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Porphyry deposits of the Urals: Geological framework and metallogeny

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ABSTRACT

Most of the Cu (±Mo,Au) porphyry and porphyry-related deposits of the Urals are located in the Tagil-Magnitogorsk, East-Uralian Volcanic and Trans-Uralian volcanic arc megaterranes. They are related to subduction zones of different ages:

(1) Silurian westward subduction: Cu-porphyry deposits of the Birgilda-Tomino ore cluster (Birgilda, Tomino, and Kalinovskoe) and the Zeleny Dol Cu-porphyry deposit;
(2) Devonian Magnitogorsk eastward subduction and the subsequent collision with the East European plate: deposits and occurrences are located in the Tagil (skarn-porphyry Gumeshevskoe etc.) and Magnitogorsk terranes (Cu-porphyry Salavat and Voznesenskoe, Mo-porphyry Verkhne-Uralskoe, Au-porphyry Yubileinoe etc.), and probably in the Alapaevsk-Techa terrane (occurrences of the Alapayevsk-Sukhoy Log cluster);
(3) Late-Devonian to Carboniferous subduction: deposits located in the Trans-Uralian megaterrane. This includes Late-Devonian to Early Carboniferous Mikheevskoe Cu-porphyry and Tarutino Cu skarn-porphyry, Carboniferous deposits of the Alexandrov volcanic arc terrane (Bataly, Varvarinskoe) and Early Carboniferous deposits formed dew to eastward subduction under the Kazakh continent (Benkala, etc.).
(4) Continent-continent collision in Late Carboniferous produced the Talitsa Mo-porphyry deposit located in the East Uralian megaterrane.

Porphyry mineralization of the Magnitogorsk megaterrane shows an evolving relationship from gabbro-diorite and quartz diorite in the Middle Devonian (Gumeshevskoe, Salavat, Voznesenskoe) to granodiorite-plagiogranodiorite in the Late Devonian (Yubileinoe Au-porphyry) and finally to granodiorite in the Carboniferous (Talitsa Mo-porphyry) with a progressive increase in total REE, Rb and Sr contents. This corresponds to the evolution of the Magnitogorsk terrane from a volcanic arc which gave place to an arc-continent collision in the Famennian.

1. Introduction

The geological literature concerning porphyry and porphyry related mineralization (incl. skarn and epithermal) of the Urals is very limited. Papers published in English usually describe single deposits (e.g. Shatov et al., 2014; Plotinskaya et al., 2014b) or describe only some particular features of them, such as Au or Re distribution etc. (Grabezhev et al., 1996; Grabezhev, 2013; Plotinskaya et al., 2014a; Kholodnov et al., 2016). Very few reviews which include Uralian porphyry deposits have been published in English (e.g. Ageyeva et al., 1984; Grabezhev, 1992; Grabezhev and Borovikov, 1993; Zvezdov et al., 1993; Seltmann et al., 2014). As a consequence, Uralian porphyry deposits are poorly represented in international literature and databases (http://www.portergeo.com.au; http://mrdata.usgs.gov/porcu; Petrov et al., 2007 etc.), see also (Hammarstrom et al., 2017).

Descriptions of Uralian porphyry deposits in the Russian literature began to appear in the late 1970s (Pavlova, 1978; Vorob'ev et al., 1978) peaking in the 1980s–1990s (Grabezhev and Belgorodskii, 1992; Krivtsov et al., 1986; Kontar and Libarova, 1997, etc.). This was

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the period when intensive prospecting work was focused on porphyry type deposits in the Urals. It resulted in the discovery of tens of porphyry occurrences, mostly located in the South Urals. The most comprehensive review of Cu deposits in the Urals (Kontar, 2001) listed about 60 Cu porphyry deposits, occurrences and prospects, but did not include Mo- and Au porphyries. It should be noted, however, that some of the porphyries listed there have never been properly studied and so might have been ascribed to the porphyry type by mistake. This has happened even in the case of well-studied deposits, for example the Shameika Mo deposit that was described as a Mo-porphyry (Mao et al., 2003) whereas most researchers classified it as greisen type (Yelokhin and Griaznov, 2012). The Bereznyakovskoe deposit was erroneously classified as an Au-porphyry (Sazonov et al., 1994; Seravkin et al., 2011) even though it is in fact an epithermal Au-Ag deposit (Lehmann et al., 1999; Grabezhev et al., 2000; Plotinskaya et al., 2009). Sometimes skarn Cu deposits related to porphyry systems, though containing only insignificant porphyry Cu (or Mo) mineralization, e.g. Gumeshevo (Grabezhev, 2010) or Tarutino (Grabezhev et al., 2004) were classified as "pure" porphyry or as "pure" skarn types. As a result of these uncertainties and contradictions, Uralian porphyry deposits are absent from several fundamental reviews published in Russian (Popov, 1977; Ovchinnikov, 1998) and thus remain unknown, even to Russian readers.

The recent era of porphyry deposit studies in the Urals began after 2000 with new exploration work and reassessment of known porphyry occurrences. At present there are three porphyry deposits being mined. These are the Yubileinoe Au porphyry, the Benkala Cu(Mo, Au) porphyry (Kazakhstan) and the Mikheevskoe Cu porphyry (Russia). The Tomino Cu porphyry deposit is being developed for exploitation in the near future. Several other porphyry occurrences are now under exploration and reevaluation and so porphyry type deposits have become economically important in the Urals (Ovcharova et al., 2007; Beskin and Alekseeva, 2016).

It is not the aim of this paper to list all porphyry occurrences of the Urals known to date, but an attempt has been made to give an overview of the spatial distribution of Cu-(Mo,Au)-porphyry and porphyry-related deposits and occurrences within the Uralian orogeny in relationship to its tectonic architecture. Geological, petrological, mineralogical, and geochemical data obtained from most of the known Uralian porphyry deposits during the last 40 years compiled with the assistance of one of us (A.I.G.) has been summarized together with data published in the Russian and international literature, supplemented by the results gathered of our recent studies. Information from the most comprehensive review published by Grabezhev and Belgorodskii (1992) has been used.

2. Distribution of porphyry and porphyry related deposits in the Urals

The distribution of porphyry and porphyry-related deposits in the Urals is shown in Fig. 1 and short descriptions are given in Table 1. This does not include all the porphyry deposits and occurrences reported in the published literature or in unpublished reports but only those for which reliable information on the geology, alteration and mineralization styles has been published. As can be seen in Fig. 1 most of porphyry and porphyry related (skarn and epithermal) deposits are confined to three major subduction-related volcanic terranes (or megazones): the Tagil-Magnitogorsk megaterrane, the East-Uralian megaterrane, and the Trans-Uralian megaterrane. Most of the porphyry deposits and occurrences are concentrated in the Southern Urals where subduction-related terranes are better exposed and to a lesser degree in the Middle Urals.

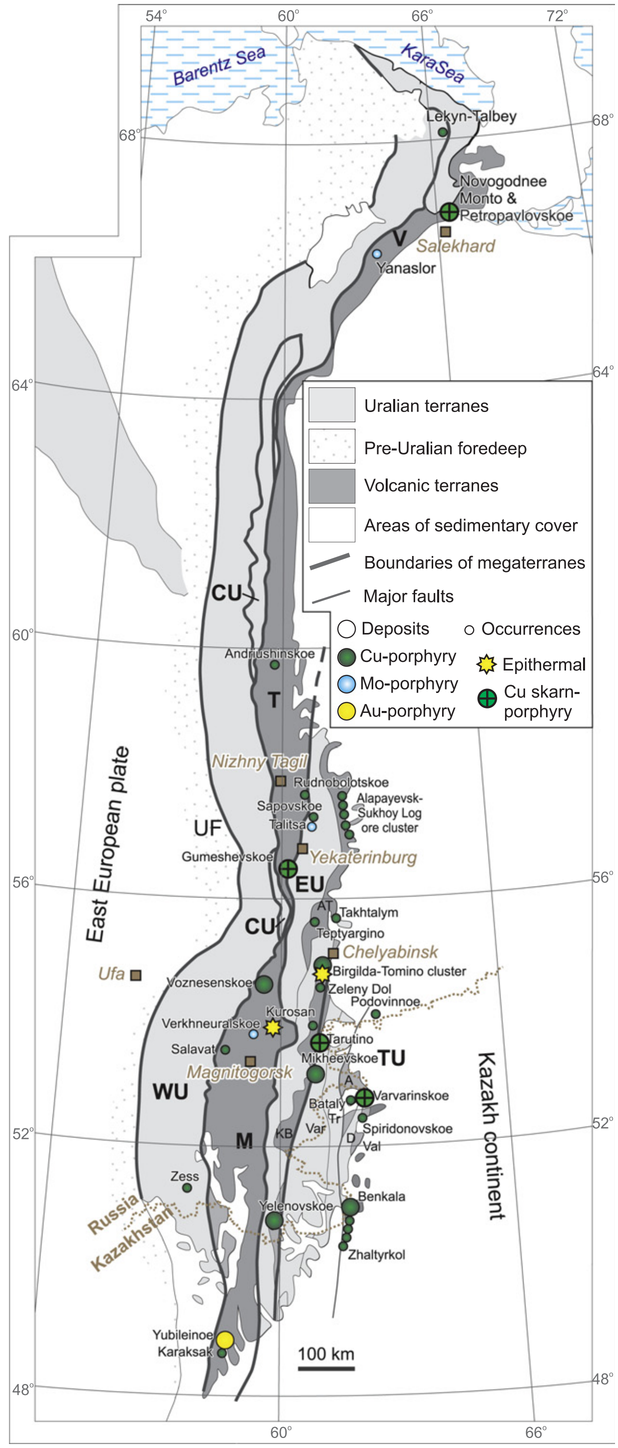

Fig. 1. Simplified tectonic scheme of the Urals and locations of porphyry and porphyry related deposits, prospects and occurrences. Modified after (Petrov et al., 2007). Megaterranes: UF – Ural Foredeep, WU – West Uralian; CU – Central Uralian; M – Magnitogorsk; EU – East Uralian with Alapaevsk-Techa (AT) and Kosobrodka-Bredy (KB) volcanic terranes, TU – Trans Uralian megaterrane with Varna (Var), Troitsk (Tr), Alexandrov (A), Denisov (D) and Valerianovka (Val) terranes.

2.1. The Tagil - Magnitogorsk megaterrane

The **Tagil** volcanic arc and its Cis-Polar analogue, the **Voikar** volcanic arc, are composed of Late Ordovician–Early Devonian intra-oceanic volcanic sequences evolving from tholeiitic through differentiated calc-alkaline to subalkalic shoshonitic compositions during westward subduction (Puchkov, 2010, 2013 and references therein). Both arcs host several porphyry occurrences together with famous PGE deposits and numerous VHMS deposits (see Puchkov, 2017). The **Voikar** terrane hosts the **Yanoslor** Mo-porphyry occurrence related to the granitic series of the same name (Yelokhin and Griaznov, 2012) and

Table 1
Porphyry and porphyry-related deposits and occurrences of the Urals.

