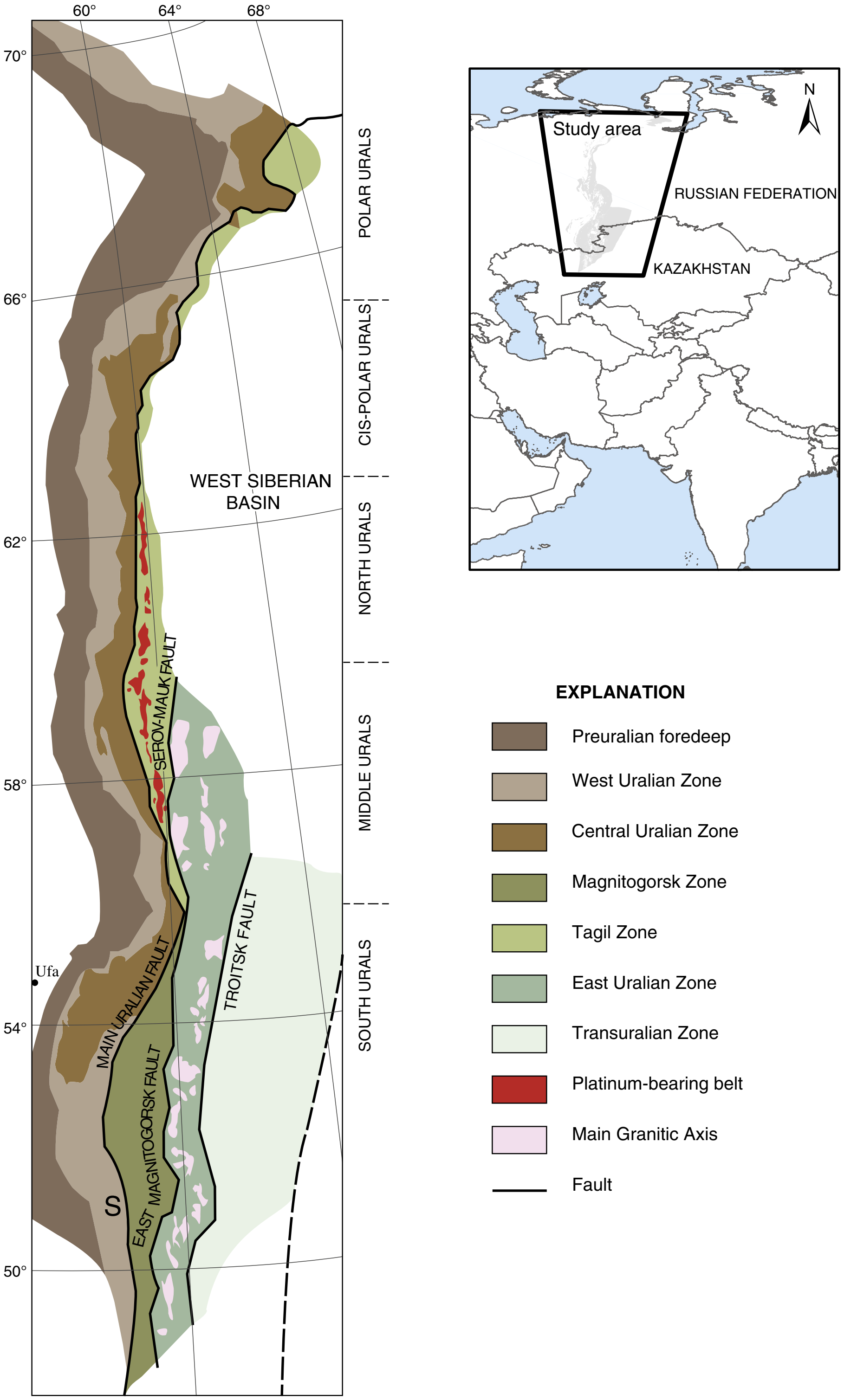


Fig. 1. Tectonic zones of the Urals. Modified from Puchkov (2009) and Herrington et al. (2005a). S, location of the Sakmara allochthon.

as permissive tracts that may host undiscovered porphyry copper deposits on the basis of geology and the distribution of known deposits and prospects, (2) estimating numbers of undiscovered deposits in those tracts, and (3) simulating amounts of undiscovered resources. In addition, an economic filter was used to evaluate the portion of the undiscovered resources that are likely to be economically recoverable based on engineering cost models (Robinson and Menzie, 2012). The Urals study was done as part of a global copper mineral resource assessment (Johnson et al., 2014).

1.2. Identified resources

Identified resources have been reported for eight porphyry copper deposits in the Urals (Table 1). Note that the identified resources for

Table 1
Identified porphyry copper resources in the Urals [t, metric tons; Mt, million metric tons, %, percent; g/t, grams per metric ton; —, no data; *, classified as a prospect by Singer et al. (2008); **, primarily a skarn deposit; for Lekyn-Talbei, resources are inferred (C2) based on data in Plotinskaya et al. (2017– in this volume)].

Tectonic zone	Name	Country	Tonnage (Mt)	Cu (%)	Mo (%)	Au (g/t)	Contained Cu (t)	Reference
Polar Central Uralian	Lekyn-Talbei*	Russia	85.6	0.54	0.009	0.1	460,000	Silaev and Andreichev (1982), Petrov et al. (2006), Singer et al. (2008), Plotinskaya et al. (2017-- in this volume)
Magnitogorsk	Yubileinoe*	Kazakhstan	10	0.41	–	6.6	41,000	Grabezhev (2007), Krivtsov (1993), Plotinskaya et al. (2014a), Seltmann et al. (2014), Shatov et al. (2014), Singer et al. (2008)
East Uralian	Tomino	Russia	331	0.47	–	0.12	1,555,700	Celtic Resources Holdings Plc. (2007), Eureka Mining Plc. (2006), Grabezhev and Borovikov (1993), Grabezhev et al. (1995), Plotinskaya et al. (2017-- in this volume)
East Uralian	Birgilda*	Russia	4.7	0.7	–	–	32,900	Grabezhev and Borovikov (1993), Grabezhev et al. (1995), Kozolov et al. (2002), Plotinskaya et al. (2014b), Romashova (1984), Singer et al. (2008), Vorob'ev et al. (1977)
Transuralian	Mikheevskoe	Russia	469	0.45	0.004	0.1	2,110,500	Celtic Resources Holdings Plc. (2007), Eureka Mining Plc. (2006), Grabezhev (2007), Grabezhev and Borovikov (1993), Girfanov et al. (1991), Lehman et al. (1999), Ocharova et al. (2008), Russian Copper Company (2014), Shargorodsky et al. (2005), Singer et al. (2008)
Transuralian	Benkala North	Kazakhstan	362	0.43	0.003	0.07	1,297,800	Grabezhev (2007), Frontier Resources Ltd. (2013)
Transuralian	Varvarinskoe	Kazakhstan	117.62	0.66	–	1.01	776,292	Dodd et al. (2005), Kazakhstan Minerals Corporation (2000), Polymetal International plc (2012), Zhukov et al. (1998)
Transuralian	Tarutino**	Russia	10	0.99	–	0.09	101,000	Herrington et al. (2005b), Polymetal International plc (2015), Plotinskaya (2017-- in this volume)
Total identified copper resources							6,400,000 metric tons of copper	

the smallest porphyry copper deposits listed in Table 1, Yubileinoe and Birgilda, were classified as porphyry copper prospects by Singer et al. (2008); Tarutino is primarily a skarn deposit. Some of the tonnage and grade data meet current internationally accepted reporting standards; other data reported in the literature use Soviet-style resource and reserve classifications. For this assessment, the term “prospect” is used for the known and suspected porphyry copper occurrences that are only partially characterized by exploration, such as those that report grade information but no ore tonnages. Undiscovered resources may be present in known prospects or in completely new areas throughout the permissive tracts.

2. Assessment strategy

2.1. Methods

The form of quantitative mineral resource assessment described by Singer and Menzie (2010) was adopted for the global mineral resource assessment of porphyry copper deposits (Johnson et al., 2014). In this form of assessment, geographic areas (permissive tracts) are delineated using available data on geologic features typically associated with the type of deposit under consideration, as reported in descriptive mineral deposit models. The amount of metal contained in undiscovered deposits is estimated using grade and tonnage models combined with probabilistic estimates of numbers of undiscovered deposits. Estimates of numbers of undiscovered deposits are made by experts at different confidence levels using a variety of estimation strategies. The estimates express the degree of belief that some fixed but unknown number of deposits exists within the tract. These estimates are a measure of the favorability of the permissive tract as well as of the uncertainty about what may exist (Singer, 2007b).

The tectonic settings, distinctive lithologies, and other diagnostic characteristics of porphyry copper deposits are based on descriptive models (John et al., 2010; Sillitoe, 2010; Cox, 1986; Panteleyev, 2005a, 2005b). Permissive tracts were outlined as geographic areas to include permissive Paleozoic igneous geologic map units and known porphyry copper deposits and prospects within a tectonic megazone (Puchkov, 2017– in this volume. See Section 3.2 for details of tract delineation.

As part of the estimation process, for each permissive tract, the assessment team reviewed the geology-based tracts with special attention to the distribution of permissive rocks, the distribution of intrusive and extrusive rocks, and the amount of cover. The nature and distribution of the deposits, prospects, and also possible porphyry-related related deposit types, such as skarns and epithermal deposits, were considered, along with the relative proportions of intrusive and volcanic rocks, which may be used as an indicator of depth of erosion.

The global grade and tonnage models for porphyry copper deposits from Singer et al. (2008) were tested to decide if they are appropriate for use in the Urals. Statistical tests comparing grades and tonnages of deposits within the Urals with grades and tonnages in the models of Singer et al. (2008) indicated that a global porphyry Cu-Au-Mo model based on 422 deposits is appropriate for the assessment of the Urals.

Monte Carlo methods are used to combine estimates of numbers of undiscovered deposits with grade and tonnage models to produce a probabilistic estimate of in-situ undiscovered resources (Root et al., 1992; Duval, 2012; Bawiec and Spanski, 2012). The results are further analyzed by applying economic filters to evaluate what portion of the in-situ undiscovered resources might be economic based on specified mining methods, metal prices, deposit depth, and quality of existing infrastructure (Robinson and Menzie, 2012).

2.2. Data

Two different packages of geologic and mineral-resource digital data were used, one for the Urals (Petrov et al., 2006) and one for Central Asia (Seltmann et al., 2015). These data packages include 1:1 million and 1:1.5 million scale geologic maps, as well as thematic maps, and mineral occurrence data. These maps were supplemented by selected geologic maps at various spatial scales (Abdulin and Zaitsev, 1976; Dragun, 1966, 1979; Dugnistaya and Maksimenko, 1965; Kozolov et al., 2002; Nalivkin, 1968; Shatov et al., 2001). In addition, regional aeromagnetic data, published journal articles, books, symposia proceedings, government publications, and information obtained from various internet web sites were used. Previous topical studies on porphyry copper deposits of the Urals provided a framework for identifying magmatic arc complexes (Herrington et al., 2005a, 2005b; Plotinskaya and Grabezhev, 2013; Plotinskaya et al., 2014a, 2014b; Puchkov, 1997, 2009, 2013, 2017–in this volume). Note that the assessment was done using information on deposits and prospects compiled as of 2014. See Table 1 of Plotinskaya et al. (2017– in this volume) for a more comprehensive list of porphyry copper occurrences in the Urals. Aeromagnetic data extracted from the magnetic anomaly grid of the Former Soviet Union (NGDC, 1997) are shown as a reduced-to-pole map for the Urals in Fig. 2, along with some of the major tectonic zones and faults.

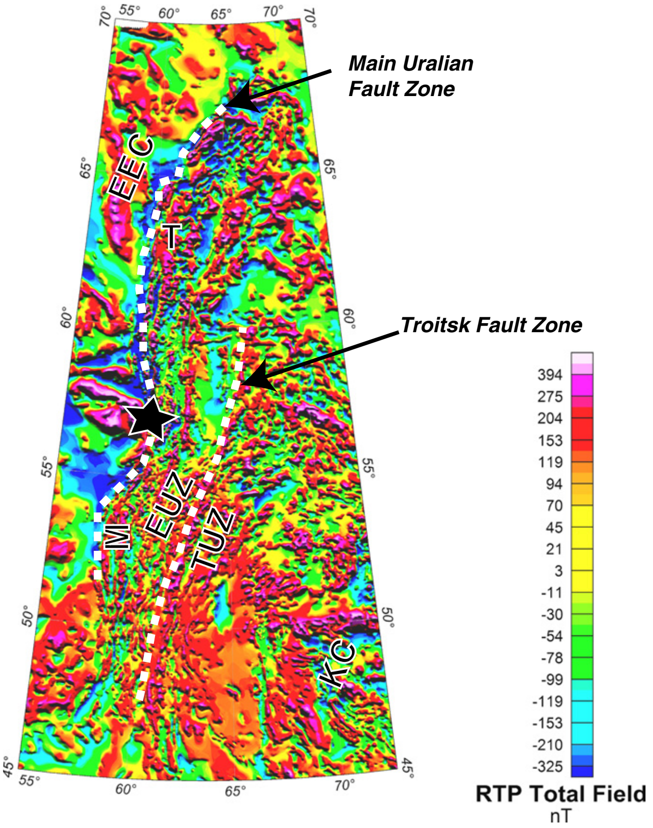


Fig. 2. Reduced-to-pole (RTP) aeromagnetic map of the Urals. Tectonic zones: EEC, East European craton; T, Tagil Zone; M, Magnitorgorsk Zone; EUZ, East Uralian Zone; TUZ, Transuralian Zone, KC, Kazakh craton. The location of the city of Yekaterinburg is shown for reference (large black star). White dashed lines, approximate traces of the Main Uralian and Troitsk Fault Zones. Note the north-south-trending prominent magnetic low that marks the trace of the Main Uralian Fault Zone separating the European craton from the accreted Tagil and Magnitogorsk zones. Data source, NGDC (1997). nT, nanotesla.