No	Deposit (other names)	Host rocks	Associated intrusion(s)	Age[a]	Alteration types	Ore minerals: common/rare	Tonnage, grade	References
The Tagil-Magnitogorsk megaterrane								
North to Middle Urals, Voikar to Tagil *terranes*								
1	**Yanoslor**	Gabbroic intrusive rocks, diorite porphyries	Granite (alaskite), porphyry granite	320–340 Ma (K-Ar)	Kfs + quartz, later stage argillisites	Magnetite, pyrite, chalcopyrire, molybdenite	Probable: Cu 178 kt, Mo-42 kt	Perminov (1994), Yelokhin and Griaznov (2012), Ural Industrial-Ural Polar (2008)
2	**Novogodnee–Monto**	Silurian to Lower Devonian volcanics, volcanic-sedimentary rocks, limestone	Early to Middle Devonian calc-alkaline series (gabbro to diorite) and Late Devonian to Early Carboniferous potassic series (monzogabbro, monzodiorite- to monzonite-porphyry, lamprophyres)	Late Devonian–Early Carboniferous (Geol); 360 ± 1.3 Ma (Rb-Sr in mica)	1) Magnetite skarn 2) Amphibole + chlorite + epidote + quartz + albite 3) Sericite + quartz + carbonate	Magnetite, pyrite, chalcopyrite, arsenopyrite, cobaltite, native Au, galena, sphalerite, tellurides/hematite, pyrrhotite, titanite	Skarn: 1.9 Mt @ 4.9 g/t Au (9.1 t Au) and 5.2 Mt @ 1.2 g/t Au (5.7 t Au); quartz–sulfide vein zones: 0.5 Mt @ 2.6–3.8 g/t Au (1.6 t Au); Cu < 0.25% up to 1.4 wt.% Cu	Soloviev et al. (2013), Newall et al. (2007)
3	**Petropavlovskoe**	Silurian to Lower Devonian volcanics, volcanic-sedimentary rocks	Early to Middle Devonian calc-alkaline series (gabbro to diorite)	Middle Devonian (Geol)	1) (Epidote)-carbonate-chlorite 2) Albite ± chlorite 3) Sericite–quartz	Pyrite/chalcopyrite, galena, native Au, tellurides	13.3 Mt @ 1.14 g/t Au and 7.6 Mt @ 1.4 g/t Au (25.9 t Au)	Mansurov (2013), Newall et al. (2007)
4	**Andriushinskoe**	Basalt, basalt-rhyolite, basalt-andesite-rhyolite (Silurian)	Diorite intrusion Late Ludlow (Geol); diorite porphyry dikes; tonalites-plagiogranites; diabase. Gabbro-diabase porphyries, gabbro porphyries	Late Silurian (Geol)	Ser-chl-qtz (center), weak kfs veinlets, epidote (margins), kaol, barite (locally)	Pyrite, chalcopyrite, minor magnetite, molybdenite/galena, sphalerite, hematite	Cu up to 0.3%	Krivtsov et al. (1986), Grabezhev and Belgorodskii (1992), Kontar (2013)
5	**Rudnobolotskoe**	Andesite-basalts	Diorite porphyry	Middle Devonian (Geol)	Ep-Grt skarn; phyllic: Ser, Qtz, Chl, Car	Magnetite, pyrite, chalcopyrite/sphalerite, Au	Unknown, Cu/Mo = 400; Mo/Au = 38	Grabezhev and Belgorodskii (1992)
6	**Gumeshevskoe (Gumeshevo)**	Lower Devonian marbles, gabbro	Quartz diorite	390 ± 2.8 Ma (U-Pb SHRIMP)	Skarn, phyllic (Qtz-Ser), propylitic	Pyrite, chalcopyrite, sphalerite, magnetite, hematite, pyrrhotite, bornite, arsenopyrite/Au, tellurides, Co-Ni sulfides	Hypog: 462 kt (1.2–1.5% Cu), prospect 798 kt	Grabezhev (2010), Steinberg (2000)
South Urals Magnitogorsk megaterrane								
7	**Mednogorskoe**	Volcanoclastic andesite-basalt Irendyk formation (Lower to Middle Devonian)	Gabbro-diorite porphyries	Mid Devonian (Geol)	Propylitic: Ab, Chl, Act, Ep	Magnetite, pyrite, chalcopyrite, pyrrhotite, pentlandite/Ni-Co sulfides, Au, Au tellurides	Cu/Mo = 600, Mo/Au = 13	Grabezhev and Belgorodskii (1992)
8	**Salavat (Salavatskoe)**	Volcanoclastic andesite-basalt Irendyk formation (Lower to Middle Devonian)	Diorite, quartz diorite porphyry, rare plagiogranodiorite, plagiogranite; postore gabbrodiorite & rhyodacite porphyry	Mid Devonian (Geol)	Propylitic: Ab, Chl, Act, Ep, Ser, Py	Pyrite (dominates), chalcopyrite/molybdenite, pyrrhotite, rutile, galena, magnetite, sphalerite etc.	Cu/Mo = 600; inferred Cu 800 Mt (@ 0.4%); Mo max 0.07.	Minina (1982), Grabezhev and Borovikov (1993), Zvezdov et al. (1993), Kontar (2013)
9	**Voznesenskoe (Voznesenka, Voznesensk)**	Basalts, Irendyk formation andesite-basalt volcanoclastics (Lower to Middle Devonian), serpentinites	Qtz-diorite-diorite-- gabbrodiorite pre-ore pluton, diorite porphyry dykes, intraore plagiogranite & plagioadamellite	381 ± 5 Ma (U-Pb SHRIMP)	Propylitic: Ser, Ab, Chl, prehnite	Chalcopyrite, molybdenite, pyrite, sphalerite	Unknown, Cu/Mo = 250	Grabezhev and Belgorodskii (1992), Shishakov et al. (1988), Grabezhev and Voudoris (2014), Kosarev et al. (2014)
10	**Verkhneuralskoe**	Basalt-trachyite (Famennian)	Gabbro-granodiorite-syenite pluton; qtz-diorite, granodiorite porphyry	Late Devonian to Early Carboniferous, (Geol); 341 ± 1 (Rb-Sr)	Phyllic: Ser, Carb; propylitic; silica and argillic alteration in peripheral zone	Molybdenite, chalcopyrite, pyrite/luzonite	Unknown, Cu/Mo = 15	Grabezhev and Belgorodskii (1992), Salikhov et al. (1994)
11	**Karaksak (Shet-Irgiz)**	Lower to Middle Devonian diabase, basalts	Diorite, Qtz-diorite. Diorite porphyry; dykes of diorite porphyry, plagiogranodiorite porphyry	Middle Devonian (Geol)	Propylitic: Chl, Ser, Car, Amf	Pyrite, chalcopyrite, galena/sphalerite, Au	Unknown, Cu/Mo = 600, Mo/Au = 8	Grabezhev and Belgorodskii (1992)
12	**Yubileinoe (Shekarabulak-II)**	Lower to Middle Devonian basalts,	Gabbrodiorite-granodiorite pluton; plagiogranite	Late Devonian 374 ± 3 Ma (U-Pb SHRIMP)	Potassic, phyllic (dominates), skarn	Magnetite, pyrite, chalcopyrite, arsenopyrite	82.80 Mt @ 1.7 ppm Au and 0.15% Cu; Cu/Mo = 500	Shatov et al. (2014), Grabezhev (2014),

(continued on next page)

Table 1 (*continued*)

No	Deposit (other names)	Host rocks	Associated intrusion(s)	Age[a]	Alteration types	Ore minerals: common/rare	Tonnage, grade	References
		andesites	porphyry stock					www.sun-gold.com
	East Uralian terrane							
13	**Talitsa (Talitskoe, Pervomayskoe)**	Serpentinised ultrabasic rocks, Middle Devonian rhyolite-basalts	Diorite-granodiorite pluton, granodiorite-porph stocks, granodiorite & granite porphyry dykes, post-ore (?) Li-F granosyenite dykes	299.9 ± 2.9 Ma (Re-Os)	Potassic (kfs, Ab), phyllic (sericite)	Molybdenite, chalcopyrite, pyrite, sphalerite, tennantite, galena, cubanite/Au, tellurides, pyrrhotite, pentlandite, mackinawite, bravoite, bornite, linneite, etc	Cu/Mo = 0.5 to 3; Mo 0.04–0.34%, Cu 0.09–0.47%; Au 0.1–0.4 ppm. 129 Mt @ 0.055% Mo ≈71 Tt Mo 0.11% Cu ≈62 Tt Cu	Azovskova and Grabezhev (2008), Zoloev et al. (2004)
14	**Sapovskoe**	Upper Silurian to Middle-Devonian basalt-andesite-dacite volcanics	Gabbro-diorite-granodiorite pluton, diorite porphyry	Mid Devonian (Geol)	Propylitic (Ser, Chl), skarn	Pyrite, chalcopyrite, sphalerite, galena	Unknown, Cu/Mo = 400; Mo/Au = 38	Grabezhev and Belgorodskii (1992)
	Middle Urals, East-Uralian volcanic megaterrane, Alapaevsk-Techa terrane							
15	**Alapayevsk-Sukhoy Log cluster:** Alapaevsk, East Artemovsk (Vostochno-Artemovskoe) Altynai, and Sukhoi Log prospects)	Lower to Middle Devonian basalt, andesite, dacite	Diorite, diorite porphyries, plagiodiorite-porphyries	404.2 ± 2.4 to 405.9 ± 3.8 (U-Pb)	Q-ser (Phy)	Pyrite/chalcopyrite, molybdenite, sphalerite, galena, fahlore, pyrrhotite, gersdorffite	(Cut off 0.25 wt.% Cu): Cu 0.35 wt.%, Au 0.1–0.2 g/t, Ag 0.5–1.4 g/t, Mo 30–50, to 200 g/t	Grabezhev et al. (2014, 2015)
16	**Takhtalym**	Early Silurian basalts, Famennian basalt-rhyolitic, Middle to Late Devonian porphyritic basalt, andesite-basalt, andesite	Middle or Late Devonian (Geol) diorite to plagiogranite, quartz-diorite porphyry dykes	Middle or Late Devonian (Geol)	Propylitization, chloritization, silicification, minor prehnitization and Kfs	Pyrite, chalcopyrite, molybdenite, magnetite/galena, pyrrhotite, arsenopyrite, marcasite, tetrahedrite	Unknown, up to 0.3–0.4% Cu, Mo 0.002%	Ageyeva et al. (1984), Grabezhev and Belgorodskii (1992)
17	**Teptiargino**	Basalts, andesites (Middle Devonian),	Diorite to plagiogranite, quartz-diorite porphyry dykes	Middle Devonian (Geol)	Propylitic & Ser-Qtz-Ab	Pyrite, chalcopyrite, molybdenite	Unknown, up to 0.3% Cu, Mo 0.01%	Grabezhev and Belgorodskii (1992)
	East Uralian volcanic megaterrane, South Urals							
18	**Birgilda (Birgildinskoe, Birgildy)**	Ordovician basalts	Breccia, plagiogranite, diorite porphyry, quartz diorite	Silurian (Geol)	Propylitic, minor phyllic: Ser, Qtz,	Chalcopyrite, pyrite, molybdenite, hematite, magnetite, tetrahedrite/pyrrhotite, bornite, tennantite, cobaltite, bismuthinite,	Cu/Mo = 150 Mo/Au = 250	Romashova (1984), Grabezhev and Belgorodskii (1992)
19	**Tomino (Tominskoe, Tominsk)**	Ordovician basalts	Breccia, quartz diorite porphyry	427 ± 6 (U-Pb)	Phyllic: Ser, Qtz, propylitic	Chalcopyrite, magnetite, molybdenite, pyrite	1,54 Mt Cu (331 Mt @ 0.47 Cu), Au 0.12 ppm	Grabezhev and Borovikov (1993), Grabezhev et al. (2013), Volchkov et al. (2015)
20	**Kalinovskoe**	Ordovician basalts	Diorite, qtz diorite porphyry	430.4 ± 2.0 (Re-Os)	Phyllic: Ser, Qtz, propylitic	Chalcopyrite, pyrite, molybdenite, bornite, Au, Bi-minerals		Plotinskaya et al. (2014b), Tessalina and Plotinskaya, 2017
21	**Yaguzak**	Ordovician basalts	Gabbro-diorite--monzodiorite-granodiorite--adamellite porphyry	Late Devonian–Carboniferous (Geol)	Phyllic: Ser, Qtz	Chalcopyrite, molybdenite, pyrite, pyrrhotite,	Unknown	Grabezhev et al. (1998)
22	**Zeleny Dol, Zelenodolskoe, Zelenodol**	Andesite-basalt tuffs	Quartz-diorite porphyry	418.3 ± 1.3 Ma (U-Pb, LA-ICP-MS)	Potassic (biotite, kfs, rare Act, Chl); mainly phyllic (Ser, Chl); propylitic (Chl, Ep, rare Act, Car)	Chalcopyrite, magnetite, molybdenite, pyrite	Cu/Mo = 220, Mo/Au = 113	Yurish (1982), Grabezhev et al. (2016)
23	**Yelenovskoe**	Andesites (Upper Silurian), basalt-rhyolite (Middle Devonian), trachyandesites (Upper Devonian)	Diorite, granodiorite, plagiogranite, granosyenite (orogenic type pluton), diorite & qtz-diorite stock, qtz-porphyry dykes	Late Devonian (geol)	Phyllic: Ser, Qtz; tourmaline	1) Qtz-tourmaline-pyrite-chalcopyrite; 2) porphyry: pyrite, chalcopyrite, molybdenite, sphalerite, galena	1) Q-Tur: Cu 2%, Cu/Mo = 122; 2) porphyry: Cu 0.1%	Talnov et al. (1986)
	Transuralian megaterrane							
24	**Tarutino (Tarutinsk, Tarutinskoe)**	Silurian to Devonian volcanics, marbles	Plagiogranodiorite pluton, quartz diorite porphyry	362 ± 4 (U-Pb SHRIMP)	Skarns, phyllic, minor Kfs and argillic	Magnetite, pyrite, chalcopyrite, molybdenite, sphalerite, galena, tetrahedrite, pyrrhotite,	Measured & indicated & inferred: 10,25 Mt & 0.99% Cu (101 kt Cu), 7.05 ppm Ag, 0.09 ppm Au	Grabezhev et al. (2004), Grabezhev and Ronkin (2011),

						arsenopyrite, Au/ altaite		http://gold.1prime.ru
25	**Mikheevskoe (Mikheev, Mikheevka, Novonikolaevsk ore field)**	Late Devonian andesite-dacite, basalts	Diorite porphyry, plagiogranodiorite porphyry, adamellite porphyry	356 ± 6 (U-Pb SHRIMP) 357.8 ± 1.8 and 356.1 ± 1.4 (Re-Os)	Potassic (biotite, rare kfs), Ca-sodic (actinolite, albite), phyllic (sericite, paragonite, phengite, carbonate), propylitic (chlorite, epidote, pyrite)	Chalcopyrite, pyrite, bornite, molybdenite, magnetite, anatase/Co-Ni sulfides, sphalerite, galena, fahlore, native Au	1.54 Mt Cu (347 Mt @ 0.45% Cu)	Belgorodskii et al. (1991), Shargorodsky et al. (2005), Grabezhev and Ronkin (2011), Volchkov et al. (2015), Tessalina and Plotinskaya, 2017
26	**Podovinnoe**	Wenlock to Lower Devonian Px-Pl basalts, andesibasalts and their tuffs, 160 m Meso-Cenozoic sedimentary cover	Diorite porphyry dykes and stocks	Early Devonian (Geol)	Sericite-chlorite-carbonate-quartz	Chalcopyrite, molybdenite	Cu 1–1.3%	Kontar (2013)
27	**Bataly (Batala, Batalinskoe, Batalinskaya,** Batalinskaya, Krasnoarmeiskoe, occurrences	Lower Carboniferous andesitic and andesite-basaltic porphyries and tuffs	Breccia, granodiorite, granodiorite porphyry, diorite porphyry	310–292 Ma (K-Ar)	1) Tourmaline + quartz, 2) quartz + albite + epidote, 3) Quartz + sericite	Pyrite, chalcopyrite, molybdenite/ bornite, cubanite, galena, arsenopyrite, fahlore, gold, scheelite, magnetite, hematite	Bataly occurrence: 0.52% Cu, 0.001% Mo, 0.18 ppm Au. Krasnoarmeiskoe occurrence: Cu <2.23%, Mo 0.06%, Au <0.5 g. Total predicted: Cu 0.55 Mt, Mo 7 t, Au 30 t	Grabezhev and Belgorodskii (1992), Syromyatnikov et al. (1986), Zhukov et al. (1997), (Tenders…)
28	**Zhaltyrkol**	Upper Devonian to Lower Carboniferous tuffs & sediments	Tonalite-granodiorite pluton	Middle to Late Carboniferous (Geol)	Biotite (hornfels), chl-Ser (periphery, Chl (margins): small zones of Kfs and Qtz-Tourm	Hematite, magnetite, pyrite, chalcopyrite/ sphalerite, pyrrhotite	Cu/Mo = 200, Mo/Au = 36	Grabezhev and Belgorodskii (1992)
29	**Varvarinskoye (Taranovskoe)**	Middle Devonian basic to intermediate lavas with lenses of limestone, siltstone, and sandstone	Early Carboniferous ultrabasic and Middle to Late Carboniferous diorite, granodiorite	Late Carboniferous (Geol)	*Porphyry-style ores*: silica, biotite, prehnite, amphibole, diopside	Chalcopyrite/ gold	92.2 Mt @ Au 1.05 ppm; Cu 0.54%; Au: 96.5 Tt, Cu:0.3 Mt	Grabezhev and Belgorodskii (1992), Zhukov et al. (1997); www.polymetal.ru
					Gold-sulfide-arsenopyrite ores: silica, albite, chlorite, carbonate	Pyrite, arsenopyrite, chalcopyrite/ gold		
					Gold-nickeline-gersdorffite ores: tremolite, talc, chlorite	Chalcopyrite, pyrite, marcasite, pyrrhotite, arsenopyrite, gersdorffite, nickeline, gold/ Fe, Co, Ni, Co silfides and sulfoarse-nides; Bi, Pb, sulfides; Bi, Au, Ag sulfotellu-rides and tellurides		
30	**Spiridonovskoe**	Ordovician to Silurian basalts, andesites, rhyolites	Late Silurian to Early Devonian (Geol) diorite, granodiorite of the Denisov massif	Late Carboniferous (Geol)	Biotite, Kfs, sericite and albite-chlorite-epidote-carbonate	Pyrite, chalcopyrite, molybdenite, magnetite, hematite, sphalerite, galena etc.	Cu0.55%, Mo 0.01–0.05%, Au 0.2 ppm. Cu/Mo = 11–55	Kontar and Libarova (1997), Kontar (2013), Seravkin et al. (2011)
31	**Benkala (Benqala)**	Early Carboniferous volcano-sedimentary: dacites, andesites, andesitic-basalt and basalt	Gabbro-granodiorite pluton, qtz-diorite--plagiogranodiorite small intrusions	318–306 (K-Ar)	1) albite, Kfs, biotite, silica and turm, & propylitic halo (chl, ep, prehnite). 2) acid quartz-sericite & Chl-Car	Pyrite, chalcopyrite, magnetite/molybdenite, bornite, chalcocite, digenite, rutile	309 Mt Cu/Mo = 71 or 100 Mt @ 0,42% Cu, 0.003 Mo 0,3ppm Au; http://www.frontiermining.com: 1.56 Mt (Cu (0.25% cut-off): 183,000 t oxide resource; 1,378,000t sulfide resource	Ageyeva (1982), Zhukov et al. (1997), Frontier Mining (2012)
Other terranes								
32	**Lekyn-Talbei ore field (Lekyntelbei, Lekyntelbeiskoe, Lekin-Talbei):** Lekyn-Talbei deposit, Solnechnoe, Yuzhnoe, Kolibri zones	Early Vendian Bedamel' series-Basalt-andesite-dacite Fm. and sedimentary Fm	Andesite, dacite porphyry, diorite porphyry, gabbro-diabase, gabbro-diorite, plagiogranite, quartz porphyry (Early Vendian Kyzylgei Complex)	Vendian (Geol)	Quartz-sericite alteration	Pyrite, chalcopyrite, bornite, molybdenite, magnetite/fahlore, galena, sphalerite, pyrrhotite, arsenopyrite, hematite	Lekyn-Talbei: Cu/Mo = 250; inferred (C2) ore 85.6 Mt, Cu 0.46 Mt, Mo 7.6 kt, Au 12 t, Ag 100 t	Silaev and Andreichev (1982), Yelokhin and Griaznov (2012), Ural Industrial- Ural Polar (2008), Kontar (2013)
						Veinlet-disseminated pyrite-chalcopyrite mineralization	*Solnechnoe*: 300–350 m, 0,8–1 m thick, Cu 0.39–0.77%, Mo 0.001–0.02% *Yuzhnoe*: 1200 m, 40–50 m thick, Cu 0.1–1.98% (mean 0.46%), Mo up to 0.01% *Kolibri*: 300 × 80–100 m, Cu 0.27-0.33%	Kontar (2013)
33	**Zess**	Silurian to Lower Devonian basalts, rhyolites	Gabbro, gabbrodiorites, diorites	Silurian to Early Devonian (Geol)	Qtz-chl-cal-ep	Chalcopyrite, pyrite, sphalerite/galena	Unknown	Starostin et al. (1972)

[a] Note. Geol = age, estimated from geological observations.

Novogodnee-Monto and **Petropavlovskoe** skarn-porphyry Au-Cu deposits (Soloviev et al., 2013 and references therein). In the **Tagil** terrane the **Andriushinskoe** and **Rudnobolotskoe** Cu-porphyry occurrences (Table 1) of unknown potential are located, both related to diorite intrusions (Krivtsov et al., 1986; Grabezhev and Belgorodskii, 1992).

The best known deposit in this terrane is the **Gumeshevskoe** Cu skarn-porphyry. Its oxidation zone has been mined for copper ore since the bronze age until now with several long breaks. In the 18th century high quality malachite was also extracted. Most of the endogenic copper mineralization is related to skarns but porphyry-style Cu mineralization related to quartz diorite is also reported (Grabezhev, 2010 and references therein). The quartz diorite was dated by the SHRIMP U-Pb zircon method at 390 ± 2.8 Ma (Grabezhev and Ronkin, 2011). This shows that the Gumeshevskoe deposit is not linked to the activity of the Tagil arc which terminated in the Early Devonian (Puchkov, 2010, 2013 and references therein) but is related to the Magnitogorsk arc (see below).

During the Emsian, the Tagil terrane accreted to the Magnitogorsk oceanic arc which formed due to eastward subduction and was active from Early Devonian (Emsian) to Late Devonian (Famennian) and then accreted to the East European plate (Brown et al., 2006). The Magnitogorsk arc is best exposed and best known in the Southern Urals as the Magnitogorsk megaterrane however Devonian subduction-related calc-alkaline complexes are traced northward to the Polar Urals (Puchkov, 2010, 2013). It is reasonable to suppose that most of the porphyry and porphyry-related deposits and occurrences of the Tagil terrane, such as the aforementioned Gumeshevskoe deposit as well as those that have not yet been dated, are also related to the activity of the Magnitogorsk arc.

In the South Urals the **Magnitogorsk megaterrane** hosts numerous VHMS deposits (see Maslennikov et al., 2017, and references therein) and also several porphyry deposits of various types. The westernmost part of the **Magnitogorsk terrane** is composed of andesite-basalt tuffs and lavas which belong mostly to the Uppermost Emsian to Lower Eifelian Irendyk Formation (Puchkov, 2010, 2013). These rocks host the **Salavat** Cu-porphyry deposit described below. The **Voznesenskoe** Cu-porphyry deposit is located in the same zone (Shishakov et al., 1988; Grabezhev and Voudoris, 2014). This deposit differs from the Salavat deposit in ore chemistry (Cu/Mo ratio approx. 250 at Voznesenskoe compared to 600 at Salavat). Grabezhev and Ronkin (2011) obtained age 381 ± 5 Ma (U-Pb SHRIMP-II) for quartz diorite, see also (Kosarev et al., 2014) for discussion. The Voznesenskoe deposit has been recently described in detail by Grabezhev and Voudoris (2014).

The **Verkhneuralskoe** Mo-porphyry occurrence described below is located in the central part of the Magnitogorsk terrane (Grabezhev and Belgorodskii, 1992; Salikhov et al., 1994). The southernmost edge of the Magnitogorsk terrane hosts the Middle Devonian **Karaksak** Cu-porphyry occurrence and the **Yubileinoe** Au-porphyry deposit. The latter is described below.

2.1.1. Salavat Cu-porphyry deposit

The Salavat deposit was studied during the period from the 1970s to 1980s and was mentioned in several English language reviews of porphyry deposits (Grabezhev and Borovikov, 1993; Zvezdov et al., 1993). The description below is derived mainly from Minina (1982).

The ore-bearing intrusion (Fig. 2) is composed of plagioclase and amphibole-plagioclase diorite porphyry cut by dykes of quartz-amphibole-plagioclase diorite porphyry, rhyolite-dacite porphyry and post-ore quartz gabbrodiorite. The host rocks are tuffs and lavas of pyroxene-plagioclase andesite-basalt with interlayers of tuffaceous siltstone and tuffaceous sandstone of the Lower to Middle Devonian Irendyck Formation.

The alteration aureole is mostly propylitic consisting mainly of chlorite and quartz with nest-like aggregates of pumpellyite, clinozoisite, chlorite, pyrite and variable quantities of carbonate and albite. The propylites contain sparse lenticular zones of quartz and quartz-sericite. Mineralization is confined to the central part of the diorite porphyry stock and occurs as disseminations and nest-like aggregates replacing the femic minerals of the diorite intrusion. Pyrite and chalcopyrite are the main ore minerals while molybdenite, pyrrhotite, rutile, tennantite, sphalerite, galena, magnetite, ilmenite, and bornite are rare. Supergene minerals are chalcocite, covellite, hematite, goethite and hydrogoethite.

No dating has been carried out but based on geological evidence this deposit was assigned a Middle Devonian age.

2.1.2. Yubileinoe Au-porphyry deposit

The Yubileinoe (or Shekarabulak-II) deposit is situated in Western Kazakhstan, at the Southern end of the Magnitogorsk megaterrane. The territory is composed of Early to Middle Devonian basic tholeiitic volcanic rocks (Mugodzhar Group) which are overlain by Middle to Late Devonian volcanics and sediments of island arc origin, mostly of the Middle Devonian Milyashy Formation (Shatov et al., 2014 and references therein). Volcanics form the North-trending Kundyzdin syncline on the eastern flank of which the Yubileinoe deposit is located (Abdulin et al., 1976). Several massive sulfide occurrences are known in the area, including the Shekarabulak-I deposit containing massive

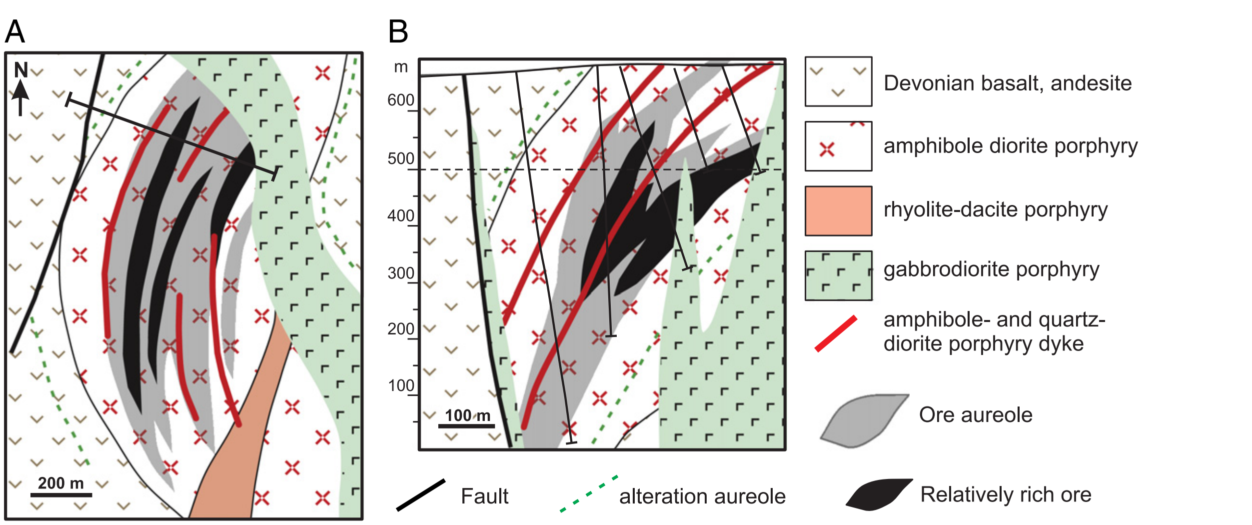

Fig. 2. The Salavat deposit: simplified geological map of the +500 m horizon (A) and a cross-section (B). After (Minina, 1982).

pyrrhotite-pyrite mineralization. These are usually ascribed to the VHMS type.

Intrusive rocks of the Airyuk Complex include at least three phases (Shatov et al., 2014): (1) gabbro and gabbro-diorite, (2) diorite and quartz-diorite, and (3) plagiogranites (leucocratic tonalite) and their porphyry varieties which are believed to have produced the Au-porphyry mineralization. The plagiogranite porphyry forms an irregular stock of approx. 400 m diameter (Fig. 3). It has been traced by drilling to a depth of approx. 600 m (Narvait et al., 1974). An early phase of biotite plagiogranite porphyry (Fig. 4A) and a late one of biotite-hornblende plagiogranite porphyry were reported by Abdulin et al. (1976). The former were dated by U-Pb in zircons (SHRIMP-II) as 374 ± 3 Ma (Grabezhev, 2014).

Mineralization is confined to the margins of the stock (Fig. 3C) and occurs both in plagiogranite and in the country rocks (Fig. 4. B,C). A network of barren quartz, quartz-sulfide, and sulfide veinlets less than 1 mm to several cm thick is accompanied by intense phyllic alteration (Shatov et al., 2014). In places where the abundance of veinlets is very high they form massive silica rocks (Abdulin et al., 1976). The most common ore minerals are magnetite, pyrite, chalcopyrite, and hematite, with less abundant scheelite, arsenopyrite, bornite, gold, Bi minerals, etc.