These data helped define some of the permissive tract boundaries. International boundaries are from the U.S. Department of State (2009).

3. Settings for porphyry copper deposits in the Urals

3.1. Tectonic zones

The Urals are the geographic expression of the complex tectonic boundary between the eastern European craton on the west, associated accreted terranes, and the composite Kazakh tectonic plate on the east. The Main Uralian Fault records the Late Devonian collision of the East European craton (represented by the Preuralian, West Uralian, and Central Uralian zones on Fig. 1) with accreted arc terranes to the east. VMS and porphyry copper deposits formed prior to collision (Herrington et al., 2005a). The arc terranes that host porphyry copper deposits in the Urals are preserved in several tectonic zones, referred to as volcanic arc megaterranes by Plotinskaya et al., 2017– in this volume. From west to east, these include the northern part of the Central Uralian zone and the Tagil zone in the North, Cis-Polar, and Polar Urals and the Magnitogorsk, East Uralian, and the Transuralian zones in the Middle and South Urals (Figs. 1 and 2). See Plotinskaya et al. (2017– in this volume) for a discussion of the geological framework, ages, and metallogeny of porphyry copper deposits of the Urals.

Each of these tectonic zones includes Paleozoic magmatic arcs and metallogenic belts that host porphyry copper deposits. The Tagil zone extends from the middle Urals through the northern, Cis-Polar, and Polar Urals (Fig. 1). The magmatic rocks of the Magnitogorsk zone are interpreted as the equivalent to the Tagil zone in the South Urals (Herrington et al., 2005c) and a number of authors refer to the composite Tagil-Magnitogorsk megazone (Brown et al., 2006; Plotinskaya et al., 2014a; Puchkov, 2017– in this volume).

The number, nature, and age range of magmatic arcs and arc fragments that now lie within the tectonic zones is not well-constrained because of the complex geologic history of the area. The oldest Paleozoic magmatic arc complexes recognized in the Urals are the Silurian to Middle Devonian arcs preserved in the Sakmara allochthon (S on Fig. 1) and Tagil zone. The Sakmara allochthon preserves Early Paleozoic sedimentary rocks that rifted off of the European craton to the west, mafic-ultramafic-complexes, and fragments of volcanic arc rocks that host chromite and VMS deposits west of the Main Uralian Fault (Herrington et al., 2005b). No porphyry copper deposits are known to be associated with the Sakmara zone. The Late Ordovician to Devonian Tagil arc within the Tagil zone is interpreted as an intra-oceanic arc that accreted to the Eastern European craton in the Early Carboniferous (Herrington et al., 2005a). In the Middle Urals, a Late Carboniferous to Permian strike-slip fault system reactivated the original Main Uralian suture and displaced the Tagil arc to the north (Brown et al., 2011). The Tagil zone is best known for a belt of the Silurian platinum-bearing zoned mafic-ultramafic complexes throughout the middle and northern Urals (Fig. 1) in the lower part of the Tagil arc. The arc evolved from tholeiitic to calc-alkaline to shoshonitic compositions, and includes both calc-alkaline and potassic igneous suites (Brown et al., 2011; Puchkov, 2013).

Although many authors discuss the Tagil-Magnitogorsk tectonic zone as a single entity, we describe them separately for the purposes of this assessment because they are geographically distinct, accreted at different times, and exhibit different degrees of deformation and metamorphism. Furthermore, the poorly exposed, structurally dismembered Tagil arc is much less thoroughly studied than the Magnitogorsk arc and other parts of the southern Urals.

During the Devonian, the Magnitogorsk oceanic arc was active above northeast-directed subducting ocean crust that separated it from the East European plate. By the end of the Early Carboniferous, both the Tagil and Magnitogorsk arcs were accreted to the East European craton. The suture between the East European craton (including the accreted Tagil and Magnitogorsk arcs) and the Kazakh craton lies within the East Uralian zone (EUZ) (Fig. 1). The Main Uralian fault zone in the southern Urals marks the likely continent-arc suture along which tectonic activity ceased by the Early Carboniferous (Ayarza et al., 2000; Brown et al., 2011).

The East Uralian zone includes Late Devonian to Early Carboniferous calc-alkaline tonalite-granodiorite complexes and syn- and post-collisional Permian granites that form the main granite axis of the Urals (Fig. 1). The post-collisional peraluminous Permian granites are not considered permissive for porphyry deposits. The deformed and metamorphosed fragments of oceanic island-arc rocks and Precambrian and Paleozoic continental rocks of the EUZ may represent an accretionary complex that accumulated in front of the Carboniferous Valerianovka (Valerianov) arc, a continental arc on the western margin (present day) of the Kazakh craton that lies within the Transuralian zone (Brown et al., 2006; Herrington et al., 2005a). The Early to Middle Carboniferous Valerianovka arc on the Kazakh plate is an Andean-type continental-margin arc formed by subduction of Transuralian basin rocks along an east-dipping subduction zone as the Uralian Ocean was closing (Herrington et al., 2005a). The Troitsk fault zone is the boundary between the East Uralian zone and the Transuralian zone to the east (Fig. 1). Outcrops of Valerianovka arc rocks are sparse due to extensive cover by Mesozoic and younger rocks, with the best exposures being found in the southeastern Ural Mountains in Kazakhstan.

3.2. Permissive tracts for porphyry copper deposits

Permissive tracts for Phanerozoic porphyry copper deposits in the Urals (Fig. 3) were constructed in a GIS by selecting map units that

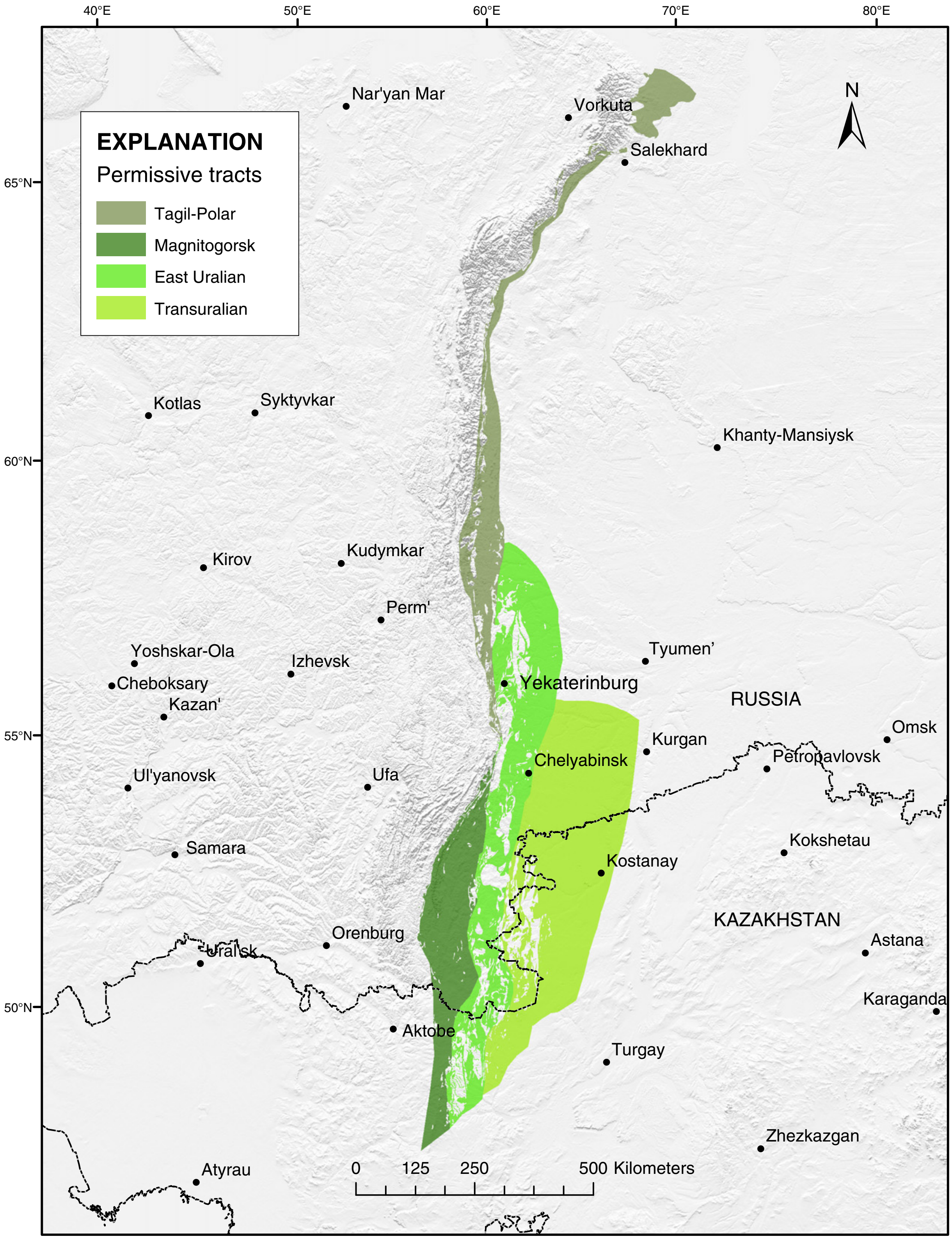


Fig. 3. Permissive tracts for porphyry copper deposits in the Urals.

contain permissive intrusive and extrusive rocks within each tectonic zone from digital geologic maps of the Urals (Fig. 4). Permissive intrusive lithologies include gabbro, gabbrodiorite, quartz diorite, diorite, quartz monzonite, monzonite, granodiorite, plagiogranite, syenite, and porphyritic variants. Porphyry copper deposits typically are not associated with gabbroic rocks. However, in the Urals, gabbros are associated with permissive diorite and plagiogranite complexes as well as with non-permissive ultramafic complexes (Fershtater et al., 2010). Stratified map units that include extrusive rocks of intermediate composition, such as andesite and dacite, and stratified formations that are described in the literature as host rocks for known porphyry copper deposits in the region were also selected. Phanerozoic granitoids generally decrease in

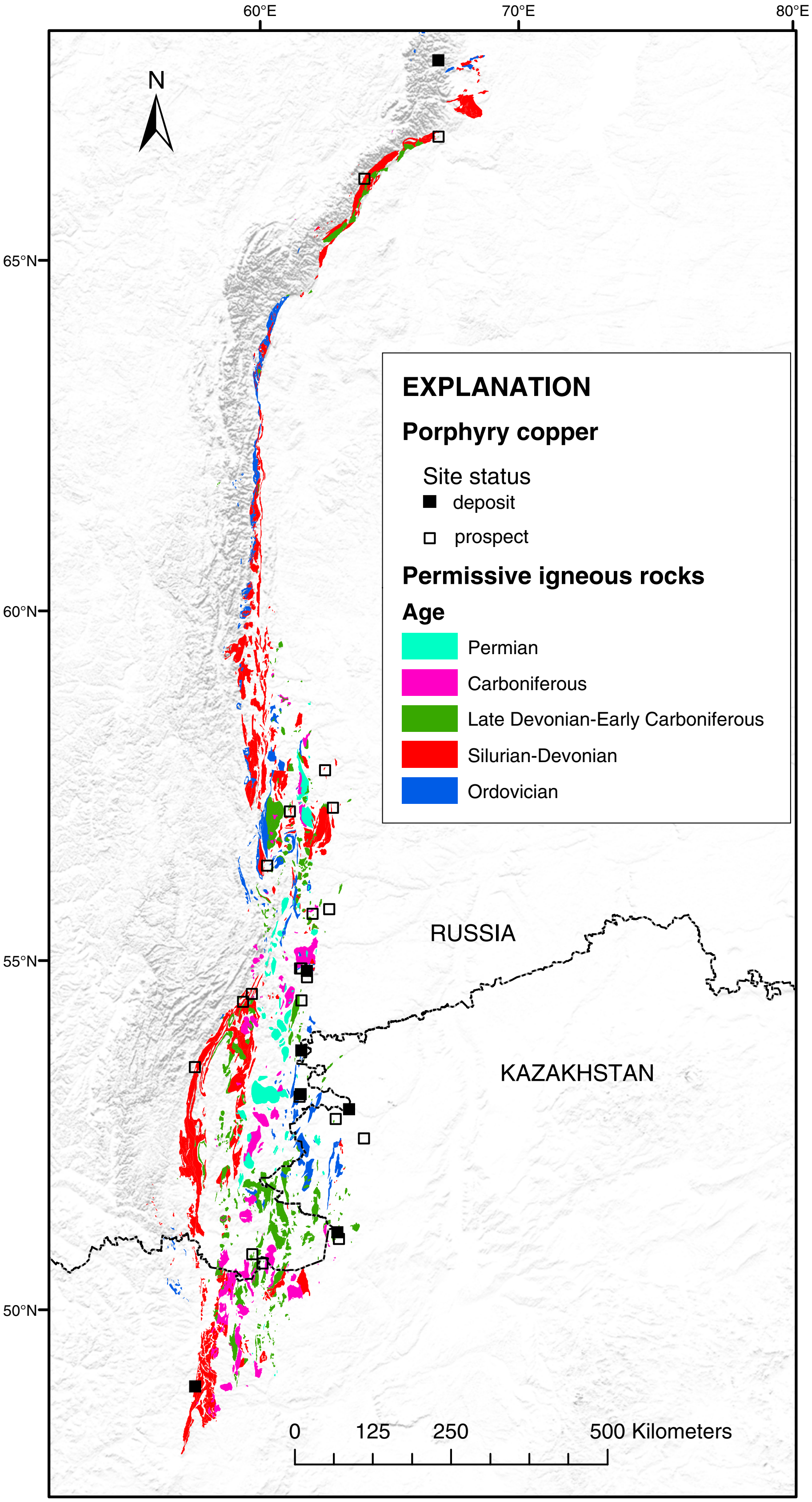


Fig. 4. Map showing Phanerozoic igneous rocks of the Urals by age. Ultramafic rocks are excluded. Stratified units that include andesitic volcanic rocks are included (data from Petrov et al., 2006). Hillshade from Danielson and Gesch (2011).

age from west to east across the Urals in the north based on ages assigned to map units (Fig. 4). In the southern Urals, where Carboniferous granitoids lie to the east of the older rocks, the eastward younging trend is punctuated by Permian granites that define the Main Granite Axis of the Urals (Fig. 1) and older rocks that may represent allochthonous island-arc fragments. Recent radiometric dating studies on porphyry deposits and associated plutons show that some deposits that were originally considered to be Devonian in age are proving to be Silurian. For example, Grabezhev et al. (2013) acquired a SHRIMP U-Pb zircon age of 428 ± 3 Ma for diorite at the Tomino porphyry copper deposit and an age of 427 ± 6 Ma for an epithermal Au-Ag deposit in the same volcanoplutonic complex. Most of the other porphyry systems that have been dated by this method have proven to be Devonian, such as the 381 ± 5 Ma Voznesenskoe porphyry copper (Kosarev et al., 2014) and the 374 ± 3 Ma Yubileinoe Au porphyry (Grabezhev, 2014).