Banded quartz-magnetite veinlets with minor hematite (Fig. 4B) probably form the earliest generation of mineralization. The later sulfide assemblage includes pyrite and arsenopyrite (Fig. 4D), followed by chalcopyrite, low-Fe sphalerite (containing up to 3 wt.% Fe), minor galena (Fig. 4E) and bornite. Scheelite ($Ca(W_{0.8}Mo_{0.2})_{\Sigma 1}O_4$ to $CaWO_4$ is believed to form part of the same assemblage (Fig. 4G to I). Native gold containing up to 5 at.% Ag (Fig. 4J) occurs as small inclusions or veinlets from 2 to 10 μm and rarely up to 40 μm in size in quartz), and more frequently as inclusions in chalcopyrite or pyrite (this gold contains 31 to 40 at.% Ag). Minerals of Bi and Pb (Fig. 4K to M) occur as small grains

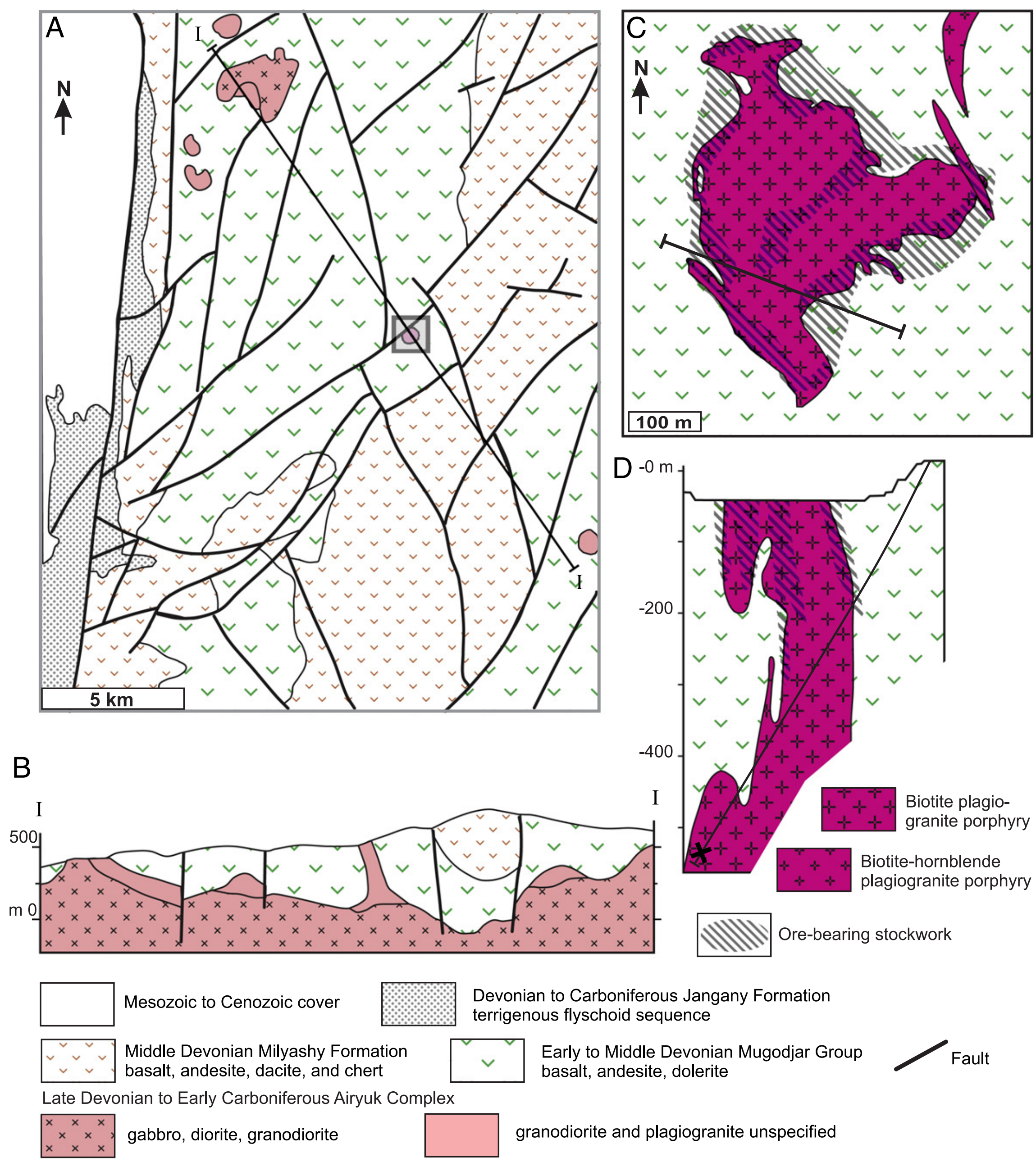

Fig. 3. Geological scheme of the Yubileinoe deposit area (A), cross-section along I–I line (B) and map of the Yubileinoe deposit. A and B are derived from Seltmann et al. (2014), C– adapted from Narvait et al. (1974), D – simplified from Grabezhev and Belgorodskii (1992).

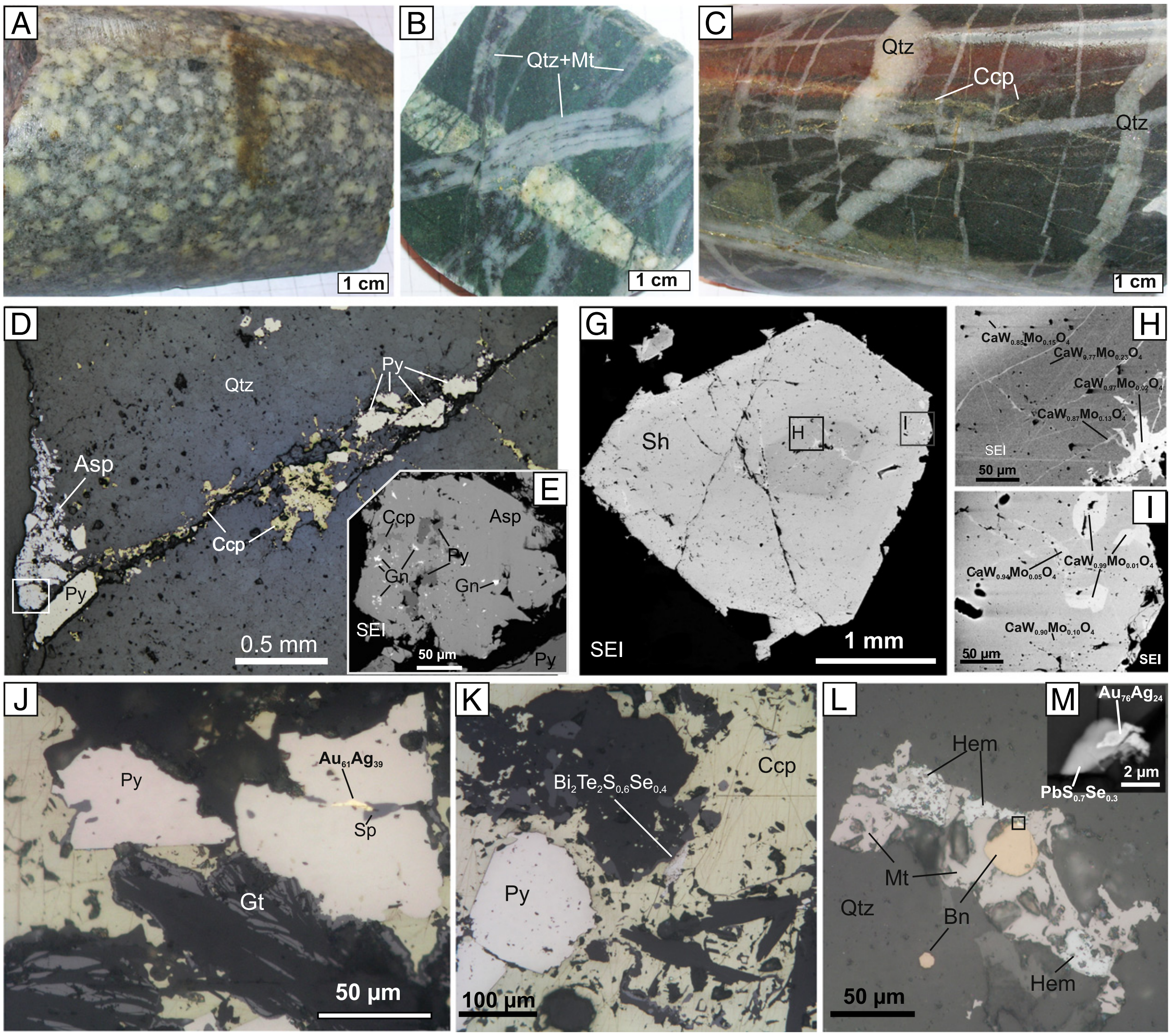

Fig. 4. Main rock and ore types of the Yubileinoe deposit. A- plagiogranite porphyry with a weak phyllic alteration; B- basalt with a small plagiogranite porphyry dyke cut by numerous quartz-magnetite (Qtz + Mt) veinlets; C- basalt with a series of white quartz veinlets (Qtz) and overlapped by a network of chalcopyrite (Ccp) stringers; D- arsenopyrite (Asp), pyrite (Py), chalcopyrite (Ccp) stringer in quartz (Qtz); E- detail of (D), inclusions of chalcopyrite and galena (gn) in arsenopyrite; G- zoned scheelite, brighter color points to scheelite depletion in Mo from center to margins; H and I- details of G; J- gold ($Au_{61}Ag_{49}$) and sphalerite cutting pyrite overgrown by chalcopyrite, partly replaced with hypergene goethite (Gt); K- tetradymite overgrowing chalcopyrite; L- bornite (Bn) droplet in magnetite (Mt) overgrown with hematite (Hem); M- detail of (L), gold intergrown with selenoan galena.

from 5 to 100 µm in size) overgrowing chalcopyrite. Minerals of the tetradymite-kawazulite series $Bi_2Te_2(S_{0.7}Se_{0.3})_{\Sigma 1}$ to $Bi_2Te_2(S_{0.5}Se_{0.5})_{\Sigma 1}$ are more common, rucklidgeite $PbBi_2(Te_{3.8}Se_{0.2})_{\Sigma 4}$ and selenoan galena $Pb(S_{0.7}Se_{0.3})_{\Sigma 1}$ are rare. Gold associated with these minerals contains 21 to 24 at.% Ag (Fig. 4K). Abdulin et al. (1976) reported stibnite as the latest ore mineral.

The Au content of the mineralization varies from 1 to 6–10 ppm (Shatov et al., 2014), and the Mo content varies from 1 to 15 ppm, occasionally reaching 30 ppm (Grabezhev, 2013). The most recent estimate by Sun Gold (2015) identifies a resource of 82.8 Mt at 1.7 g/t Au and 0.15% Cu with 4.59 M oz. contained Au.

2.1.3. Verkhneuralskoe Mo-porphyry occurrence

This is located in the central Magnitogorsk megaterrane and confined to the eastern part of the Verkhneuralsk pluton. The latter consists of a gabbro-granite intrusive series linked to a subduction-related rift and a later series of syenitic intrusions (Fershtater, 2013). Mineralization occurs within a granodiorite stock (Fig. 5) surrounded by quartz diorite and syenite intruding Upper Famennian basalt-trachyte volcanics (Grabezhev and Belgorodskii, 1992).

The alteration aureole is 1.5 km long and 0.8 km wide and follows approximately the shape of the granodiorite stock. Sericite alteration is dominant in the central zone, while on the periphery it gives way to carbonate-sericite, and then, to propylitic alteration (Fig. 5B). Siliceous and argillic alteration zones are confined to the margins of the system. Albite alteration is present as a halo of veinlets or forms zones up to 8 m thick. K-feldspar (Kfs) alteration is rare and forms selvages around quartz-pyrite veinlets (Grabezhev and Belgorodskii, 1992).

Pyrite and chalcopyrite occur as disseminations or in quartz veinlets. Molybdenite is confined to the lower parts of the alteration aureole as 15 to 20 m thick zones of quartz veinlets or molybdenite stringers. These contains high concentrations of rhenium reaching as much as 0.84 wt.% (Grabezhev, 2013). The quartz-sericite alteration has a Rb-Sr isochron age of 341 ± 1 Ma (Salikhov et al., 1994).

2.2. The East Uralian megaterrane

The East Uralian megaterrane comprises Proterozoic gneisses and schists overlain by clastic and carbonate sedimentary strata of Ordovician to Devonian age intruded by Late Paleozoic granite batholiths that form the Main Granitic Axis of the Urals. In the Early to Middle

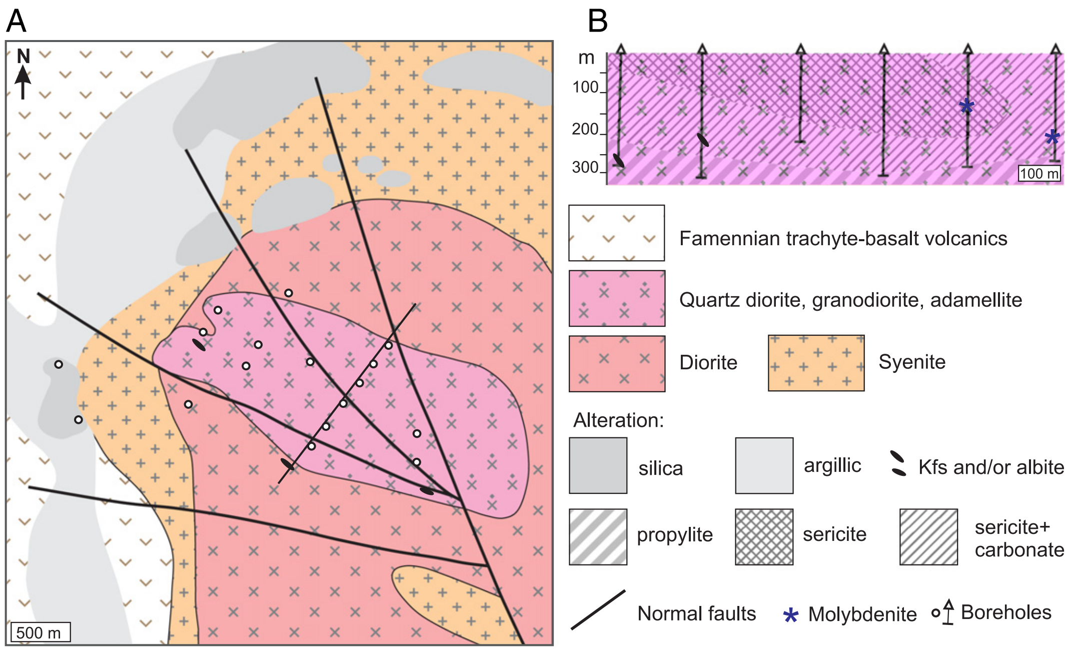

Fig. 5. Schematic geological map (A) and a cross-section (B) of the Verkhneuralskoe Mo-porphyry occurrence, after (Grabezhev and Belgorodskii, 1992).

Palaeozoic it formed the East Ural microcontinent (Samygin and Burtman, 2009) and references therein). The East Uralian megaterrane also contains tectonically emplaced sheets of Palaeozoic (Ordovician–Lower Carboniferous) oceanic and island arc complexes (Puchkov, 2010, 2013). Most of these are located in the easternmost part of the East Uralian megaterrane where they are united to form the **East Uralian Volcanic terrane** while the Proterozoic part is usually referred as **East Uralian Sialic terrane**. The latter hosts the **Sapovskoe** Cu porphyry occurrence and the **Talitsa** Mo-porphyry deposit which is described below. Both are located near the **Tagil** terrane which is separated from the East Uralian sialic terrane by the East Magnitogorsk-Serov-Mauk fault system (Fig. 1).

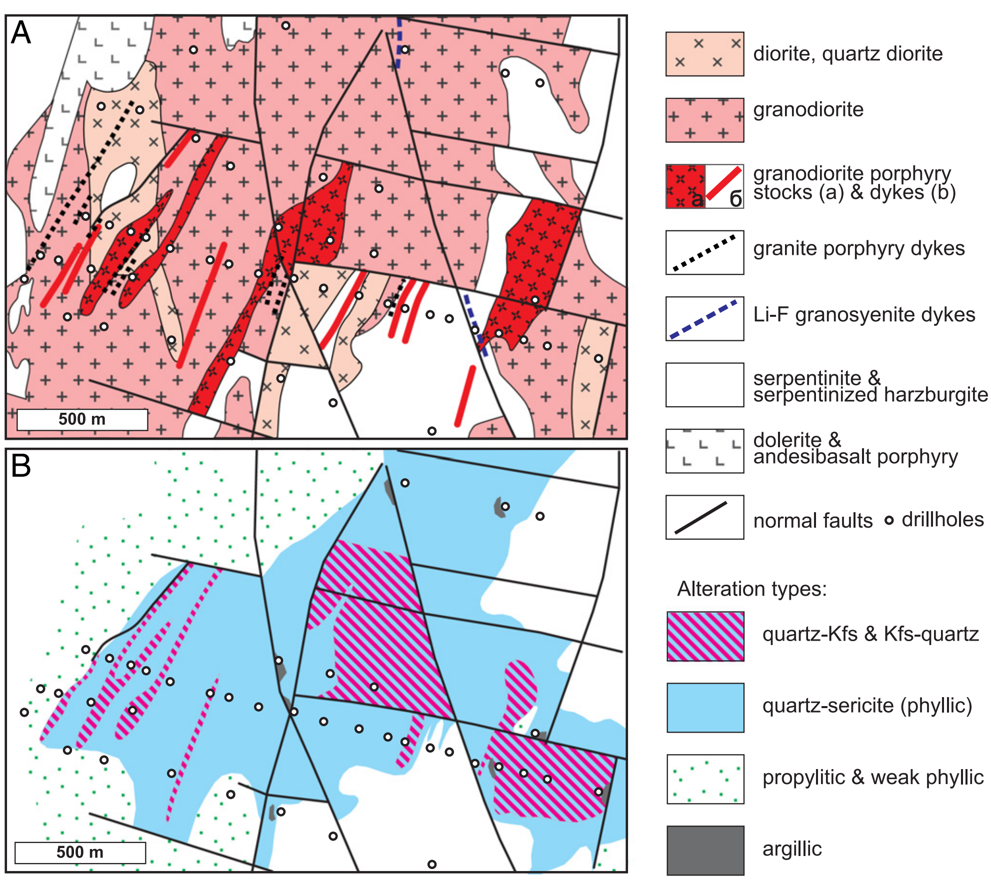

Fig. 6. Geological (a) and alteration (b) maps of the Talitsa deposit (Azovskova and Grabezhev, 2008).

The **East Uralian Volcanic terrane** in the Middle Urals is represented by the **Alapaevsk-Techa terrane** composed of Devonian andesitic volcanoclastics intruded by calc-alkaline intrusions of diorite to granite composition (Grabezhev et al., 2014, 2015). This terrane is supposed to be the Mid-Uralian section of the Magnitogorsk arc overthrusted onto the East Uralian megaterrane (Puchkov, 2010, 2013 and references therein). The **Alapaevsk-Sukhoi Log** trend of porphyry-style prospects extends North for more than 100 km and includes numerous Cu-porphyry occurrences (Fig. 1, Table 1) of unknown economic potential contained within several intrusions of diorite to plagiogranite (leucocratic tonalite) dated by U-Pb (SHRIMP-II) at 411 ± 3 to 397 ± 4 Ma (Grabezhev et al., 2014, 2015). Two less-studied Cu porphyry occurrences, **Thakhtalym** and **Teptiargino** are located 150–200 km to the South (Grabezhev and Belgorodskii, 1992).

In the South Urals the **East Uralian Volcanic terrane** is represented by the Kosobrodka-Bredy terrane. Here the **Birgilda-Tomino** ore cluster is the best studied (Grabezhev et al., 1998; Plotinskaya et al., 2014b and references therein). The **Birgilda**, **Tomino**, and **Kalinovskoe** Cu-porphyry deposits are hosted by Ordovician basalts (Grabezhev et al., 1998). In the less eroded parts of this territory the Biksizak Zn carbonate replacement mineralization (Plotinskaya et al., 2010, 2015a) and the Bereznyakovskoe Au-Ag epithermal ore field of high to intermediate sulfidation style (Lehmann et al., 1999; Grabezhev et al., 2000; Plotinskaya et al., 2009, 2014b) are found. The **Zeleny Dol** Cu-porphyry occurrence located several km to the South is related to a similar (or the same) intrusive series and shows similar styles of mineralization and alteration (Yurish, 1982). The age of the deposits and the porphyry intrusions with which they are associated was estimated as Late-Devonian to Early Carboniferous based on geological observations and K-Ar dating of sericite (Grabezhev et al., 1998). However recent U-Pb SHRIMP dating of the Tomino and Berezniakovskoe deposits (Grabezhev et al., 2013) gave zircon ages of 428 ± 3 Ma and 427 ± 6 Ma, while Re-Os dating of molybdenite from the Kalinovskoe deposit (Tessalina and Plotinskaya, 2017) gives an age of 430.4 ± 2.0 Ma. A similar age (418.3 ± 1.3 Ma) has recently been obtained for the Zeleny Dol deposit (Grabezhev et al., 2016) using the LA-ICP-MS method on zircon. This leads to the conclusion that these deposits are related to a Silurian volcanic arc which could have been the southern end of the Tagil arc or one developed independently (Yazeva and Bochkarev, 1995; Puchkov, 2017).

The **Yelenovskoe** deposit is located at the southernmost end of the East Uralian Volcanic terrane (Fig. 1). It is related to Late Devonian diorite to granosyenite intrusives and includes Cu-rich quartz-tourmaline zones that have been exploited and a poorly explored stockwork of Cu porphyry-style (Talnov et al., 1986).

2.2.1. Talitsa Mo-porphyry deposit

This deposit is located in the Middle Urals within the East-Uralian megaterrane lying approx. 40 km to the east of its boundary with the Tagil megaterrane. The deposit was discovered and explored in 1987, the description below is derived from (Azovskova and Grabezhev, 2008).

The host rocks are serpentinized ultrabasic rocks of the Pervomaisky dunite-harzburgite massif of Ordovician age and an Early to Middle Devonian rhyolite–basalt volcano-sedimentary sequence.

The Talitsa deposit is located within a small (approx. 4 km^2) massif of the same name composed mainly of sub-alkaline granodiorite-granite and minor diorite and syenite (Fig. 6). Granodiorite porphyry stocks

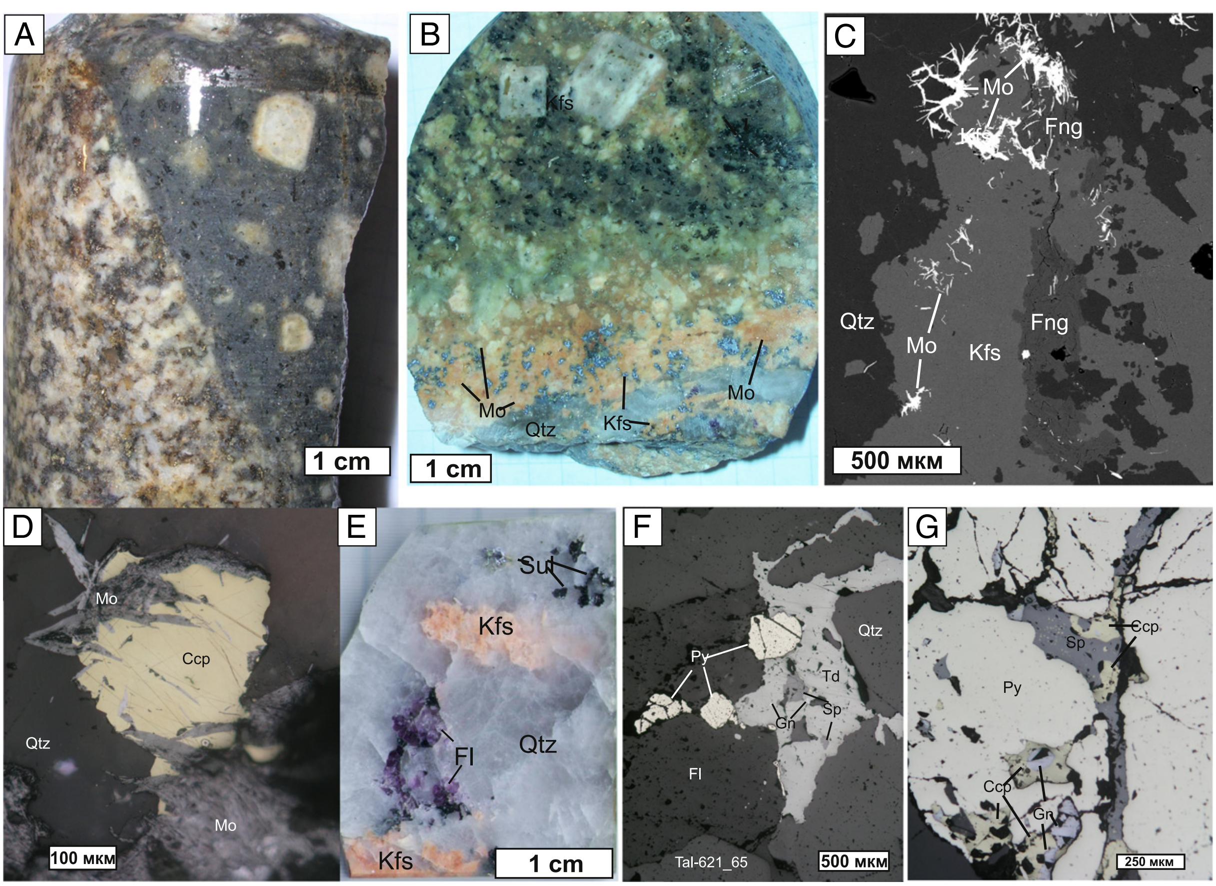

Fig. 7. Main rock, alteration, and ore types of the Talitsa deposit. A– granodiorite porphyry cutting granodiorite; B– quartz veinlet with Kfs alteration halo and molybdenite nests in granodiorite; C– the same veinlet under SEM, note that molybdenite is confined to Kfs; D– molybdenite overgrowing chalcopyrite, reflected light; E to G– base-metal stage: E– quartz veinlet with relics of Kfs and nests of fluorine and sulfides; F– the same quartz veinlet in reflected light, pyrite and tetrahedrite cutting and overgrowing fluorine; G– sphalerite, chalcopyrite, and galena cutting pyrite, reflected light.

and dykes are common in the central part of the massif. Both gradual transition and cross-cutting relationships between porphyritic and equigranular intrusive rocks were observed (Fig. 6a). Dykes of granite-porphyry and, to a lesser extent, syenite porphyry are also common. Dykes of Li-F granosyenite mark the latest episode of intrusive activity and are probably related to another stage of magmatic activity in the region (Azovskova and Grabezhev, 2008).

Mineralization forms three stockworks each 300 to 500 m long and 80 to 100 m wide elongated in a N to NNE direction. The Mo content varies from 0.04 to 0.34%, most commonly ranging from 0.04 to 0.07% (0.055% on average), Cu contents vary from 0.09 to 0.47%, and fall mainly in the range from 0.10 to 0.13% (0.11% on average), the Cu/Mo ratio is 2. The content of Au varies from 0.10 to 0.42 ppm, the usual range being from 0.1 to 0.17 ppm (Zoloev et al., 2004; Yelokhin and Griaznov, 2012). Mo mineralization is confined to the inner zones of the alteration aureole whereas Cu is more abundant in the margins (Yelokhin and Griaznov, 2012).

There are several aureoles of **potassic** alteration in the central zone of the Talitsa massif, usually confined to granodiorite porphyry stocks and dykes (Fig. 7A and B). Most common are K-feldspar haloes around quartz veinlets (Fig. 7B) but sometimes K-feldspar forms massive zones tens of meters thick with K-feldspar crystals reaching several cm in size. Molybdenite is the major ore mineral associated with potassic alteration, while pyrite and chalcopyrite are minor (Fig. 7C and D). Studies of fluid inclusions in quartz from the Kfs-molybdenite stage (Groznova et al., 2015) showed that mineralization was deposited at temperature of 320 to 510 °C and pressures of 900 to 1700 bar from high-salinity fluids (25 to 35 wt.%-eq. NaCl). The liquid phase contained Mg-Na- and Na-chlorides, while CO_2, and to a lesser extent CH_4, were present in the vapor phase.

Phyllic alteration is more widespread on the margins of the massif (Fig. 7B). This includes (1) sericite (muscovite) and minor albite replacing feldspar, (2) an assemblage of biotite + rutile + magnetite replacing magmatic biotite, and (3) phengite + siderite replacing biotite. This accompanies the formation of quartz veinlets with fluorite containing pyrite and chalcopyrite as well as minor amounts of pyrrhotite, cubanite, tetrahedrite, sphalerite, and galena that are designated as the **base-metal stage** (Fig. 7E to G). Studies of fluid inclusions from quartz and fluorite belonging to the base-metal stage have homogenisation temperatures of 200 to 450 °C and pressures as high as 400 to 1300 bar. Fluids were of moderate salinity (5 to 15 wt.%-eq.NaCl), with Na-chloride composition, the vapor phase containing CO_2, minor CH_4 and N_2 (Groznova et al., 2015).