Tract boundaries are based primarily on the megazone (or megaterrane) boundaries of Puchkov (2017– in this volume).The eastern boundaries of tracts that border the West Siberian Basin are subjective. Permissive rocks may extend an unknown distance to the east under post-Paleozoic (mainly Cretaceous) cover. Western tract boundaries are defined by megazone-bounding faults. The tracts contain "holes" that represent non-permissive rocks that were excluded from the tracts. The holes represent Precambrian basement rocks, ultramafic rocks, and deep-seated Permian granitoids, such as the Dzhabyk batholith (Fershtater et al., 1997).These deep-seated, anatectic granitoids are unlikely to host porphyry copper deposits, which typically form at shallow (1–5 km) crustal levels.

Four geographic areas are delineated as permissive tracts for Paleozoic porphyry copper deposits east of the Main Uralian Fault in the Urals (Table 2, Fig. 3). Each tectonic zone, and therefore each permissive tract, may contain one or more magmatic arcs or arc fragments. Tract areas were calculated in a GIS using an equal area projection. Table 2 lists each tract area, along with the approximate percentage of each tract that is occupied by permissive rock, Precambrian basement, and post-Early Carboniferous sedimentary (or undifferentiated) cover rocks based on analysis of the geologic map of Petrov et al. (2006). Identified resources for porphyry copper deposits in the Urals, i.e., those deposits that have well-defined tonnages and ore grades, are summarized in Table 1. Prospects associated with each permissive tract are listed in Table 3, and briefly described below. In both tables, deposits and prospects are listed from north to south within each tract. See Plotinskaya et al. (this volume and references therein) for more information on individual porphyry copper occurrences and ages.

3.2.1. Polar Central Uralian zone

Most of the Polar Urals area is occupied by Precambrian complexes associated with the Neoproterozoic Timanide (600–550 Ma) stage of development of the Urals (Puchkov, 2017– in this volume). Examples of porphyry copper deposits and prospects are rare in the Cis- and Polar Urals (Plotinskaya and Grabezhev, 2013). No permissive tract was drawn for the areas west of the Main Uralian Fault in the Central Urals zone (Fig. 1) because of uncertainties about exact location, age, and nature of the only porphyry copper deposit with reported resources, which is **Lekyn-Talbei.** The approximate location of the deposit is west of the Paleozoic Tagil-Polar tract (Fig. 5). Lekyn-Talbei has been described as a poorly explored porphyry copper deposit formed in an island-arc setting similar to the setting for deposits further south (Grabezhev, 2013) and as a porphyry molybdenum-copper occurrence in exposed northern parts of the Central Uralian zone (Internides). The deposit is assigned an age range of 362 to 207 Ma based on K-Ar dating of sericite (Silaev and Andreichev, 1982). However, Plotinskaya et al. (2017– in this volume) suggest a more likely Vendian age based on geology, pending further investigations. The deposit consists of lens-shaped lodes, veins, and disseminated mineralization associated with the (Proterozoic?) Lekyn-Talbey volcanic complex (Petrov et al., 2006). Reported resources include 251.7 kt of copper and 4.2 kt of molybdenum in the C1 category along with P1 resources of 830 kt copper and 13.8 kt of molybdenum. Plotinskaya et al. (2017– in this volume) cited inferred (C2) resources of 85.6 Mt of ore, 0.46 Mt of copper, 7.6 kt of molybdenum, 12 t of gold and 100 t of silver.

3.2.2. Tagil-Polar Urals tract

The Tagil-Polar Urals tract includes two segments (Figs. 3 and 5). The northernmost Polar Urals segment outlines Phanerozoic igneous rocks in the Polar region east of the Main Uralian Fault that are associated with a magnetic high area that lies just south of an arm of the Arctic Ocean. In some studies, this area is included as a northern extension of volcanic sequences associated with the Tagil arc (see Fig. 1B of Soloviev et al., 2013). Intrusive rocks mapped in the tract area include Silurian to Middle Devonian diorite, quartz diorite, and granodiorite (Puchkov, 2017– in this volume; Petrov et al., 2006).

The larger segment of the Tagil-Polar Urals tract includes Ordovician through Devonian intrusive and stratified rocks that lie east of the Main Uralian Fault in an area extending from the Middle Urals and extending through the North and Cis-Polar Urals. The eastern boundary of the tract is based on an approximation of the extent of permissive rocks under shallow cover below the West Siberian Basin. Permissive intrusive rocks include alkaline gabbro, diorite, gabbro, gabbrodiorite, granodiorite, plagiogranite, quartz diorite, syenite, and syenodiorite. Stratified rocks that mention andesite, basaltic andesite, basalt, and (or) trachyte in lithologic descriptions are included as permissive extrusive rocks (Smirnov et al., 2008). Ultramafic complexes are excluded (these appear as holes in the permissive tract). Silurian andesitic rocks are overlain by Lower Devonian trachytes and volcaniclastic rocks to the east,

Table 2
Permissive tracts for porphyry copper deposits in the Urals [younger cover is defined as sedimentary or unclassified rock that is younger than Early Carboniferous for the Tagil-Polar and East Uralian tract, younger than Late Devonian for the Magnitogorsk tract, and younger than Carboniferous for the Transuralian tract. Areas are based on equal area calculations from map units of Petrov et al., 2006].

Tract name	Geologic feature assessed	Tract area (km^2)	Percentage of total tract area		
			Exposed permissive igneous rock	Exposed Precambrian basement	Younger cover
Tagil-Polar Urals	Silurian, Devonian, and Early Carboniferous Tagil intra-oceanic volcanic arc and Middle Paleozoic calc-alkaline intrusions and volcanic rocks of the northern and Polar Urals	49,600	31%	1%	24%
Magnitogorsk	Middle to Late Devonian Magnitogorsk intra-oceanic volcanic arc in the Magnitogorsk tectonic zone	49,320	32%	1%	45%
East Uralian	Ordovician to Early Carboniferous fragments of tectonically emplaced island and continental arc fragments in the East Uralian tectonic zone.	80,240	27%	20%	35%
Transuralian	Early Carboniferous subduction-related calc-alkaline complexes in the Transuralian tectonic zone. Includes the Valerianovka continental margin arc in the east and the Alexandrovskaya and Irgizskaya arcs in the west (Hawkins et al., 2017-- in this volume).	128,800	5%	6%	72%

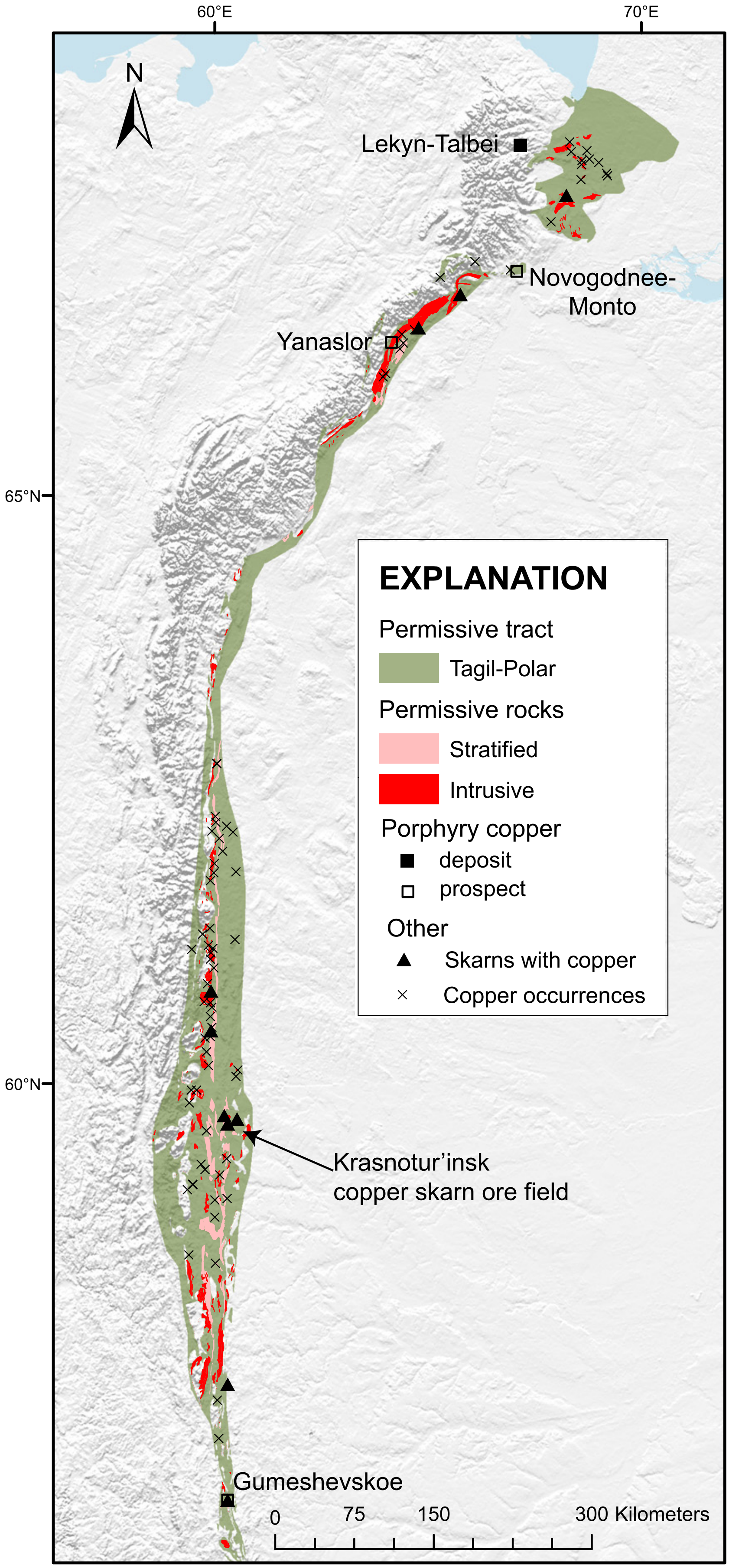
Table 3
Porphyry copper prospects in the Urals [kt, thousand metric tons; Mt, million metric tons, %, percent; g/t, grams per metric ton; ppm, parts per million; avg, average; −, no data. Some locations are approximate. See Plotinskaya et al. (2017– in this volume) for additional information, including ages].