Propylitic alteration is typical of the marginal zones of the Talitsa massif (Fig. 7B). Chlorite, epidote, actinolite and minor pyrite and chalcopyrite replace mafic minerals while albite replaces plagioclase. **Post-ore argillic** alteration occurs locally.

The Re-Os age of molybdenite 299.9 ± 2.9 Ma (Tessalina and Plotinskaya, 2017) suggests that the Talitsa deposit is related to the collision between East European plate and the Kazakh continent which started in the Bashkirian and lasted till the Late Permian (Puchkov, 2013).

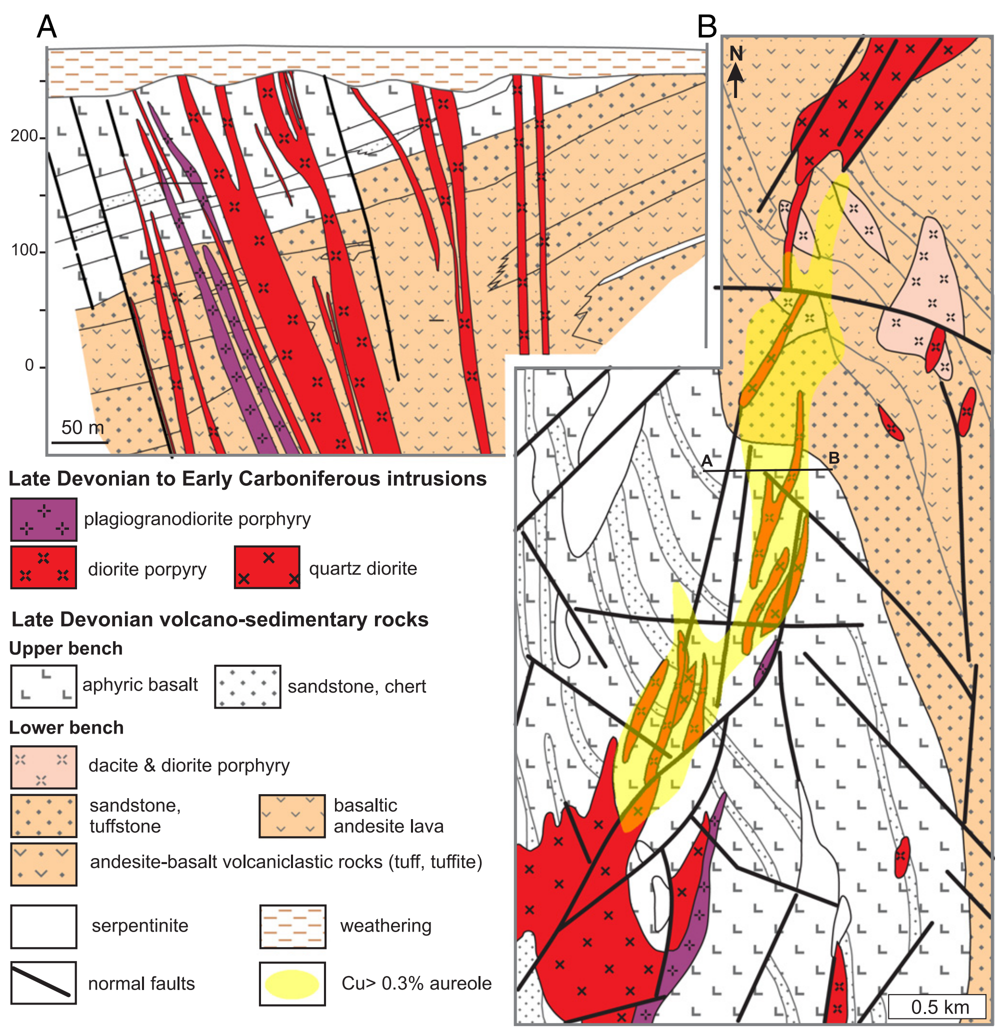

Fig. 8. Geological scheme of the Mikheevskoe deposit after (Shargorodsky et al., 2005) and a cross-section along A-B line adapted from Russian Copper Company.

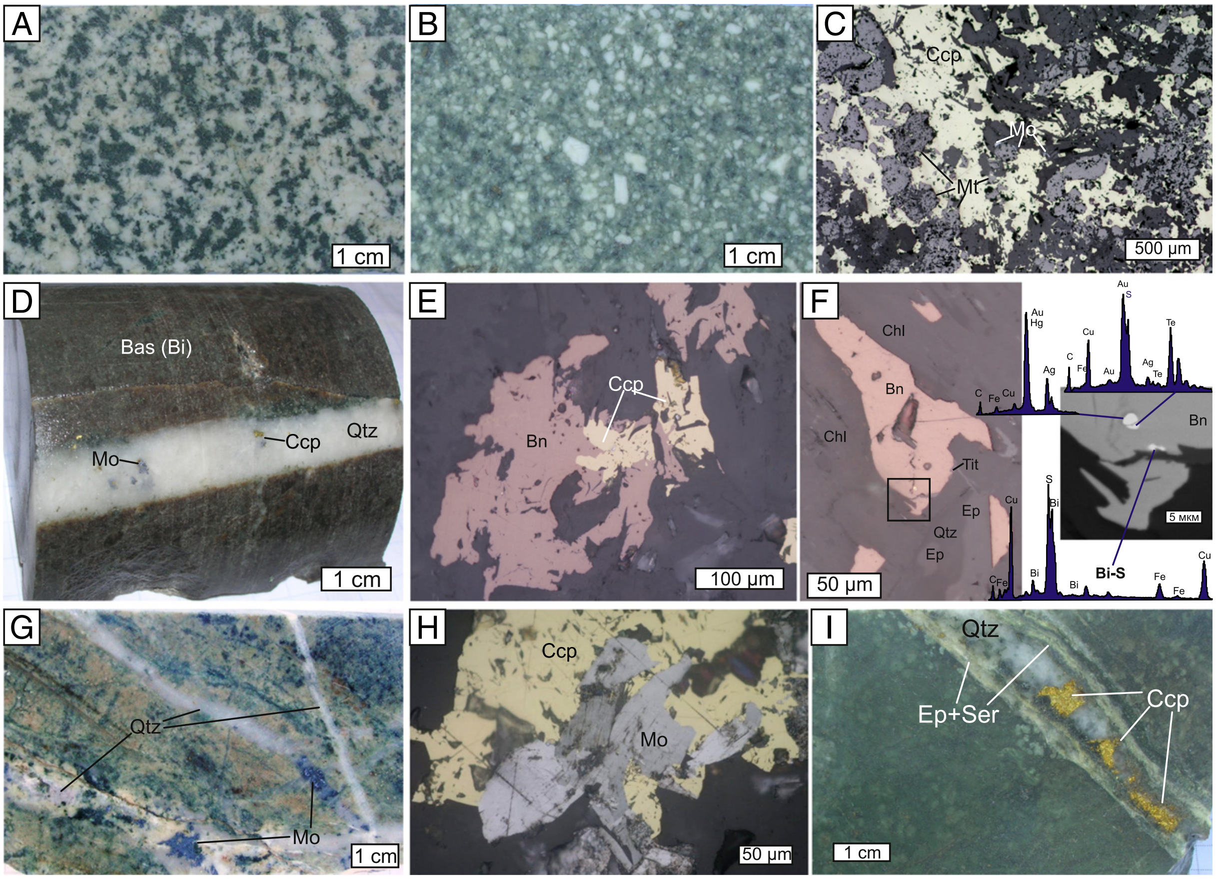

Fig. 9. Main rock, alteration, and ore types of the Mikheevskoe deposit. a) diorite, the Southern intrusion; b) diorite porphyry dyke; c) calcic-sodic alteration magnetite (Mt) and actinolite (Act) cemented by later chalcopyrite (Ccp); d) basaltic andesite with pervasive biotite alteration a white quartz veinlet; e) bornite (Bn) and chalcopyrite intergrowth; f) native gold, and Au-Ag and Bi tellurides overlapping bornite and their EDS-spectra; g) basaltic andesite with phyllic alteration and a network of white quartz veinlets with molybdenite (Mo) nests; h) chalcopyrite overgrowing molybdenite; i) basaltic andesite porphyry lava with pervasive propylitic alteration and quartz veinlet with large chalcopyrite nests, accompanied by epidote stringers (Ep).

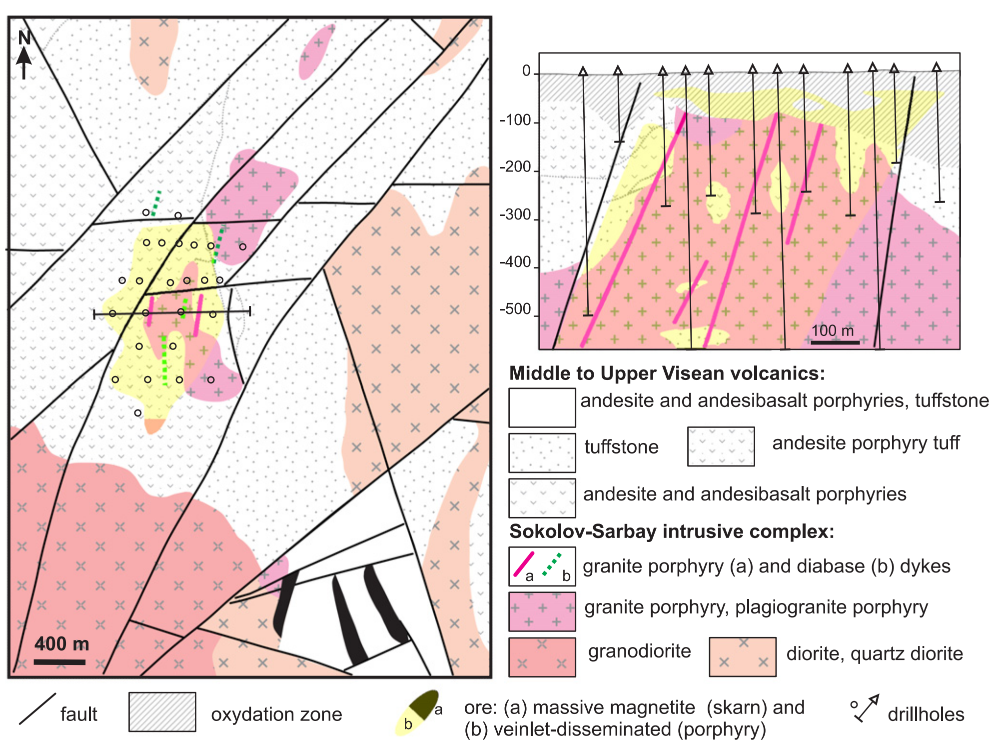

Fig. 10. Schematic geological map and a cross-section of the Benkala deposit (Gachkevich et al., 1986).

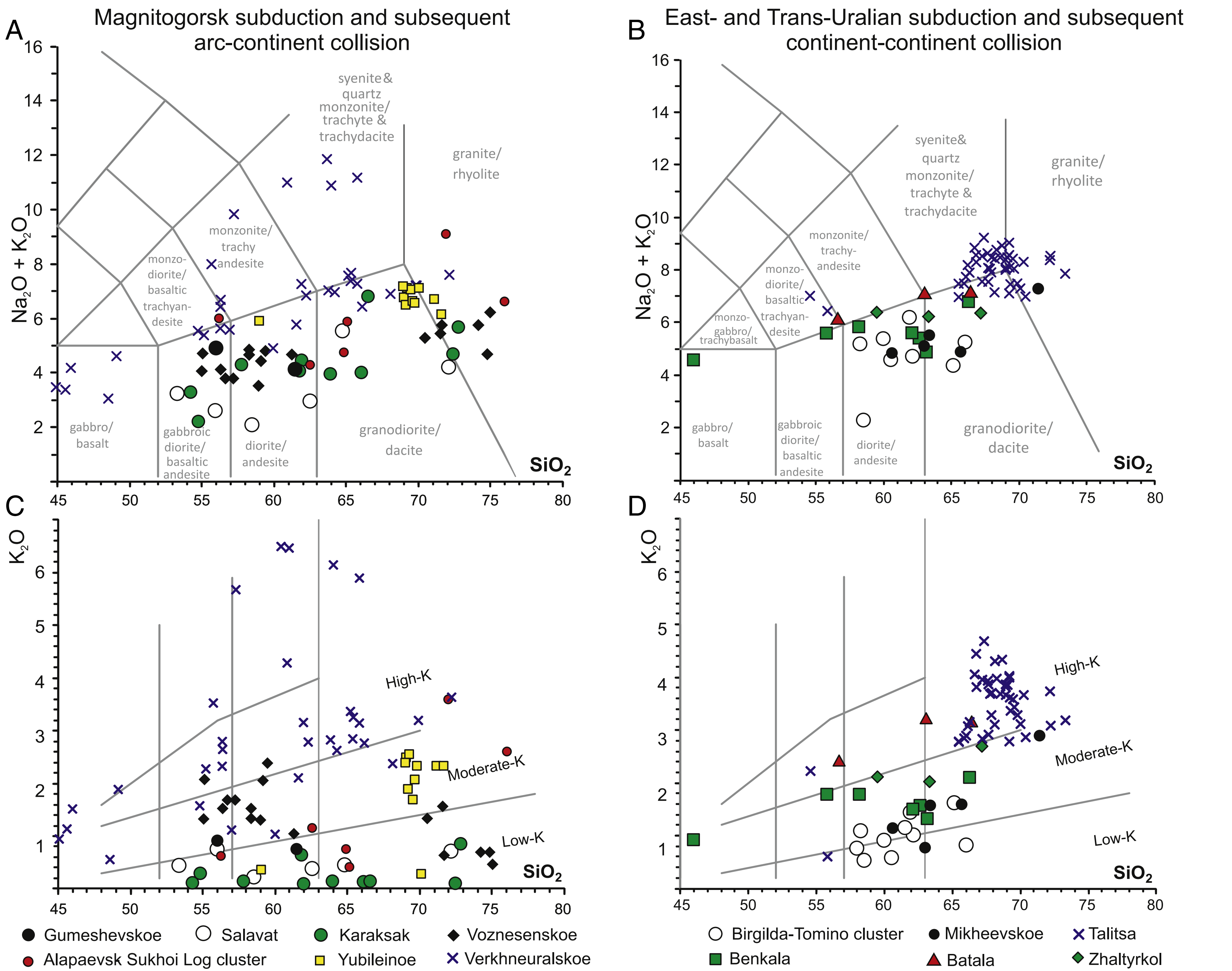

Fig. 11. K + Na – SiO_2 (A,B) and K/Na – SiO_2 (C,D) diagrams for the least altered porphyry rocks of the Tagil-Magnitogorsk (A,C) and East- and Trans-Uralian megaterranes (B,D). Data from the Appendix A.