Name	Latitude	Longitude	Commodities	Comment	References
Tagil-Polar Urals tract					
Novogodnee-Monto	66.811	66.517	Cu, Au	Oxidized gold-bearing magnetite skarn and porphyry copper; Cu grades <0.25%	Soloviev et al. (2013), Plotinskaya et al. (2017-- in this volume)
Yanaslor	66.293	63.733	Cu, Mo, Au	No tonnage; avg. grade 0.3–0.4% Cu; 0.002% Mo	Petrov et al. (2006), Plotinskaya et al. (2017-- in this volume)
Gumeshevskoe (Gumeshevo)	56.477	60.187	Cu, Mo, Au, Ag	Skarn-porphyry Cu-Au prospect. Cu/Mo in ore = 600–1700; Mo in ore 1–4 ppm	Grabezhev et al. (2007), Zavaritsky (1950), Grabezhev (2013), Plotinskaya et al. (2017-- in this volume)
Magnitogorsk tract					
Voznesenskoe (Vosnesenka)	54.633	59.800	Cu, Au, Mo	Ore Cu/Mo > 250. Avg grade 0.48% Cu. Au in pyrite 0.02 to 0.07 ppm	Grabezhev and Borovikov (1993), Grabezhev et al. (1996), Vorob'ev et al. (1977), Shishakov et al. (1988), Singer et al. (2008), Plotinskaya et al. (2017-- in this volume)
Dunguray (Gavrilovsky rudnik)	54.524	59.589	Cu, Mo	Small (<100 kt Cu) porphyry copper deposit associated with gabbro-dolerite, diorite of the Utchaly Complex.	Petrov et al. (2006), Kozolov et al. (2002)
Salavat	53.573	58.435	Cu, Mo, Au	Prospective resources of 1 Mt Cu at 0.5% Cu. Cu/Mo in ore = 600.	Grabezhev (2007), Grabezhev and Borovikov (1993), Grabezhev et al. (1996), Kozolov et al. (2002), Krivtsov et al. (1986), Magadeev and Timergazina (1970), Pavlova (1978), Plotinskaya et al. (2014a, 2017-- in this volume), Vorob'ev et al. (1977), Zvezdov et al. (1993)
East Uralian tract					
Alapaevsk	61.751	57.838	Cu	Small porphyry copper deposits associated with diorite-quartz diorite-plagiogranite plutons in the Alapaevsk-Sukhoi Log porphyry copper zone	Grabezhev et al. (2014, 2015), Petrov et al. (2006), Plotinskaya et al. (2017-- in this volume)
Artemovskoe	61.943	57.293	Cu, Mo		
Kalinovskoe	61.173	54.870	Cu	One of three deposits in the Tomino ore zone; reconnaissance drilling showed 0.3–0.6% Cu; Re-rich molybdenite (up to 0.95% Re)	Grabezhev et al. (1998), Plotinskaya and Grabezhev (2013), Plotinskaya et al. (2014a, 2014b)
Soyuznoe	60.057	50.762	Cu, Au	Occurrence; no resource information available	Seltmann et al. (2015)
Talitsa	57.254	60.797	Cu, Mo, Au	Cu/Mo in ore 0.5–3; 0.09–0.47% Cu; 0.04–0.34%, 0.1–0.4 ppm Au.	Azovskova and Grabezhev (2008), Plotinskaya et al. (2017-- in this volume)
Takhtalym	55.842	61.767	Cu, Mo, Au	Small deposit (<100 kt Cu); 0.3–0.4% Cu; 0.002% Mo.	Petrov et al. (2006), Kozolov et al. (2002), Plotinskaya et al. (2017-- in this volume)
Karagaikul	55.777	61.333	Cu	Occurrence in mélange zone of Main Uralian fault; no resource information available	Kosarev et al. (2014)
Yaguzak	54.994	61.003	Cu, Mo	Part of the Birgilda-Tomino ore cluster. Described as a zone with uneconomic Au-Au-Mo mineralization.	Grabezhev and Borovikov (1993), Grabezhev et al. (1995, 1998), Plotinskaya et al. (2009)
Zelenodolskoe	54.538	61.029	Cu, Mo, Zn, Au	Ore: 0.15–0.50% Cu, 2–50 ppm Mo, 0.01–0.09 ppm Re	Grabezhev (1992), Grabezhev and Borovikov (1993), Grabezhev et al. (1996), Herrington et al. (2005b), Kozolov et al. (2002), Krivtsov et al. (1986)
Yelenovskoe	50.891	59.832	Cu, Mo, Au, Pb, Zn	Ore lodes 2–45 m thick; extend downdip 100 m; extent 69 m and 135 m. Quartz-tourmaline alteration. Resources: 19.1 kt Cu at 2.88% Cu; 2200 kg Au at 2.16 ppm Au; 3.5 t Ag; 0.024% Mo; 3.2–8% Zn; 0.02–0.08% Pb; 1% B	Petrov et al. (2006), Plotinskaya et al. (2017-- in this volume)
Transuralian tract					
Novonikolaevsk	53.152	60.948	Cu	Au content in ore minerals: 1.9 g/t in pyrite, and 6.9 g/t in chalcopyrite	Grabezhev (1992), Grabezhev and Borovikov (1993), Grabezhev et al. (1996)
Bataly	52.822	61.795	Cu, Mo, Au	100% of the deposit area is covered by Mesozoic-Cenozoic sediments	Grabezhev and Borovikov (1993), Kolesnikov et al. (1986), Krivtsov et al. (1986), Zhukov et al. (1998), Plotinskaya et al. (2017-- in this volume)
Spiridonovskoe	52.532	62.449	Cu, Au	Drilling data indicate small resources at 0.3–1.5% Cu, 0.01–0.05% Mo, and ≤0.2 g/t Au. 100% of the deposit area is covered by unlithified sediments.	Zhukov et al. (1998), Singer et al. (2008), Plotinskaya et al. (2017-- in this volume)
Benkala South	51.099	61.800	Cu, Mo, Au, Ag	C2 reserve estimate based on Soviet drilling in 1979: 151.5 Mt primary ore average grade 0.34% Cu, 0.008% Mo, 0.17 g/t Ag, with 23.62 Mt secondary ore at 0.4% (cutoff grade 0.25%).	Frontier Mining LTD (2011, 2013)

which are in turn, overlain by 2 km of Devonian limestone and locally intercalated calc-alkaline volcanic rocks (Brown et al., 2011). The calc-alkaline magmatism in the eastern part of the Tagil arc continued into the Late Devonian, overlapping in time with the Magnitogorsk magmatism to the south (Brown et al., 2011). According to Puchkov (2013), Tagil arc magmatism ceased in the Early Devonian, but the collision with the European continent did not occur until Late Devonian or Early Carboniferous time. Therefore, Late Devonian-Early Carboniferous (D$_3$-C$_1$) igneous rocks within the Tagil zone may be products of syn- to post-collisional magmatism. These younger rocks include lithologies that are permissive for porphyry copper deposits. Prospects are listed in Table 3 and plotted on Fig. 5.

Novogodnee-Monto is an oxidized Au-Cu magnetite skarn and porphyry prospect area in a complex geologic setting in the Polar Urals.

Fig. 5. Map showing the distribution of permissive rocks, porphyry copper prospects, copper occurrences, and other significant deposit types in the Tagil-Polar permissive tract. Hillshade from Danielson and Gesch (2011).


60°E
70°E
65°N
60°N
N
Lekyn-Talbei
Novogodnee-Monto
Yanaslor
Krasnotur'insk copper skarn ore field
Gumeshevskoe
0
75
150
300 Kilometers
EXPLANATION
Permissive tract
Tagil-Polar
Permissive rocks
Stratified
Intrusive
Porphyry copper
■ deposit
□ prospect
Other
▲ Skarns with copper
× Copper occurrences

Both an Early Devonian gabbroic to dioritic calc-alkaline suite and a Late Devonian-Early Carboniferous monzonite porphyry associated with a potassic suite are preserved (Soloviev et al., 2013). The older rocks appear to indicate an island-arc setting. Gold and copper mineralization overprints earlier magnetite skarn and forms porphyry-style stockworks that are associated with the younger, post-subduction magmatism. The skarns are cut by monzonitic rocks of the younger potassic suite, which are pervasively altered (potassic, phyllic, and propylitic) and chalcopyrite-bearing (Soloviev et al., 2013).

Yanaslor is classified as a Cu-Mo-Au porphyry copper occurrence (Table 3). Reported grades of 0.3–0.4% Cu and 0.002% Mo are characteristic of porphyry copper deposits; no tonnage data are available.

Gumeshevskoe (Gumeshevo) is a skarn-porphyry system associated with Middle Devonian quartz diorite and porphyry diorite dikes. Ore mineral assemblages include chalcopyrite, magnetite, bornite, and pyrrhotite, with ore Cu/Mo ratios ranging from 600 to 1700 (Grabezhev, 2013).

The Krasnotur'insk copper skarn ore field (Fig. 5) contains magnetite skarns associated with quartz diorite, diorite, and gabbrodiorite; small diorite plutons host disseminated porphyry copper-style mineralization. U/Pb zircon ages for quartz diorite of 404 Ma suggest an Early Devonian age for the porphyry mineralization (Grabezhev et al., 2014). The deposit type for the many other copper occurrences in the Tagil-Polar Urals tract is unknown; many of these occurrences may represent VMS-style mineralization. The tract includes >40 iron skarns, which may or may not be indicators of a porphyry environment.

3.2.3. Magnitogorsk tract

The Magnitogorsk arc in the Magnitogorsk tectonic zone is the best exposed volcanic arc segment in the Urals and defines the Magnitogorsk tract (Fig. 6). The development of the Middle to Late Devonian Magnitogorsk intra-oceanic volcanic arc in the southern Urals was synchronous with the break-up of the Tagil arc to the north. The permissive tract is bounded by the Main Uralian Fault on the west and the Magnitogorsk fault zone on the east, and was delineated primarily on the basis of maps shown in Herrington et al. (2005a) and Puchkov (2017– in this volume). The tract includes Middle through Late Devonian gabbro, diorite, granodiorite, plagiogranite, gabbrodiorite, quartz diorite, alkaline gabbro, syenodiorite, syenite, minor rhyodacite, and rhyolite. Stratified units include tholeiitic and calc-alkaline rocks of the Irendyk Formation in the west and Karamalytash Formation in the east. Ultramafic complexes are excluded (these appear as holes in the permissive tract).

Yubileinoe is an undeveloped, reportedly economic Cu-Au porphyry system associated with a small (300 by 210 m) plagiogranite porphyry stock (Grabezhev, 2014) in the southern part of the tract (Fig. 6). The deposit was discovered in 1961 and has been drilled to a depth of 600 m. Mineralization at Yubileinoe formed as skarn and also in potassic and phyllic alteration zones; stockworks are commonly localized along intersecting fault zones. Reported resources include 10 Mt of ore at an average grade of 0.41% Cu and 6.6 g/t Au (Table 1). Gold grades range from 3 to 11 g/t Au, and 65 g/t Ag. Shatov et al. (2014) reported that the deposit has produced 0.832 Moz of gold at 6.5 g/t Au and noted that Sun Gold (2013) estimated resources at 82.8 Mt of ore at 1.7 g/t Au and 0.15% Cu.

The deposit includes several ore bodies: an 80–240 m long and 9–12 m thick western ore body along an intrusive contact; a northern, volcanic-hosted ore body; a southeastern ore body along contacts of a plagiogranite porphyry stock; and a central ore body within the stock (Seltmann et al., 2014; Rudenko and Gilmanov, 1980).

A U-Pb zircon age of 374 ± 3 Ma from altered porphyry in drill core at Yubileinoe, along with ages and geochemical analyses of ore-bearing granitoids in the Magnitogorsk and Tagil tectonic zones, suggests that porphyry deposits in the region may have formed over a protracted period of time from the Middle Devonian to the Early Carboniferous. Older island-arc related Cu-Au deposits were followed by more Mo-rich deposits in the Early Carboniferous. Grabezhev (2014) showed that the geochemistry of granitoids associated with porphyry copper systems in the Magnitogorsk and Tagil zones indicate an increasing crustal component in source material as the arcs evolved, as reflected by increasing SiO$_2$, K$_2$O, Rb, REE and $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_t$ and decreasing $(\varepsilon\mathrm{Nd})_t$.

Salavat is an undeveloped Devonian porphyry Cu-Au prospect in calc-alkalic basaltic andesite of the Irendyk Formation associated with co-magmatic granodiorite and diorite stocks and dikes (Herrington et al., 2005a). It is described as a medium-size deposit with average grades of 0.5% Cu, 0.003% Mo; 0.01 to 0.05 ppm Au is reported in pyrite. Ore contains <0.01 to 0.47 ppm Re (Grabezhev, 2007). A resource has not been delineated at Salavat.

Other prospects in the tract include the Late Devonian **Voznesensk(oe)** Cu-Mo-Au porphyry in altered quartz diorite and a small prospect reported at **Dunguray** (Fig. 6). The tract hosts a variety of different types of significant VMS deposits (Cyprus-, Urals-, Baimak- and Besshi-types) that have produced most of the copper in the region and magnetite skarns that fueled iron and steel production in Magnitogorsk in the early 1900s (Herrington et al., 2005a). A few small to medium size volcanic-associated epithermal gold deposits are present in the northern part of the tract (Fig. 6).

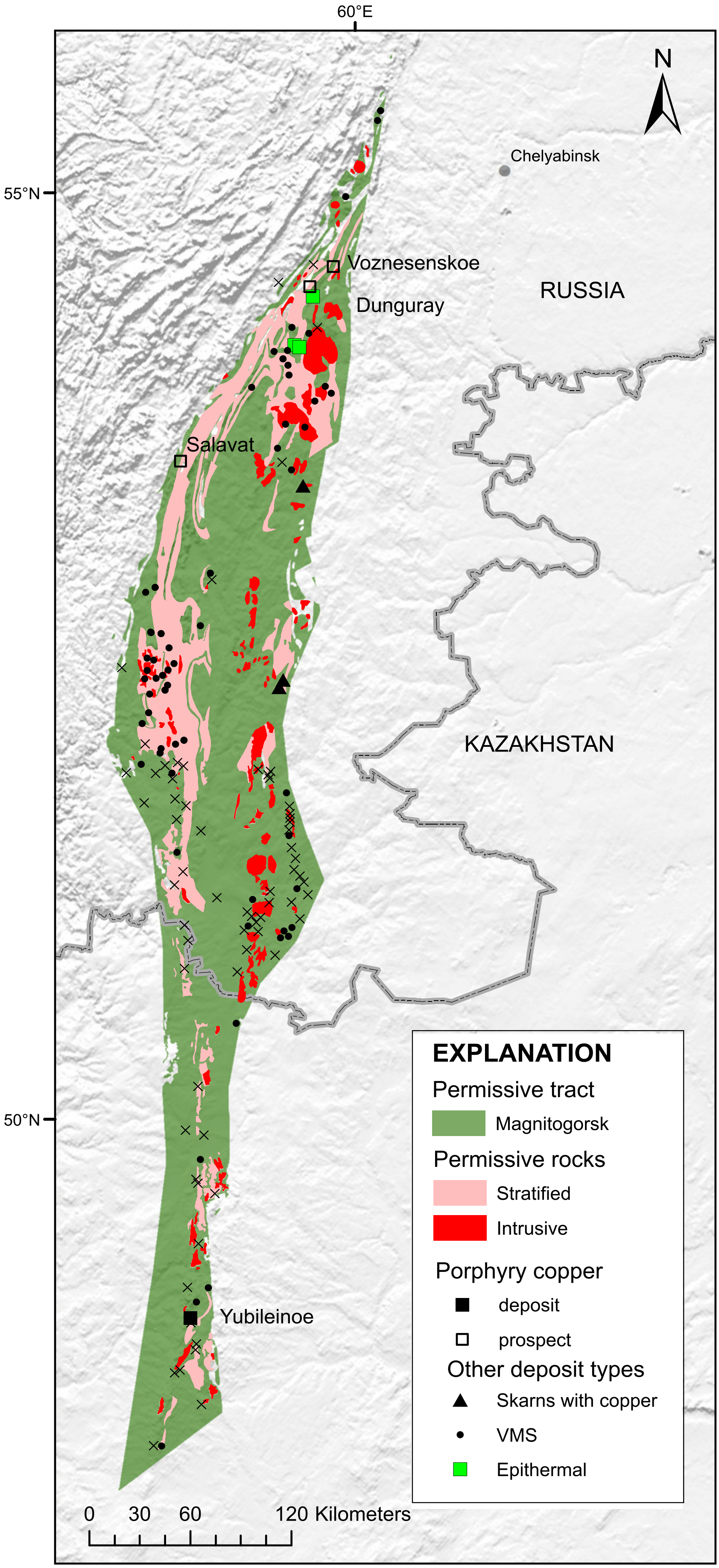
3.2.4. East Uralian tract

The East Uralian Zone (EUZ) represents the suture between the East European craton (including the accreted Tagil and Magnitogorsk arcs) and the Kazakh craton. The EUZ is an intensely deformed and metamorphosed belt of rocks derived from both the Eurasian and Kazakh cratons and intervening ocean. Two stages of magmatism are recognized within the EUZ: (1) an early stage of Late Devonian to Early Carboniferous calc-alkalic intermediate-composition intrusions (2) Late Carboniferous and Permian granitoid batholiths, along with diorite and gabbro intrusions (Herrington et al., 2005b; Fershtater et al., 1997; Bea et al., 1997). Late Carboniferous and Permian magmatism produced voluminous 275–290 Ma granite batholiths (Bea et al., 1997), including two-mica granites and associated Be- and Ta- pegmatites. The known porphyry copper deposits in the East Uralian tectonic zone are associated with the older Late Devonian-Early Carboniferous intermediate-composition calc-alkalic rocks. These permissive Late Devonian and Early Carboniferous lithologies were used to define the East Uralian tract, which also includes older Ordovician through Middle Devonian rocks (Fig. 7). The “holes” in the tract represent Permian granites that are not permissive for porphyry copper deposits (Fig. 7).

The western tract boundary is the approximate location of the East Magnitogorsk and Serov-Mauk fault zones. The eastern boundary is the approximate location of the Troitsk fault in the southern Urals; in the north, the boundary with the Transuralian zone to the east is covered by the West Siberian Basin.

The East Uralian tract hosts **Birgilda-Tomino ore cluster,** which includes the large (1.5 Mt copper) Tomino and the smaller Birgilda deposits (Fig. 7; Tables 1 and 3). These porphyry copper deposits are associated with a Silurian igneous complex of hydrothermally altered calc-alkaline diorite porphyry stocks, subvolcanic andesite porphyries, and extrusive rocks. The ore cluster includes porphyry, epithermal, and skarn deposits in a series of five mineralized zones along a 40 km by 20–25 km north-trending zone (Plotinskaya et al., 2014b). The Tomino, North Tomino, and Kalinovskoe systems occur within a 10 km-long by 5–6 km wide zone (Plotinskaya et al., 2014b). The Birgilda deposit is spatially separated from the shallower Tomino area by the Michurino zone, which hosts the Bereznyakovskoe Au-Ag epithermal deposits and by the Yaguzak zone. Uneconomic Cu-Mo-Au prospects that may be associated with younger Carboniferous

Fig. 6. Map showing the distribution of permissive rocks, porphyry copper deposits and prospects, copper occurrences, and other significant deposit types in the Magnitogorsk tract. Hillshade from Danielson and Gesch (2011).


60°E
55°N
50°N
N
Chelyabinsk
Voznesenskoe
Dunguray
RUSSIA
Salavat
KAZAKHSTAN
Yubileinoe
EXPLANATION
Permissive tract
Magnitogorsk
Permissive rocks
Stratified
Intrusive
Porphyry copper
deposit
prospect
Other deposit types
Skarns with copper
VMS
Epithermal
0 30 60 120 Kilometers

monzogranodiorite porphyries are present in the Yaguzak zone (Plotinskaya et al., 2014b).

Alapaevesk and Artemovsk are described as small porphyry copper prospects associated with diorite-quartz diorite-plagiogranite plutons in the 100-km-long Alapaevsk-Sukhoi Log porphyry copper zone in the Middle Urals (Grabezhev et al., 2014).

Several porphyry copper prospects occur within the tract, as well as the 299 Ma Talitsa porphyry molybdenum deposit (Table 3). Talitsa was considered an incompletely explored prospect at the time of our assessment; however, an ore tonnage of 129 Mt at 0.055% Mo and 0.11% Cu is cited by Plotinskaya et al. (2017– in this volume).

3.2.5. Transuralian tract

The Transuralian tract includes remnants of at least three Devonian and Carboniferous calc-alkaline volcano-plutonic complexes within the Transuralian tectonic zone: the Irgizskaya and Alexandrovskaya arcs on the west and the Valerianovka (Valerianov) arc to the east. Most of the tract is in western Kazakhstan and covered by post-Carboniferous sedimentary rocks.

The western boundary of the Transuralian tract is the boundary between the Transuralian zone and the East Uralian zone along the Troitsk fault (Hawkins et al., 2017– in this volume Puchkov, 2017– in this volume). The eastern boundary is partly along the Anapov fault as shown by Hawkins et al. (2017– in this volume) and the boundary identified Herrington et al. (2005b) as the approximate boundary of Mesozoic cover under the West Siberian basin. Our Transuralian tract partly overlaps the larger tract previously described by Berger et al. (2014) as the Valerianovka arc in a porphyry copper assessment of western Central Asia. However, we did not incorporate those results in the current assessment of the Transuralian tract.

Seltmann et al. (2015) show porphyry copper occurrences in the Transuralian zone, but descriptive information is not available for most of them. Zhukov et al. (1998) describe three of the occurrences—Bataly, Benkala North, and Spiridonovskoe. Varvarinskoe, listed as a porphyry copper deposit by Singer et al. (2008), is classified as a gold-copper skarn deposit by Zhukov et al. (1998). Vavarinskoe is associated with the Alexandrovskaya arc within the Transuralian zone. Taranovskoe is described as a medium-size (100 to 1000 kt Cu) porphyry copper deposit (Seltmann et al., 2015).

Tarutino is a skarn and porphyry Cu-Mo prospect in the western part of the tract (Fig. 8). Ore was deposited in two stages: an early stage skarn and chalcopyrite-pyrite mineralization in quartz diorite and porphyritic diorite, and a later stage of molybdenite mineralization in granodiorite (Grabezhev, 2013). The deposit was discovered in 1995. In 2006, Eureka Mining evaluated the deposit and concluded that it was uneconomic (Eureka Mining plc., 2006). Various estimates of total resources have been reported. The high copper grade reported suggests that the resources apply mostly to skarn portions of the deposit. Results from a 2013–2014 drilling campaign were used to estimate JORC-compliant total measured, indicated, and inferred resources of 10 Mt or ore with an average grade of 0.99% copper (Polymetal International plc, 2015). Previous estimates cited much larger ore tonnages (21 and 41 Mt), similar copper grades, and grades for gold, silver, molybdenum, and iron.

Mikheevskoe (Mikheevsky), the only porphyry copper deposit that has been developed in the Urals in Russia, is the largest deposit in the study area with over 2 million metric tons of contained copper (Table 1). The deposit is associated with Late Devonian to Carboniferous quartz diorite, diorite, granodiorite, and subvolcanic intrusions (Shargorodsky et al., 2005; Grabezhev, 2013) within an ore field that includes other porphyry occurrences. It was discovered in 1997 and mining began in 2013.

Ore is concentrated in a 0.5 by 3 km area between two large diorite stocks. Chalcopyrite is the main copper ore mineral, along with bornite (Plotinskaya et al., 2015). Alteration assemblages include potassic, Ca-sodic, phyllic, and propylitic. A detailed study of the rhenium distributions in ore and molybdenite showed the ore grades typically are <0.5 g/t Re and that the Re grade is correlated with Mo grade (Plotinskaya et al., 2015).

Benkala (Tables 1, 3), also known as Benkala North is associated with Early Carboniferous tuffaceous sands and silts and volcanic rocks intruded by Early to middle Carboniferous porphyritic quartz diorites and granodiorites (Zhukov et al., 1998). Zhukov et al. (1998) show the Benkala mineralization as oval in plan with the long axis over 1 km long and the short axis 500–700 m wide. A thin supergene blanket overlies the deposit.

Benkala was discovered in 1968 and drilled during Soviet exploration from 1976 to 1979. Open pit mining of near-surface oxide ore began in 2012 (Frontier Mining Ltd., 2015). Production of cathode copper by SX-EW increased from 792 t of copper to 1702 t in 2013. JORC-compliant 2011 measured, indicated, and inferred oxide and sulfide resources were reported as 361,916,000 metric tons of ore at an average grade of 0.41% Cu based on a cutoff grade of 0.25% Cu (Frontier Mining Ltd., 2013). Reserve estimates (C2 category) based on Soviet era drilling indicated average grades of 0.008% Mo and 0.17 g/t silver in primary ore (Frontier Mining Ltd., 2013).

The Benkala South prospect, located 10 km from the Benkala project, has preliminary resource estimates of 95,000 metric tons of oxide copper and 515,000 metric tons of sulfide copper (Frontier Mining LTD, 2011). The data are based on 1979 Soviet estimates at a copper cutoff grade of 0.25%. Plans for both projects include mining oxide (chalcocite) ores to a depth of 100 to 150 m followed by mining primary sulfide (chalcopyrite) ore (Frontier Mining Ltd., 2013).

Bataly is a copper-molybdenum prospect in a complex of granodiorite and granodiorite porphyry intrusions north of Benkala. Zhukov et al. (1998) describe a paleovolcanic structure of two neck-like zones of intrusive rock that coalesce at depth into a single, larger composite intrusion of regional dimensions (14 km by 6–9 km). Zhukov et al. (1998) note that the deposit is not completely drilled at depth and warrants further exploration.

Varvarinskoe, a few kilometers north-northeast of the Bataly, was classified as a porphyry copper-gold deposit (Singer et al., 2008). Varvarinskoe has been classified in various ways by different investigators (Zhukov et al., 1998); Dodd et al. (2005) classified it is as a skarn. The primary ore occurs as stratiform massive and disseminated sulfides, as alterations of garnet-pyroxene skarn in calcareous volcanic rocks, marbleized limestone, and volcanic breccias. A second ore type consists of vein and disseminated sulfides and stockworks at the contacts of porphyritic diorite and serpentinite intrusions and tectonic breccias. The deposit is oxidized at the surface and some supergene mineralization occurs. Dodd et al. (2005) note that there is additional reserve potential at depth beyond what has already been delineated, but a possible relationship to an underlying granodiorite stock is apparently wholly speculative.

The deposit was discovered in 1981 and developed as an open-pit mine by European Minerals Corporation, and subsequently by Orsu Metals. Mining started in 2006. The mine was acquired by Polymetal International plc in 2009 and is in production as the Varvara Mine with mine life projected to 2030. The deposit produced 6900 t of copper in 2011 (Polymetal International plc, 2012).

Spiridonovskoe is a porphyry Cu-Mo prospect located between Benkala and Bataly (Fig. 8). The age of the deposit is equivocal. Zhukov et al. (1998) associate it with tuffs and diorite to granodiorite intrusive rocks of a Late Silurian to Early Devonian massif. Based on geology, Plotinskaya et al. (2017– in this volume) assign a Late Carboniferous age and report grades of 0.55% copper, with Mo and Au.

Magnetite-copper skarn deposits are associated with the intrusive complexes that host many of the porphyry copper occurrences in the tract area, such as Benkala. Some iron-copper skarn deposits may be considered as a favorable indication for the possibility of an undiscovered porphyry-style deposit in the same intrusive complex in which the skarns occur. However, the classification of the huge magnetite

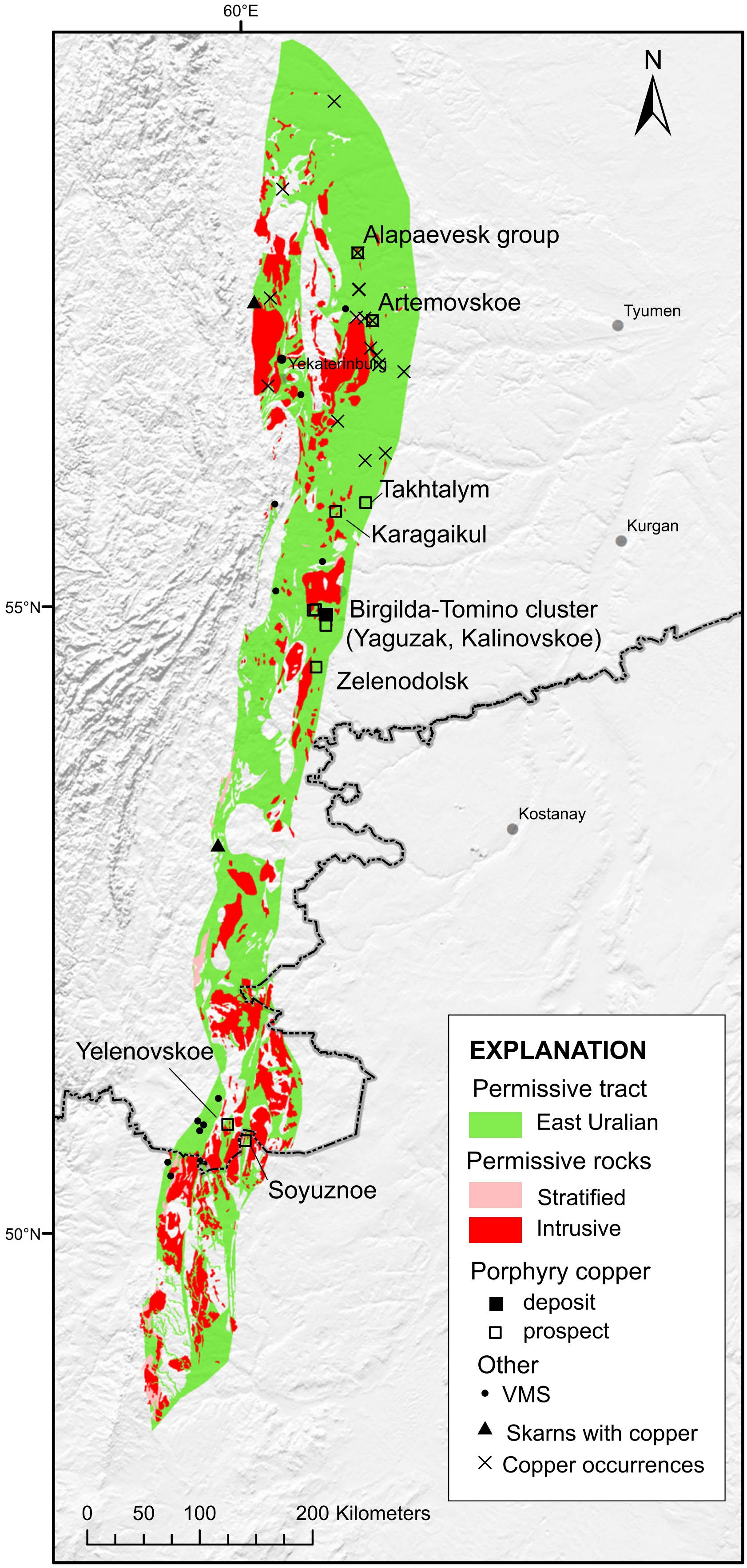


Fig. 7. Map showing the distribution of permissive rocks, porphyry copper deposits and prospects, copper occurrences, and other significant deposit types in the East Uralian tract. VMS, volcanogenic massive sulfide. Hillshade from Danielson and Gesch (2011).