2.3. The Transuralian megaterrane

The Transuralian megaterrane contains pre-Carboniferous complexes which formed in a variety of tectonic settings. There are gneisses, schists and weakly metamorphosed sediments, coarse terrigenous sediments and volcanics related to Ordovician rifting and oceanic ophiolites, etc. Those are unconformably overlain by Lower Carboniferous suprasubductional volcanogenic sequences (Puchkov, 2010, 2013). It should be noted however that the border between the East- and Trans-Uralian megaterranes has been under discussion for many years and in some models the East Uralian megaterrane extends westwards up to the Valerianovka arc (Petrov et al., 2007 and many others). In this paper the present day subdivision of the Urals presented in detail by Puchkov (2017) is adopted.

Subduction-related volcanic activity began in the Early Carboniferous after the Magnitogorsk arc activity had ceased and the subduction "jumped" eastward (Puchkov, 2017). This led to the formation of two spatially separated calc-alkaline complexes: the Alexandrov and Valerianovka terranes. It is generally accepted that the Valeryanovka arc was formed as a result of eastward subduction under the Kazakh continent and formed at an Andean-type (or some suppose, Californian type) continental margin (Puchkov, 2010, 2013).

The **Tarutino** Cu skarn deposit and the **Mikheevskoe** Cu porphyry deposit (described below in detail) are confined to a narrow north-trending terrane which is considered to mark the transition between the East- and Transuralian megaterranes. The **Tarutino** deposit is hosted by Silurian to Devonian volcanics, sediments, and marbles (Grabezhev et al., 2004) intruded by granodiorite and their porphyry varieties, containing zircons dated as 362 ± 4 Ma using the U-Pb method (Grabezhev and Ronkin, 2011). Skarns and magnetite, magnetite-pyrite chalcopyrite bodies were formed by metasomatic replacement of marble relics within the granodiorite massif while igneous rocks were subjected to propylitic and phyllic alteration and contain porphyry-style pyrite-chalcopyrite mineralization. Post-ore plagiogranite (leucocratic tonalite) dykes with potassic alteration contain associated Mo-porphyry mineralization, though this is not of economic importance (Grabezhev, 2013; Grabezhev et al., 2004).

The Alexandrov terrane consists mainly of andesite and minor basalt, basaltic andesite and felsic rocks with limestone interbeds of Visean age (Samygin and Burtman, 2009). It hosts the **Bataly** ore cluster (Fig. 1 and Table 1) with the **Bataly** Cu-porphyry (Cu/Mo = 150) deposit which was dated by K-Ar in biotite and sericite as 310 and 292 Ma (Syromyatnikov et al., 1986 and references therein).

The **Denisov** terrane separating the Alexandrov and Valerianovka terranes is formed by an Ordovician ophiolitic assemblage (Puchkov, 2010, 2013). The **Varvarinskoye** skarn Cu-Au deposit related to an Early Carboniferous diorite-granodiorite intrusion (Grabezhev and Belgorodskii, 1992) and the poorly studied Spiridonov occurrence are located here (Fig. 1 and Table 1).

The easternmost, **Valeryanovka** terrane consists of Middle–Upper Visean and Serpukhovian–Bashkirian sequences. Basalt, basaltic andesite, andesite, tuff, tuffite, and tuffstone are the main components (Samygin and Burtman, 2009). The **Benkala** Cu-porphyry deposit (described below), the **Zhaltyrkol** Cu porphyry occurrence (Grabezhev and Belgorodskii, 1992) and several less studied porphyry-style occurrences as well as the giant Fe skarn deposits, see (Hawkins et al., 2017, and references therein) are located here.

2.3.1. Mikheevskoe Cu-porpyry deposit

The Mikheevskoe deposit, situated approximately 200 km south of Chelyabinsk (Fig. 1), is a part of the Novonikolaevka ore field, which also includes several poorly-explored porphyry occurrences (Shargorodsky et al., 2005). According to Belgorodskii et al. (1991) the area of the Mikheevskoe deposit (Fig. 8) is formed by Late Devonian to Early Carboniferous volcanics. The lower part of the sequence consists of interbedded sandstone, tuffstone, basaltic andesite, tuffs and tuffaceous breccia with subordinate siltstone, carbonaceous cherty rocks, and basalt. Based on the contained fossil fauna, this sequence was dated as Late-Devonian to Tournaisian (Belgorodskii et al., 1991). The upper volcanic bench is composed of aphyric basaltic lava and pyroclastics with intercalated sandstone, quartzite, and carbonaceous–cherty rocks intruded by numerous serpentinite bodies.

The intrusive rocks belong to the Ulyanovsk and Mikheevskoe igneous complexes which are often considered as "sub-stages" of a single composite igneous complex (Belgorodskii et al., 1991). The intrusions forming the **Ulyanovsk Complex** are stocks and dikes of porphyritic

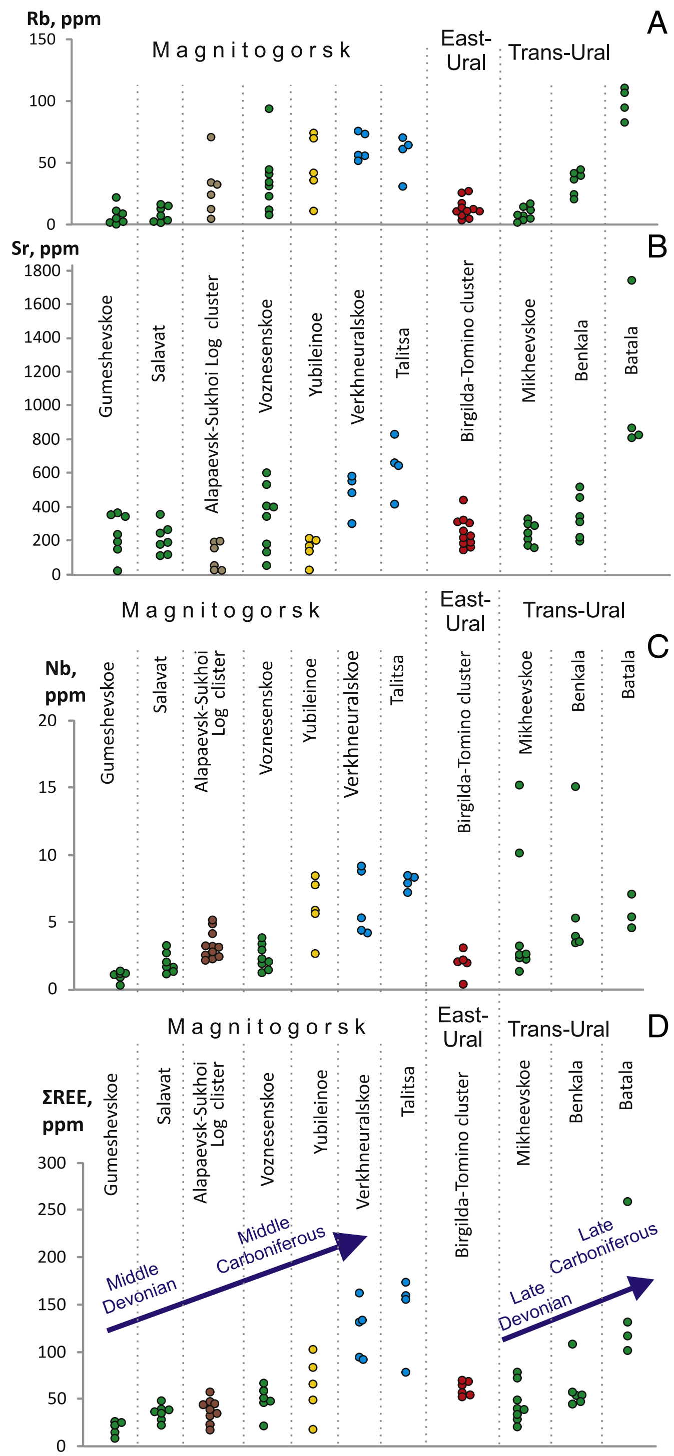

Fig. 12. Rb, Sr, and Nb total REE contents in intrusive rocks associated with porphyry deposits of the Urals.

diorite and andesite, and less frequent dacite, rhyodacite, and dolerite. Based on geological evidence, these are thought to be of Late Devonian to Early Carboniferous age. Porphyry copper–molybdenum mineralization is related to the rocks of the **Mikheevskoe Complex** (Belgorodskii et al., 1991). These are diorite, plagiogranodiorite and their porphyry equivalents (Fig. 9a,b), as well as post-ore adamellite porphyry (Belgorodskii et al., 1991). At depth, the dikes and stocks may merge into the parental pluton (Grabezhev and Belgorodskii, 1992).

Pyrite and chalcopyrite are the main hypogene ore minerals. Bornite, molybdenite, magnetite, and rutile are less abundant while cobaltite–gersdorffite, arsenopyrite, sphalerite, galena, tetrahedrite, and native gold are minor components. The oxidation zone is approximately 15 m thick and composed of clays with residual quartz and nests and concretions of malachite and azurite.

Endogenic porphyry-style mineralization is diorite, plagiogranodiorite and their porphyry equivalents covering an area of 0.5 × 3 km in that trends approximately S-N between two large diorite stocks (ca. 1 km in diameter) of the Mikheevskoe Complex. This configuration makes it impossible to clearly determine the pattern of hydrothermal alteration and ore zoning. Therefore, only a brief description of the main types of alteration and associated mineralization is given here (Plotinskaya et al., 2015b).

The **sodic–calcic alteration** found in the central zone of the deposit is composed of an actinolite ± epidote assemblage. It accompanies a stage of magnetite mineralization (Fig. 9 c). **Potassic alteration** is abundant in the central part of the ore stockwork, particularly in the northern sector of the deposit. Altered rocks composed of biotite + muscovite ± potassium feldspar accompany bornite–chalcopyrite mineralization (Fig. 9d,e). Rare micron-size inclusions of native gold and tellurides of Au, Ag, Pb, Bi, etc. are found in bornite grains, but these seem to belong to a later stage of the paragenetic sequence (Fig. 9f). **Phyllic alteration** (quartz–sericite altered rocks) accompany molybdenite–chalcopyrite mineralization (Fig. 9g,h). **Propylites** (chlorite + epidote + sericite) are abundant on the margins of the deposit (Fig. 9i). The most abundant **chlorite–sericite** metasomatic rocks form transitional zones between phyllic and propylitic alteration. **Base- metal mineralization** (arsenopyrite, tetrahedrite, galena, sphalerite) superimposed on the earlier minerals is rare. Groznova et al. (2015) estimated that the formation of propylitic-related mineralization took place at temperatures of 150 to 350 °C and pressures of 100 to 650 bar from saline (10–35 wt.%-eq.NaCl) fluids of Ca(Mg,Na), Mg, and Na chloride composition with CO_2 and minor N_2 in the vapor phase.

Zircon from the Mikheevskoe diorite porphyry was dated as 356 ± 6 Ma by the U-Pb SHRIMP method (Grabezhev and Ronkin, 2011). This is in a good agreement with the Re-Os dating of molybdenite that gave ages of 357.8 ± 1.8 Ma and 356.1 ± 1.4 Ma (Tessalina and Plotinskaya, 2017).

Estimated reserves of the Mikheevskoe deposit for January 1st 2014 are approx. 347 Mt of ore at 0.45% Cu and 0.1 ppm Au with 1.54 Mt of contained Cu and 47 t of contained Au (Volchkov et al., 2015).

2.3.2. Benkala Cu-porphyry deposit

Mineralization of the Benkala (Benkala North) deposit is associated with Early to Middle Carboniferous intrusions and dykes of the Sokolov-Sarbai diorite–granite complex that intrude a Middle to Upper Visean (Lower Carboniferous) sequence of volcano-sedimentary

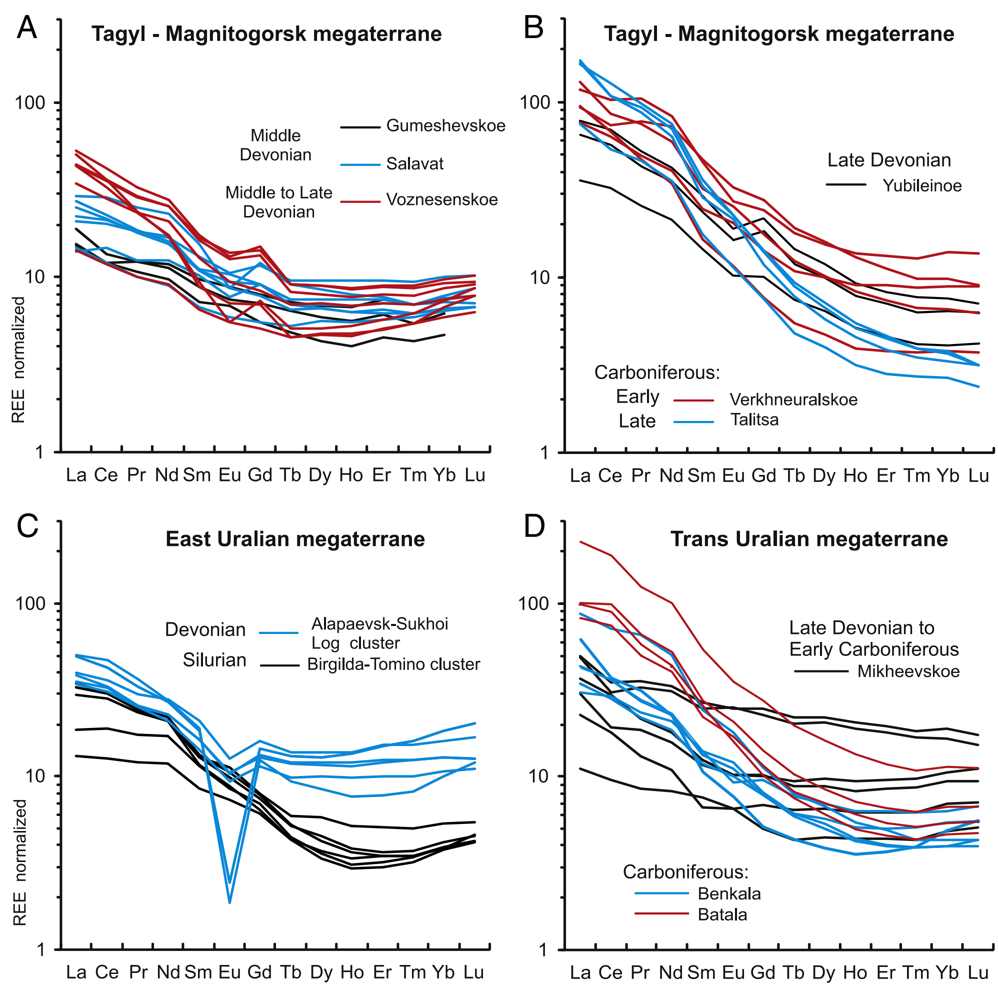

Fig. 13. Chondrite normalized REE spectra of intrusive rocks associated with porphyry deposits. The chondrite normalizing values are from Evensen et al. (1978).

rocks. The description below is derived mainly from (Gachkevich et al., 1986). In the western part of the area the country rocks are predominantly dacites, andesites, andesitic-basalt and basalt porphyry. Whereas in the east there are tuffaceous sandstones, siltstones and argillites, with thin interbeds of lavas and other sedimentary rocks (Fig. 10).