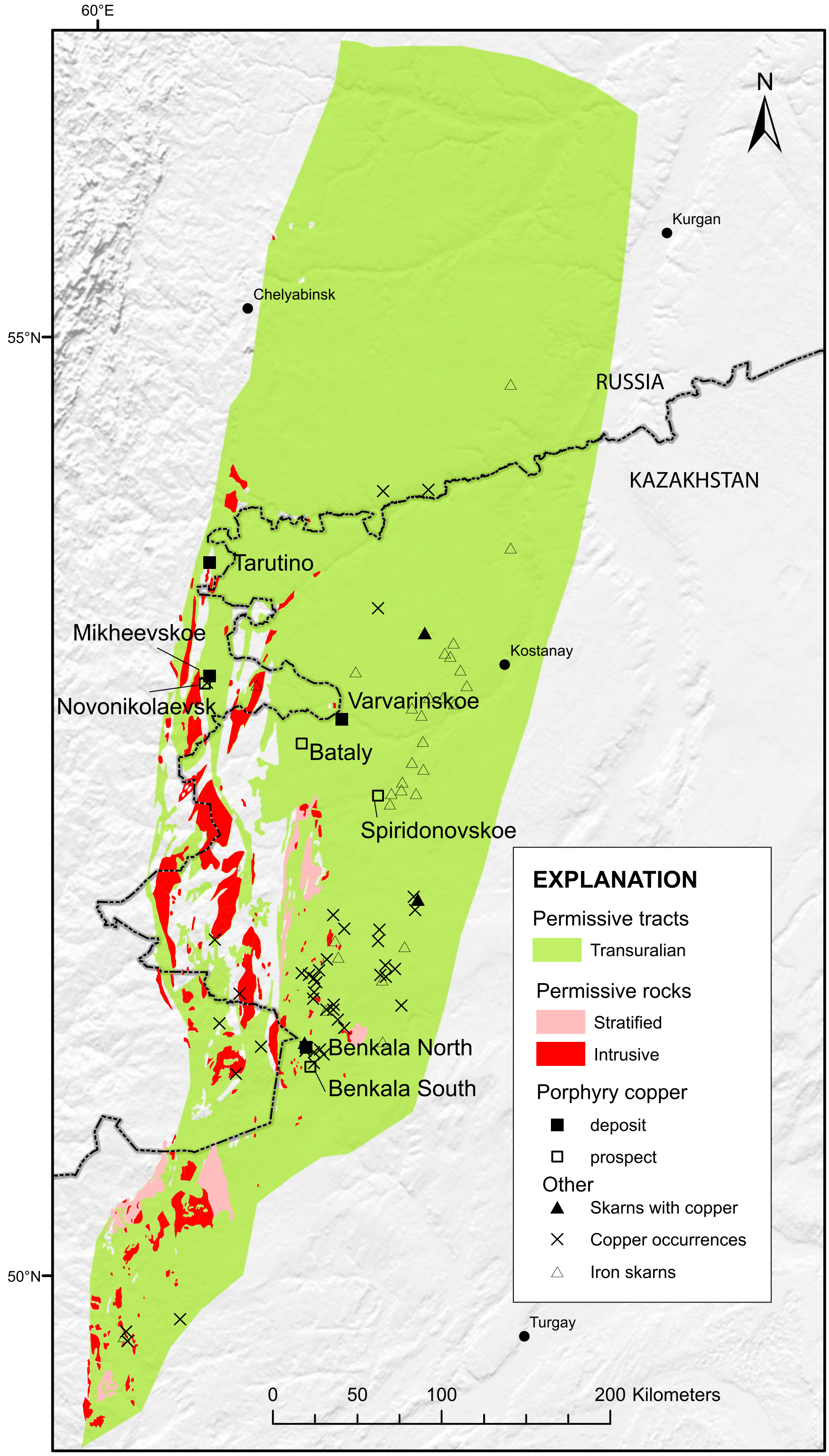


Fig. 8. Map showing the distribution of permissive rocks, porphyry copper deposits and prospects, copper occurrences, and other significant deposit types in the Transuralian tract. Hillshade from Danielson and Gesch (2011).

deposits in the Transuralian zone as simple iron skarns or as porphyry-related is problematic (Hawkins et al., 2017– in this volume). These deposits have extensive scapolite alteration, are described as distal to associated mafic intrusions, and may be better described as analogs to the Kiruna-type magnetite deposits of Sweden (Herrington et al., 2005b) or as variants of IOCG deposits. Copper, gold, and silver are reported at Kachar; most of the other skarns only contain iron. All of the known VMS deposits occur to the west of the tract. Therefore, the numerous copper occurrences (including Cu-Mo and Cu-Au) shown on Fig. 8 may be porphyry-related whereas many copper occurrences in other tracts are as likely to be associated with VMS deposits as with porphyry–skarn systems, pending further investigation.

Table 4
Summary of numbers of deposits, prospects, copper-bearing skarns, and other copper occurrences in each permissive tract.

Tract name	Deposits (identified resources)	Prospects	Skarns with major copper	Copper occurrences	Exposed permissive igneous rock area
Tagil-Polar Urals	0	3	8	63	31%
Magnitogorsk	1	3	3	64	32%
East Uralian	2	10	2	55 (11 Cu-Mo)	27%
Transuralian	4	4	2	49 (1Cu-Mo)	5%

Table 5
Estimates of numbers of undiscovered porphyry copper deposits in the Urals [NXX, estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; area, area of permissive tract in square kilometers; density, deposit density reported as the total number of deposits per 100,000 km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005). –, no estimate made].

Tract name	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/100k km^2)
	N90	N50	N10	N05	N01	N_{und}	s	C_v%	N_{known}	N_{total}		
Tagil-Polar Urals	1	3	8	12	20	4.4	4.4	101	0	4.4	49,600	10
Magnitogorsk	2	4	6	12	18	4.5	3.5	77	1	5.5	49,320	10
East Uralian	3	5	10	15	30	6.5	5.6	85	2	8.5	80,240	11
Transuralian	2	4	10	18	32	6.1	6.4	100	4	10	128,800	7.8
Totals						22	-	-	7	38	307,960	-

4. Mineral resource assessment for porphyry copper deposits in the Urals

The assessment team discussed the available geologic, mineral occurrence, and exploration data for each permissive tract and considered the numbers of prospects, copper skarns, copper occurrences, and the amount of exposed permissive igneous rock in each tract (Table 4). The assessment team made probabilistic estimates of numbers of undiscovered deposits for each tract at different levels of certainty (Table 5). Estimators were asked for the least number of deposits of a given type that they believe could be present at three specified levels of certainty (90%, 50%, and 10%). For example, on the basis of all the available data, a team member may have estimated a 90% chance (or better) of at least one, a 50% chance of at least three, and a 10% chance of at least five undiscovered deposits in a permissive tract. The individual estimates were then shared and discussed by the group, and a consensus estimate was agreed upon to use as input for the Monte Carlo simulation of undiscovered resources. The probabilistic estimates of undiscovered resources for each permissive tract are determined as:

$$\text{mean undiscovered resource} = \text{number of undiscovered deposits} \times \text{tonnage} \times \text{grade},$$

where number of deposits, tonnage, and grade are each described by probability distributions and modeled using Monte Carlo simulation (Singer and Menzie, 2010). Simulation results include an expected number of deposits, a variance, and estimates of undiscovered amounts of copper, molybdenum, gold, silver, and ore reported at selected quantiles as well as a mean.

The mean number of undiscovered deposits and associated standard deviation are based on the algorithm developed by Singer and Menzie (2005) that replicates the deposit distribution originally described by Root et al. (1992). The algorithm is described by the following general equations to calculate a mean number of undiscovered deposits (λ) and a standard deviation (s_x) based on estimates predicted at different quantile levels[2] (N_{90} = 90-percent level, N_{50} = 50-percent level, and so on):

$$\lambda = 0.233\,N_{90} + 0.4\,N_{50} + 0.225\,N_{10} + 0.045\,N_{05} + 0.03\,N_{01} \qquad (1)$$

$$s_x = 0.121 – 0.237\,N_{90} – 0.093\,N_{50} + 0.183\,N_{10} + 0.073\,N_{05} + 0.123\,N_{01}. \qquad (2)$$

These equations were programmed in a spreadsheet to allow the team to interactively evaluate estimates. Estimates of numbers of deposits as a probability distribution explicitly represent the probability (or degree of belief) that some fixed but unknown number of undiscovered deposits exist in the delineated tracts (Singer, 2007a). The difference between the number of undiscovered deposits associated with the 90th percentile and the 10th percentile or 1st percentile is a measure of uncertainty; large differences suggest great uncertainty. Another useful parameter for reporting uncertainty associated with an estimate is the coefficient of variation (C_v), defined as:

$$C_v = s_x/\lambda. \qquad (3)$$

The coefficient of variation is often reported as percent relative variation (100 × C_v). Thus, the final team estimates reflect both the favorability (λ) and the uncertainty (C_v) of what may exist in the tract (Singer, 2007a).

The following sections describe the rationale for estimates of numbers of undiscovered porphyry copper deposits for each permissive tract along with some of the data considered in arriving at the estimates (Table 4) and the estimates (Table 5).

4.1. Tagil-Polar tract

The Tagil arc extends from the Middle Urals to the Polar Urals region (Fig. 1). The area is remote and poorly studied relative to the southern Urals. Permissive igneous intrusions and stratified map units that include volcanic lithologies that could be associated with porphyry copper deposits crop out over about half of the tract area (Table 1). Although porphyry copper resources are not yet thoroughly delineated in the tract, three porphyry-skarn prospects, eight copper skarn occurrences, and 63 occurrences where copper is reported as a major commodity are present (Table 4). In addition, Plotinskaya et al. (2017– in this volume) mention 3 additional porphyry-related deposits in the North to Middle Urals in the Tagil-Magnitogorsk megaterrane (Petropavlovskoe, Andrushinskoe, and Rudnobolotskoe). If fully explored, identified resources may become available for these and other prospects, all of which presently are indicative of undiscovered copper resources in the tract. Copper occurrences may or may not be indicative

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[2] To use the equation in cases where three non-zero quantiles (90-50-10) are estimated, use the N_{10} values for N_{05} and N_{01}; where four quantiles (90-50-10-5) are estimated, use the N_{05} value for N_{01}.

of a porphyry system; volcanogenic massive sulfide (VMS) deposits throughout the Urals are also copper-rich (Herrington et al., 2005c).

Prognostic studies were done by Urals geologists and by the Central Research Geological Exploration Institute of Nonferrous and Precious Metals in Moscow for many years with a focus on VMS deposits, and exploration for porphyry copper deposits was done during the years 1974 to 1984 (Ageyeva et al., 1984). Some parts of the tract include coeval intrusive and extrusive permissive rocks suggesting an appropriate depth of porphyry preservation. Other parts of the tract are primarily intrusive and may be too deeply eroded to preserve many porphyry deposits.

Estimates of a 90% chance of 1 or more deposits, a 50% chance of 3 or more deposits, and a 10% chance of 8 or more deposits resulted in a mean of 4.4 undiscovered deposits for the 49,600 km^2 tract area (Table 5). The relatively high coefficient of variation ($C_v\% = 101$) associated with the probability distribution for undiscovered deposits within the tract reflects a relatively high degree of uncertainty for this little-known area, much of which consists of undifferentiated early Paleozoic rocks.

4.2. Magnitogorsk tract

The Magnitogorsk tract has been extensively explored studied for VMS deposits (Herrington et al., 2005c). Although both VMS and magnetite skarn deposits have been the main exploration focus in the area, a number of small porphyry copper prospects are known but have not been developed (Fig. 4). Resources of 41,000 metric tons of contained copper are reported for the Yubileinoe deposit (Table 1). Almost 40% of the tract is covered by rocks that are younger than Late Devonian (Table 2). About a third of the tract area is occupied by permissive igneous rocks exposed at the surface, and more than half of those are stratified map units that include volcanic rocks. The presence of coeval intrusive and extrusive rocks suggests that the level of exposure preserved within the tract area is optimal for preservation of porphyry copper deposits. The tract hosts 64 copper occurrences (Petrov et al., 2006). Most of these occurrences only report Cu; two are described as Cu-Au and two as Cu-Mo. Most of the skarns in the tract area are magnetite skarns; one is a W-Cu-Mo skarn.

The team concluded that Salavat is an incompletely explored prospect that upon further investigation is likely to become a viable deposit. In addition, Yubileinoe (10 Mt of ore) may not be fully delineated. With an area of 49,320 km^2 (Table 2), the Magnitogorsk tract is the about the same size as the Tagil-Polar Urals tract to the north. The team estimated a 90% chance of 2 or more undiscovered deposits, a 50% chance of 4 or more deposits and a 10% chance of 6 or more deposits (Table 5). The relatively low coefficient of variation ($C_v\% = 77$) associated with the probability distribution for undiscovered deposits within the tract and the relatively high deposit density of about 10 deposits 100,000 km^2 (Table 5) indicate that the team considered the tract favorable for the occurrence of undiscovered porphyry copper deposits.

4.3. East Uralian tract

The East Uralian tract hosts the Birgilda and Tomino porphyry copper deposits and the largest number of important porphyry copper prospects (10). The tract is more thoroughly explored than the tracts to the north. About a third of the tract area is occupied by permissive igneous rocks exposed at the surface and the ratio of permissive intrusive rocks to extrusive rocks is about 3 to 1, suggesting that some parts are more deeply eroded than others. About 20% of the tract is characterized by exposed Precambrian rocks and sedimentary rocks younger then Early Carboniferous cover 35% of the tract area (Table 2).

The tract hosts two copper skarns (Fig. 7) and an additional 55 copper occurrences that are listed in the database of Petrov et al. (2006). Of these, 11 are Cu-Mo occurrences and two others list Cu and Au. The recognition of large zones of porphyry-type mineralization within the tract (Birgilda-Tomino ore cluster, Alapaevsk-Sukhoi Log porphyry copper zone) suggests that additional deposits are likely to exist within the tract.

The team estimated a 90% chance of 3 or more undiscovered deposits, a 50% chance of 5 or more deposits and a 10% chance of 10 or more deposits for a mean of 6.5 undiscovered porphyry copper deposits (Table 5). Estimates at the lower percentiles reflect the team's conclusion that some proportion of the skarns and many copper occurrences within the tract could be associated with porphyry copper systems, and that some systems may exist in completely unexplored areas. A relatively low coefficient of variation ($C_v\% = 85$) is associated with the probability distribution for undiscovered deposits because of the extensive exploration in this tract.

4.4. Transuralian tract

Porphyry copper occurrences and potentially linked deposit types in the Transuralian tract are possible indicators of undiscovered deposits. The depth of erosion of the terrane east of the EUZ was not excessive, and because of low topographic relief, poor bedrock exposures, and remoteness of much of the area, there were many prospective areas left unexplored despite some Soviet-era investment in the region. The consensus was that less than a tenth of the delineated tract was of the correct age and/or the correct igneous rock types to host porphyry copper deposits. However, some of the known deposits are completely covered and younger sediments cover >70% of the tract area. In addition to the 4 known deposits, the tract hosts 4 porphyry copper prospects, 2 copper skarns, and 49 other copper occurrences (Table 4). The team estimated a mean of 6.1 undiscovered deposits, based on a 90% chance of 2 or more deposits, a 50% chance of 4 deposits, a 10% chance of 10 deposits, and lower probabilities of as many as 18 or 32 deposits (Table 5). The high coefficient of variation ($C_v\% = 100$), associated with the probability distribution for undiscovered deposit within the tracts reflects a relatively high degree of uncertainty.

5. Assessment results

5.1. In-place undiscovered resources

Consensus estimates for each permissive tract (Table 5) were combined with the global porphyry copper grade and tonnage model of Singer et al. (2008) in a Monte Carlo simulation using the EMINERS computer program (Root et al., 1992; Bawiec and Spanski, 2012; Duval, 2012). The resulting probabilistic estimates of amounts of in-place resources that could be associated with undiscovered deposits within each tract are listed in Table 6. Monte Carlo simulation results for each commodity in each tract are shown graphically in Fig. 9, using a log scale for the amount of each material. The probability distributions display a range of possible amounts of undiscovered resources for each commodity and for bulk ore tonnage. Note that there is some probability of no resources for all commodities and all tracts (Table 6). For example, the probability of no undiscovered copper for the Tagil tract is 0.06 (Table 6). In addition, the mean is greater than the median (probability = 0.5) in all cases.

A mean of 17 million metric tons (Mt) of copper is estimated for both the Tagil and Magnitogorsk tracts. The Tagil tract is about the same size as the Magnitogorsk tract (Table 3), each of the tracts contains three known porphyry copper prospects, and the amount of exposed permissive rock is similar (Table 4). The higher coefficient of variance associated with the estimates for the Tagil-Polar tract ($C_v\%$ 101 vs. 77) reflects a higher degree of uncertainty although the mean number of undiscovered deposits is about the same (Table 5).

The mean amounts of copper in undiscovered deposits in both the East Uralian and Transuralian tracts are higher, at 24 Mt in each (Table 7). In addition to copper, the simulation results imply that significant amounts of molybdenum, gold, and silver may also occur.

Table 6
Results of Monte Carlo simulations of undiscovered resources [Cu, copper; Mo, molybdenum; Au, gold; and Ag, silver; in metric tons; Rock, in million metric tons].

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
				Tagil-Polar Urals tract				
Cu	0	320,000	7,100,000	43,000,000	70,000,000	17,000,000	0.28	0.06
Mo	0	0	110,000	1,200,000	2,000,000	460,000	0.24	0.19
Au	0	0	160	1100	1700	430	0.28	0.16
Ag	0	0	1200	14,000	26,000	5400	0.24	0.27
Rock	0	73	1600	8800	14,000	3400	0.29	0.06
				Magnitogorsk tract				
Cu	300,000	1,200,000	8,200,000	41,000,000	67,000,000	17,000,000	0.27	0.04
Mo	0	0	140,000	1,100,000	2,000,000	470,000	0.23	0.11
Au	0	3	190	1100	1700	440	0.28	0.09
Ag	0	0	1500	12,000	23,000	5500	0.22	0.19
Rock	67	300	1800	8100	14,000	3500	0.29	0.04
				East Uralian tract				
Cu	550,000	2,000,000	13,000,000	61,000,000	94,000,000	24,000,000	0.29	0.03
Mo	0	7100	240,000	1,700,000	2,900,000	680,000	0.25	0.08
Au	0	17	310	1500	2200	610	0.30	0.06
Ag	0	0	2600	21,000	33,000	8100	0.25	0.13
Rock	130	490	2800	13,000	19,000	5000	0.30	0.03
				Transuralian tract				
Cu	210,000	1,000,000	11,000,000	64,000,000	100,000,000	24,000,000	0.28	0.04
Mo	0	0	200,000	1,800,000	3,000,000	660,000	0.25	0.11
Au	0	3	240	1600	2400	610	0.28	0.1
Ag	0	0	2100	21,000	33,000	8000	0.24	0.17
Rock	49	250	2300	13,000	20,000	4900	0.29	0.04

The ratio of mean undiscovered copper resources to identified porphyry copper resources indicates that about 14 times more copper in Paleozoic porphyry copper deposits than is presently known may exist in the Urals (Table 7). Additional data on identified resources that were not available at the time of the assessment would, of course, change these ratios.

5.2. Economic filters

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

The economic resource is estimated as:

$$\text{economic resource} = \text{resource} \times \text{economic filter},$$

where “resource” is the mean undiscovered resource estimated by the Monte Carlo simulation (Table 5) and the “economic filter” is the fraction of the resources estimated to be economic based on the grade and tonnage model used in the simulation, the depth distribution for the undiscovered deposits, and adjustments for cost settings. Results of the Monte Carlo simulation and economic filter analysis provide an estimate of undiscovered resources, potential economic resources, and the probability of failure (probability of no economic resource) for each tract (Table 8).

The economic filters were computed using an Excel workbook developed by Robinson and Menzie (2012). The 20-year (1989–2008) average metal prices and metallurgical recovery rates were used in the filter calculations, along with the specified depth percentage and cost settings.

The depth distribution affects the amount of material that would have to be moved to develop a mine. Some deposits are exposed at the surface. However, many are not and the amount of cover material that must be removed to access the ore adds to the cost of developing a mine. These costs can make the difference between an economic and an uneconomic deposit. For each tract, a subjective estimate of a hypothetical depth distribution of undiscovered deposits was made. These estimates refer to the part of the upper kilometer of the earth's crust that the tops of any undiscovered porphyry copper deposits are expected to lie within. As a default, 25% of the undiscovered deposits are accessible in the upper 250 m of the crust, 25% are accessible between 250 and 500 m, and 50% lie below 500 m but above 1 km. For areas that have significant amounts of volcanic rocks or other cover such as the Transuralian tract, it was assumed that a greater percentage of the undiscovered deposits would lie at deeper depths, so the distribution was skewed to: 10% of the undiscovered deposits in the upper 250 m of the crust, 30% between 250 and 500 m, and 60% below 500 m but above 1 km.

The economic viability of a deposit also depends on the availability of existing infrastructure for developing a mine (e.g., transportation routes, power and water, nearby towns for logistical support). As an independent guide to selecting appropriate cost settings for mining for each tract, we considered the infrastructure rankings compiled by the Fraser Institute for Russia (McMahon and Cervantes, 2012) and applied a ranking of “typical cost” setting to tracts that have existing regional infrastructure to support mining. For the Tagil tract, which includes very remote northern regions, a “high cost” setting was used. The Transuralian tract, where much of the permissive rock lies under cover, was also assumed to be a “high cost” setting. The other two tracts were considered a mix of “typical” and “high cost” settings.

Application of the filter to the assessment results shows that about half of the mean amount of undiscovered copper could be economic based on the assumptions used in the modeling (Table 8; Fig. 10). Approximately 30 to 50% of the mean amounts of molybdenum, gold, and silver pass the filter as potentially economic commodities (Table 8).

5.3. Discussion

The porphyry copper deposits of the Urals occur in both Russia and Kazakhstan. Russia ranked 7th in global copper mine production in 2014, with production of 850,000 metric tons of copper

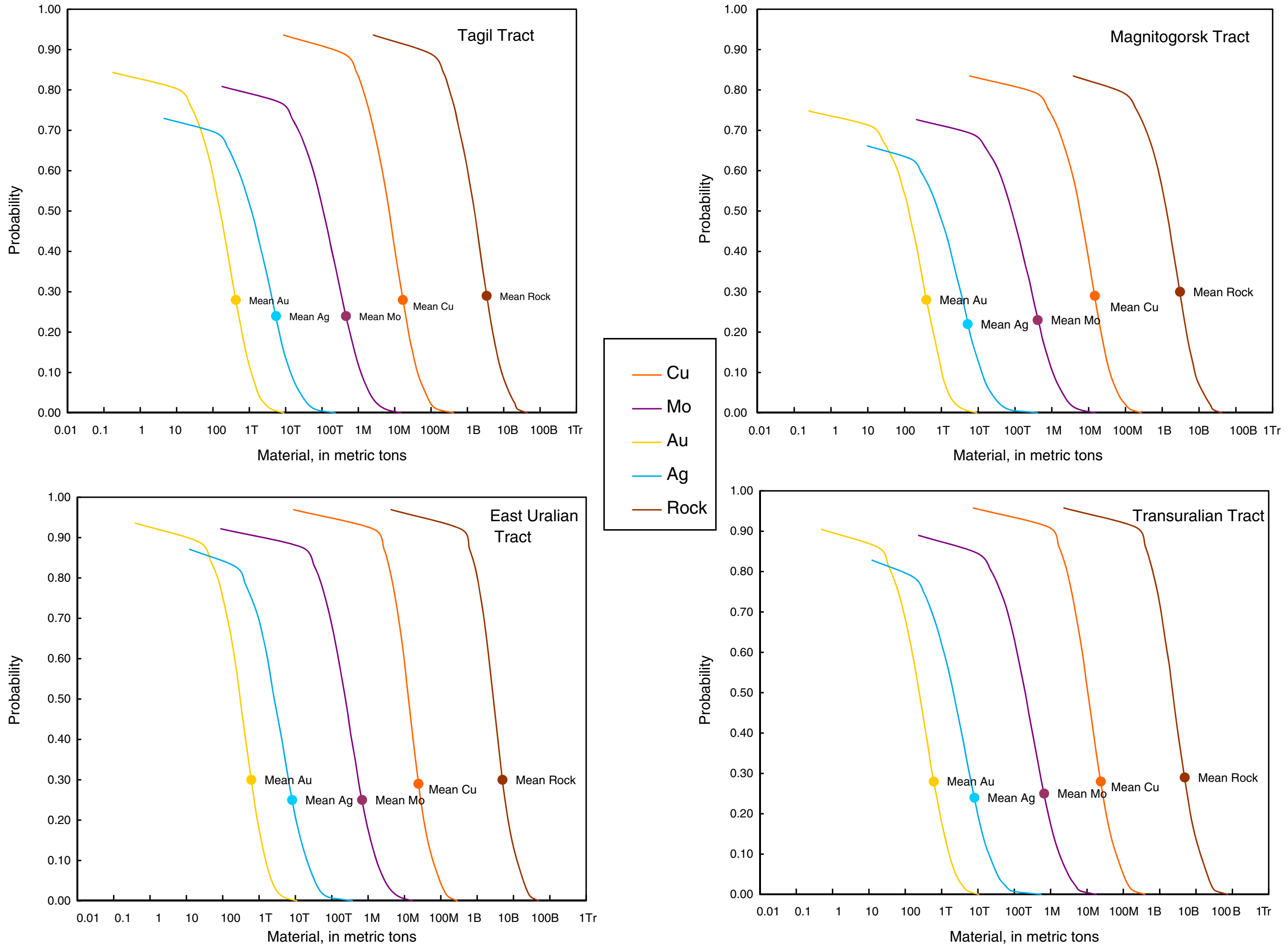

Fig. 9. Probabilistic assessment results. Cumulative frequency plots showing results of Monte Carlo computer simulations of undiscovered resources. T = thousands, M = millions, B = billions, Tr = trillions.

(U.S. Geological Survey, 2015). Most of the production in Russia was from the magmatic sulfide-rich Ni-Cu-PGE deposits of the Noril'sk-Talnakh area. Since 2000, development activity has been reported at some porphyry copper deposits in the Urals in Russia (Safirova, 2015; International Copper Study Group, 2013). The Russian Copper Company (RMK, Russkaya Mednaya Kompaniya) is developing the mines and processing plants for the Mikheevskoe and Tomino porphyry copper deposits. Construction at Mikheevskoe began in 2011 as the largest new mining project to be constructed in Russia in recent times. An open pit mine planned for Tomino (feasibility stage) includes a processing plant slated to come on line in 2015 with a capacity to produce 52,000 t of copper concentrate per year. A hydrometallurgical (SX-EW) pilot plant at Gumeshevskoe went into operation in 2005 to produce 5000 t of copper cathode per year. In Kazakhstan, which produced 430,000 metric tons of copper in 2014, most of the copper comes from porphyry copper deposits in the eastern part of the country (Seltmann et al., 2014; Berger et al., 2014) and from sediment-hosted stratabound copper deposits at Dzhezkazgan in the Chu Sarysu Basin of south-central Kazakhstan (Box et al., 2013). In the Urals area, copper production at Yubileinoe began in 2006, at Vavarinskoye in 2007, and at Benkala in 2012 (International Copper Study Group, 2013).

Potentially economic copper resources in 22 undiscovered porphyry copper deposits in the four permissive tracts (38 Mt) exceed the 6 Mt of identified porphyry copper resources in the Urals (Table 1). These undiscovered resources are comparable in magnitude to the 30 Mt of copper reserves reported for Russia and 6 Mt of copper reserves reported for Kazakhstan for all deposit types in 2014. However, the discovery and potential development of undiscovered resources depends on continued exploration as well as social, economic, environmental, and political license to pursue mineral resource development. The complex

Table 7
Summary of simulations of undiscovered resources in porphyry copper deposits in the Urals [t, metric tons; Mt, million metric tons, NA, not applicable].

Tract name	Identified copper resources (t)	Mean estimate of in-place undiscovered resources of					Undiscovered copper/identified copper
		Copper (t)	Molybdenum (t)	Gold (t)	Silver (t)	Rock (Mt)	
Tagil-Polar Urals	0	17,000,000	460,000	430	5400	3400	NA
Magnitogorsk	41,000	17,000,000	470,000	440	5500	3500	7
East Uralian	1,588,600	24,000,000	680,000	610	8100	5000	15
Transuralian	4,285,592	24,000,000	660,000	610	8000	4900	6
Total	5,915,192	82,000,000	2,270,000	2090	27,000	16,800	NA

Table 8
Economic filter results [cost setting, see text for explanation; Depth distribution of undiscovered deposits, Default: 25% in upper 250 m, 25% between 250 and 500 m, and 50% below 500 m; Skewed deep: 10% in upper 250 m, 30% between 250 and 500 m, and 60% below 500 m; t, metric ton; Filter input, mean estimates of undiscovered resources and probability of no resources as reported in Table 5; Filter output, amount of potentially economic resources based on assumed cost settings and depth distribution (Robinson and Menzie, 2012); Economic/Mean undiscovered resources, Filter output/filter input as a percentage; NA, not applicable].

Tract	Cost setting	Depth distribution	Economic filter	Copper (t)	Molybdenum (t)	Gold (t)	Silver (t)	Probability of no resource	Probability of no economic resource
Tagil-Polar Urals	High cost	Default	Filter input	17,000,000	460,000	430	5400	6%	NA
			Filter output	8,300,000	180,000	150	2500	NA	57%
			Economic/mean undiscovered resources	49%	39%	35%	46%	NA	NA
Magnitogorsk	Mixed	Default	Filter input	17,000,000	470,000	440	5500	4%	NA
			Filter output	10,000,000	210,000	200	3000	NA	32%
			Economic/mean undiscovered resources	59%	45%	45%	55%	NA	NA
East Uralian	Mixed	Default	Filter input	24,000,000	680,000	610	8100	3%	NA
			Filter output	14,000,000	30,0000	270	4500	NA	20%
			Economic/mean undiscovered resources	58%	44%	44%	56%	NA	NA
Transuralian	High cost	Skewed deep	Filter input	24,000,000	610,000	610	8000	4%	NA
			Filter output	11,000,000	240,000	180	3500	NA	57%
			Economic/mean undiscovered resources	46%	36%	30%	44%	NA	NA

geology of the Urals poses challenges for exploration. Much of the permissive geology lies under cover in the West Siberian Basin. Exposed areas in the southern Urals have low topography and deep weathering, and some areas are likely too deeply eroded to preserve porphyry copper deposits. The most prospective areas for additional porphyry copper deposits are the East Uralian and Transuralian tract areas, which host the most important deposits identified to date. Both the Magnitogorsk and Tagil-Polar tracts may represent future sources of copper in porphyry and porphyry-related skarn deposits.

In addition to copper, undiscovered porphyry copper deposits in the Urals may contain significant amounts of molybdenum, gold, and silver. The fact that molybdenite in porphyry copper deposits provides most of the world's rhenium prompted a number of studies of the rhenium content of molybdenite in porphyry copper deposits of the Urals (Grabezhev, 2007, 2013; Grabezhev and Voudoris, 2014; Plotinskaya et al., 2015).

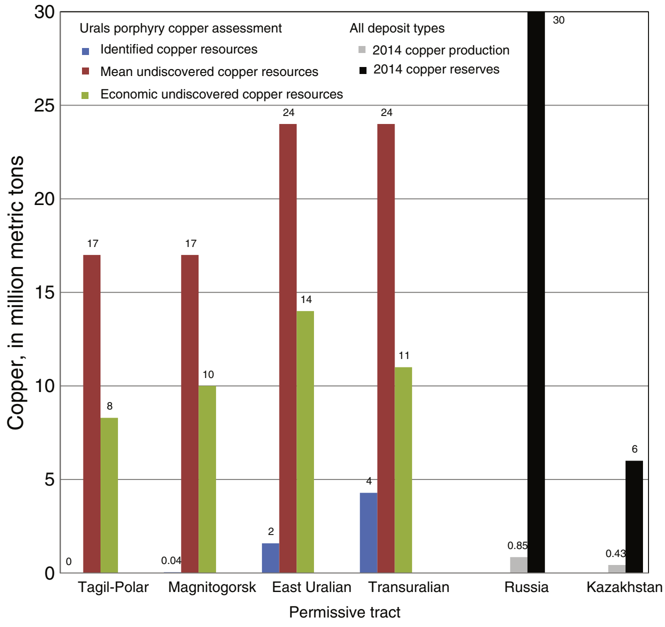

Fig. 10. Bar charts comparing identified porphyry copper resources, mean undiscovered copper resources, and mean economic undiscovered resources. See text for methods and assumptions. Data for 2014 Russia copper production and copper reserves for all deposit types from U.S. Geological Survey (2015).

6. Paleozoic porphyry copper deposits in the Urals and continental Asia

The distribution of Paleozoic magmatic arc complexes that host porphyry copper deposits in Asia reflects the complex history of amalgamation of the major Paleozoic orogenic systems on the continent (Fig. 11). The Uralides orogenic system records the amalgamation of island arcs accreted to the European craton and the continental margin of the Kazakh craton, whereas the predominantly east-west continental margin and island-arc complexes of the Central Asian Orogenic Belt mark the collision of the Siberian craton with craton blocks of China to the south and the closure of the PaleoAsian and Tethyan oceans. The southern Asia belts of Paleozoic rocks that are permissive for porphyry copper deposits include early Paleozoic island arcs and Devonian continental arcs related to north-directed subduction of the Paleotethys Ocean and accretion to the Central Asian Orogenic Belt. In contrast to the Urals, the other Paleozoic orogens of Asia have a long and complex post-Carboniferous tectonic and magmatic history related to Mesozoic evolution of the Pacific margin and ongoing Alpine-Himalayan tectonics along the Tethysides orogenic belt (Fig. 11).

Permissive tracts for Paleozoic porphyry copper deposits in continental Asia from the global mineral resource assessment are symbolized by dominant tectonic setting on Fig. 11 (this study; Berger et al., 2014; Mihalasky et al., 2015). Many of the permissive tracts for porphyry copper deposits in Asia are large, generalized, and cover long time periods. In detail, many of the permissive tracts represent mixed and overprinted tectonic settings. Nevertheless, some broad patterns emerge. The world class Devonian Oyu Tolgoi porphyry copper deposit (Fig. 11) in Mongolia is associated with primitive island-arc rocks in an area where Paleozoic island- and continental-margin arcs accreted to the margin of Asia (Khashgerel et al., 2008). Oyu Tolgoi remained buried until Cretaceous uplift brought the deposit near to the surface. A similar juxtaposition of Paleozoic accreted island- and continental- margins arcs occurs in the eastern Urals, where the Mesozoic and Cenozoic sedimentary rocks of the West Siberian Basin may conceal deeply buried undiscovered porphyry copper deposits within the Paleozoic basement, especially along the westernmost margins of the basin.

Many porphyry copper deposits throughout the world are valued more for their gold or molybdenum than for their copper. Commodities

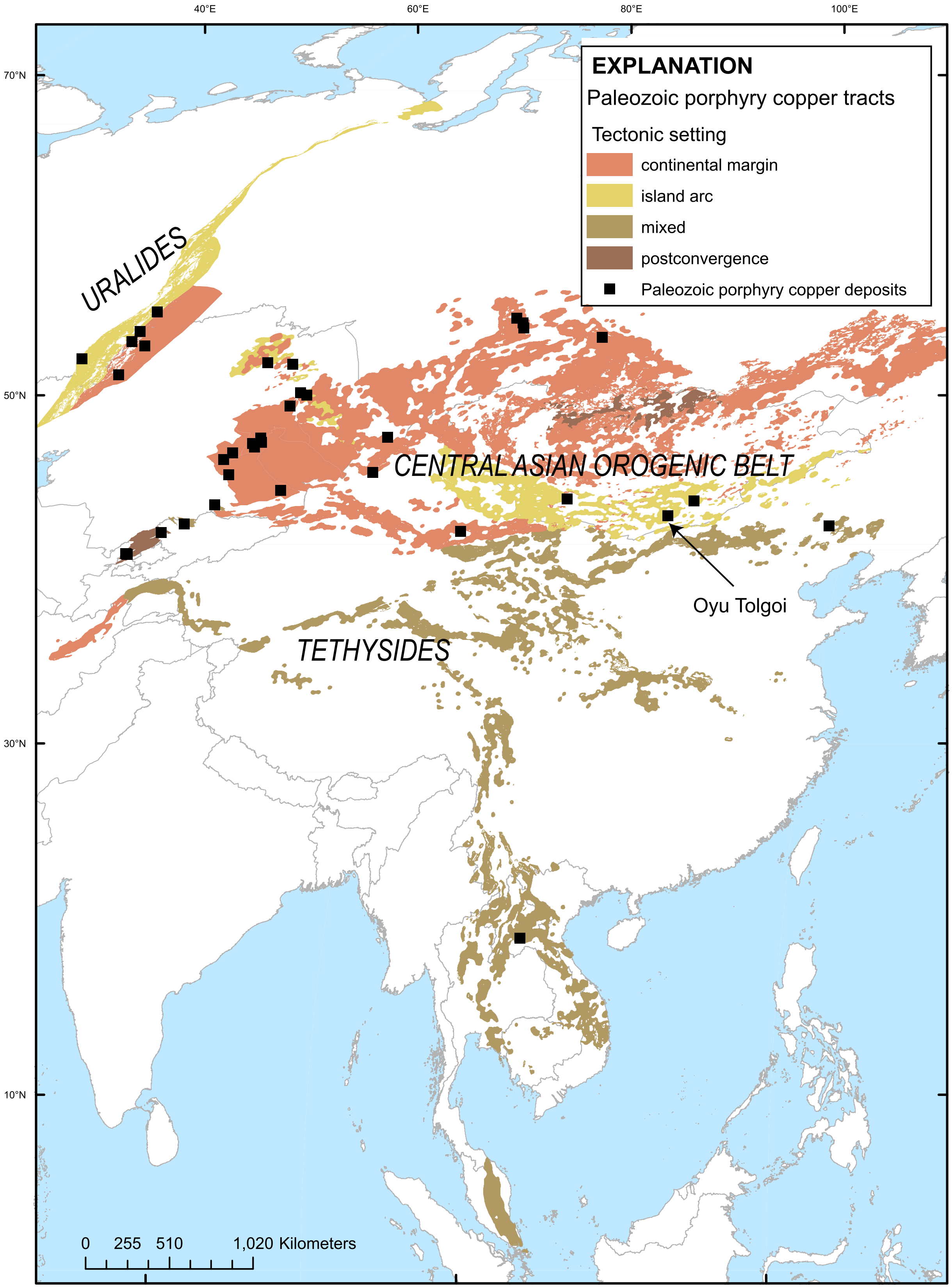

Fig. 11. Map of permissive tracts for Paleozoic porphyry copper deposits in the Urals and continental Asia from the USGS global copper assessment (Johnson et al., 2014). Sources: This study, Dicken et al. (2016). Robinson projection.

reported for porphyry copper occurrences in the Urals (Table 3) suggest that both Mo-rich and Au-rich systems are present in all of the permissive tracts. An analysis of distinctions in metal contents in global porphyry copper deposits as a function of tectonic setting showed that tonnages and copper grades are not significantly different among deposits formed in island arcs, continental-margin arcs, and postconvergent (also known as post-collisional or post-subduction) settings (Ludington et al., 2014). However, average molybdenum grades are highest in deposits in postconvergent settings and lowest in island arc-hosted deposits. Average gold grades in deposits in postconvergent and island-arc settings are higher than those in deposits found in continental-margin arcs. The presence of some younger rocks with permissive lithologies for porphyry copper deposits in close proximity to the older island-arc rocks in the Tagil-Polar tract (Fig. 5) such as at Novogodnee-Monto suggests that both island arc and postconvergent porphyry copper mineralization occurred in the Urals, which may be reflected in apparent enrichments in both gold and molybdenum. Lack of information about metal grades however, precludes more detailed analysis. Use of larger-scale geologic maps (>1:1,000,000) and more detailed information on the relative amounts of permissive volcanic rocks included in map units for stratified rocks would help refine the tract delineations. Similarly, regional compilations of locations, age, and geochemistry of igneous rocks would help define permissive tectonic settings for porphyry copper deposits.

Conflicts of interest

No conflicts of interest.

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