The mineralized intrusion is approximately 1.8 to 1 km in diameter forming a northern apophysis of the Benkala pluton. The intrusion consists of an early stage of porphyritic quartz diorite and granodiorite that is followed by ore-bearing plagiogranite porphyries. Pre-ore granite-porphyry dykes and post-ore microdiabase, lamprophyre, and diabase porphyry dykes are common.

Mineralization forms a stockwork of about 1200 × 800 m in area at surface which extends to a depth of at least 700 m. The early **alkaline phase** is marked by the formation of a biotite-magnetite assemblage (with apatite and titanite) which is most abundant on the margins overlapped by chlorite-quartz-pyrite, chlorite-chalcopyrite, and quartz-prehnite-epidote-chalcopyrite assemblages. Quartz-Kfs veinlets with chalcopyrite, minor bornite and rare molybdenite, chalcocite and digenite occur in the core zone. A quartz-tourmaline assemblage also belongs to the alkaline phase**.** This was overprinted **by a stage of acidic (quartz–sericite) alteration** during which an **assemblage** with pyrite and chalcopyrite was formed. The last phase comprises quartz-carbonate veinlets with pyrite, minor barite, gypsum, and clay minerals. The zone of supergene oxidation reaches up to 110 m below surface. Chalcocite and covellite are major ore minerals.

Frontier Mining (2012) have delineated a JORC-compliant resource of 362 Mt at 0.43% Cu at Benkala containing 1.56 Mt of Cu (0.25% cut-off), 0.183 Mt of which is oxide ore with a grade of 0.54% Cu, with the remaining 1.378 Mt being a sulfide resource with a grade of 0.43% Cu (Wardell Armstrong International, 2011). **Benkala South** is a similar but smaller system located 10 km to the South of the Benkala North. It contains estimated reserves of as much as 0.61 Mt of Cu (Frontier Mining, 2012).

2.4. Deposits in other terranes

Lekyn-Talbey is the northernmost porphyry deposit known in the Urals (Yelokhin and Griaznov, 2012 and references therein), it is located in the Central Uralian megaterrane formed of Precambrian (predominantly Meso- and Neoproterozoic) crystalline basement (Puchkov, 2013). Several gold-bearing base-metal occurrences of uncertain origin have been identified in the surrounding area (Yelokhin and Griaznov, 2012 and references therein). A Neoproterozoic (Russian Vendian) age for this deposit was presumed because of petrochemical similarities between the host Neoproterozoic (Russian Early Vendian) basalt-andesite-dacite sequence and the porphyry intrusion with which the mineralization is associated (Dushin, 1997 and references therein). This makes the Lekyn-Talbey the oldest porphyry deposit in the Urals related to the pre-Uralide orogenic cycle (Puchkov, 2017). Silaev and Andreichev (1982) however estimated an age of 362 to 207 Ma using K-Ar dating and concluded that the deposit was formed during the Uralide cycle. Thus, the tectonic position of the deposit remains unclear and requires farther investigation.

The **Zess** Cu-porphyry occurrence containing pyrite-chalcopyrite and minor base-metal mineralization is located within the Sakmara allochthon within the Ordovician Blyava basalt-rhyolite formation (Starostin et al., 1972). This formation was overthrusted onto the East-European platform in the Late Palaeozoic. Some investigators believe that it formed within the small Middle to Late Ordovician Guberlya volcanic arc (Puchkov, 2017).

2.5. Summary

Despite many uncertainties surrounding the ages of the porphyry mineralization, and therefore of their geodynamic settings, most of the Cu (±Mo,Au) porphyry deposits listed above can be classified into several groups according to the tectonic events to which they are related:

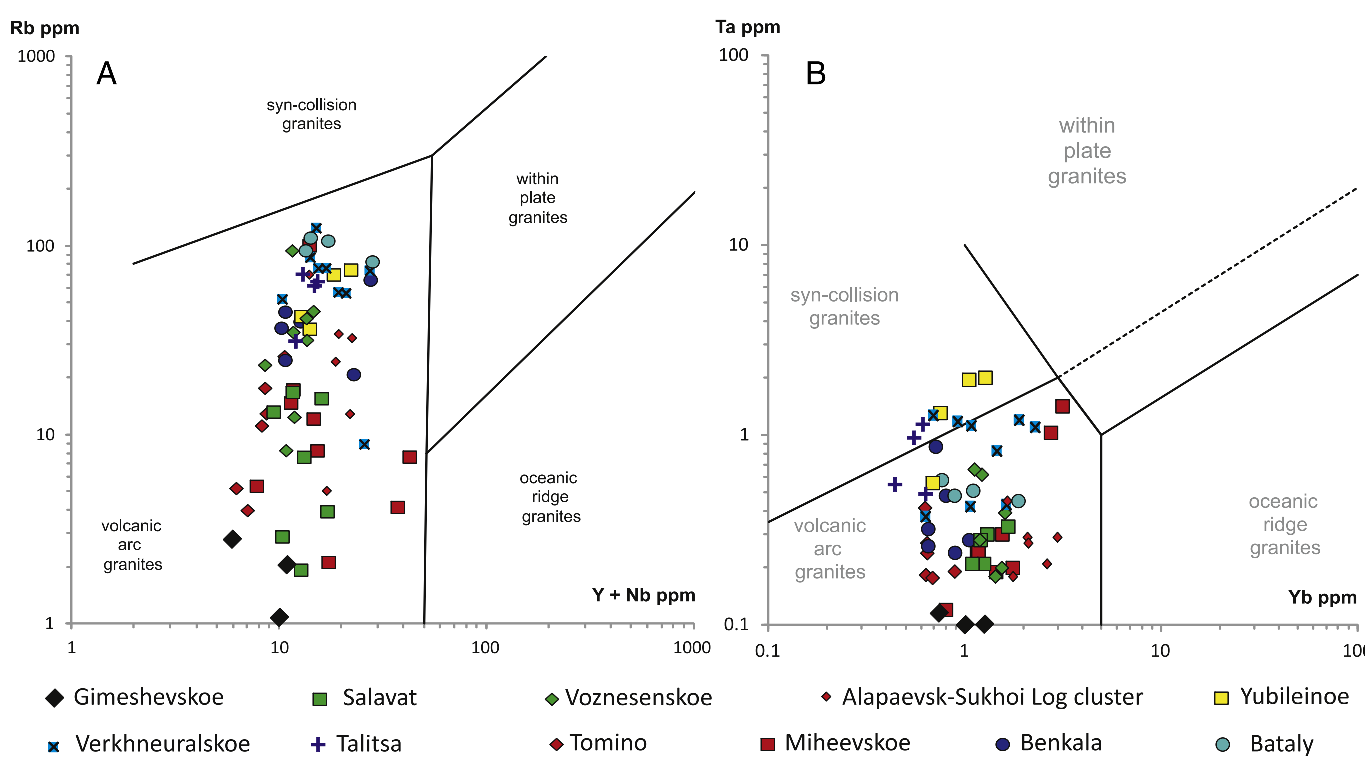

Fig. 14. Rb versus (Y + Nb) (A) and Ta vs. Yb, (B) discrimination diagrams of Pearce et al. (1984) for igneous rocks associated with porphyry deposits. Data from the Appendix B.

(1) Deposits related to Silurian westward intra-oceanic subduction: deposits of the Birgilda-Tomino ore cluster and the Zeleny Dol deposit located in the East Uralian volcanic terrane;
(2) Deposits related to the Devonian Magnitogorsk eastward intra-oceanic subduction as well as to its subsequent collision with the East European plate in the Late Devonian: deposits and occurrences located in the Tagil (Gumeshevskoe) and Magnitogorsk terranes; occurrences from the Alapaevsk-Techa terrane are believed to be related to the same event.
(3) Deposits located in the Transuralian megaterrane and related to Carboniferous volcanic arc activities: from Mikheevskoe in the Early Carboniferous intra-oceanic volcanic arc to Benkala in the Early Carboniferous and others in the Valeryanovka Andean-type margin of the Kazakh continent.
(4) Talitsa Mo-porphyry deposit related to the Late Carboniferous continent-continent collision.

3. General features of the chemistry of the porphyry intrusives

The aim of this section is to summarize only the general features of the chemistry of the porphyry intrusions. A comprehensive study of major and minor element geochemistry would require a detailed study of individual deposits. Major oxides and REE chemistry were selected as being known to be most informative (Castillo et al., 1999; Richards and Kerrich, 2007; Kay and Mpodozis, 2001; Richards et al., 2001; Richards and Kerrich, 2007; Zarasvandi et al., 2016 and many others). Major oxides were analyzed by wet chemistry in the Central Uralian Chemical Laboratory during 1980s–1990s (presented in the Appendix A). REE and other minor elements were analyzed by ICP-MS (Elan 9000) at the Institute of Geology and Geochemistry, Ural Branch of the RAS (given in the Appendix B).

3.1. Major oxides

Cu-(Mo)-porphyry bearing intrusions of both the Tagil and Magnitogorsk megaterranes are remarkably variable in composition (Fig. 11A,C and Appendix A). Middle Devonian Cu-porphyry occurrences (Karaksak and Salavat) formed at intermediate stages of development of the volcanic arc are related to gabbro-diorite to diorite, up to granodiorite rocks of the low-K calc-alkaline series. The Middle Devonian Gumeshevskoe skarn-porphyry is related to similar rocks. Devonian intrusions hosting the occurrences of the Alapaevsk-Sukhoi Log trend are close to these in composition except for the granite which might be related to a separate tectonic event. The Voznesenskoe deposit is related to rocks similar to Karaksak and Salavat but of the moderate-K series. The Late-Devonian Yubileinoe deposit is linked to much more felsic granodiorite to granite rocks but also belonging of the moderate-K calc-alkaline series. The Early Carboniferous Verkhneuralskoe occurrence is related to subalkaline rocks of the high-K series, though several analyzes have K_2O contents above 3.5 wt% are interpreted as a result of a potassic alteration.

Porphyry intrusions of the Birgilda-Tomino ore cluster and Zeleny Dol deposit are usually altered and their primary compositions are difficult to determine. The least-altered varieties are mostly diorites of the low-K calc-alkaline series that differ from Devonian deposits of the Magnitogorsk terrane by their slightly higher alkalinity (Fig. 11B and D).

Igneous rocks of the Mikheevskoe Cu-porphyry deposit range from diorite to granodiorite and granite (Fig. 11B) of the moderate-K calc-alkaline series (Fig. 11D). Carboniferous Intrusions from Zhaltyrkol and Benkala deposit from the Valerianovka terrane belong to the moderate-K sub-alkaline series. Rocks of the Batala Cu porphyry occurrence also belong to the sub-alkaline series but of the high-K series. Intrusions of the Talitsa Mo-porphyry deposit are mainly granodiorite to granite of the high-K series.

3.2. Minor element geochemistry

The Rb and Sr contents of the diorite to granodiorite rocks associated with porphyry mineralization are generally low: up to 100 ppm and 500–600 ppm respectively (Appendix B and Fig. 12A and B).

As illustrated in Fig. 12A,B, intrusions related to the Magnitogorsk subduction show a remarkable increase in Rb and Sr contents from the Early to Middle Devonian Gumeshevskoe and Salavat deposits (Rb < 20 ppm and Sr < 400 ppm) through the Middle to Late Devonian Voznesenskoe deposit (Rb up to 50 ppm and Sr up to 600 ppm) to the Early to Late Carboniferous Verkhneuralskoe and Talitsa deposits (Rb 50–70 ppm and Sr 400–800 ppm). Ta and Nb (Fig. 12C) as well as total REE contents (Fig. 12D) display the same pattern of temporal evolution. For example, the total REE in Gumeshevskoe are below 50 ppm whereas they are up to 200 ppm in Talitsa. Deposits of the Alapaevsk-Sukhoi Log have minor element signatures and other minor element contents similar to those, like Salavat or Voznesenskoe from the Magnitogorsk terrane. This supports the idea that they belong to a Northern part of the Magnitogorsk arc.

A similar trend, though not so clearly pronounced, is shown by the intrusions located in the Trans-Uralian mega terrane, i.e. from the Late Devonian - Early Carboniferous Mikheevskoe deposit to the Late Carboniferous Bataly deposit. All the deposits studied show profiles enriched in light REE (LREE) though they differ depending on terrane and age.

In the Tagil-Magnitogorsk megaterrane the oldest (Middle Devonian) Gumeshevskoe and Salavat deposits have similar REE

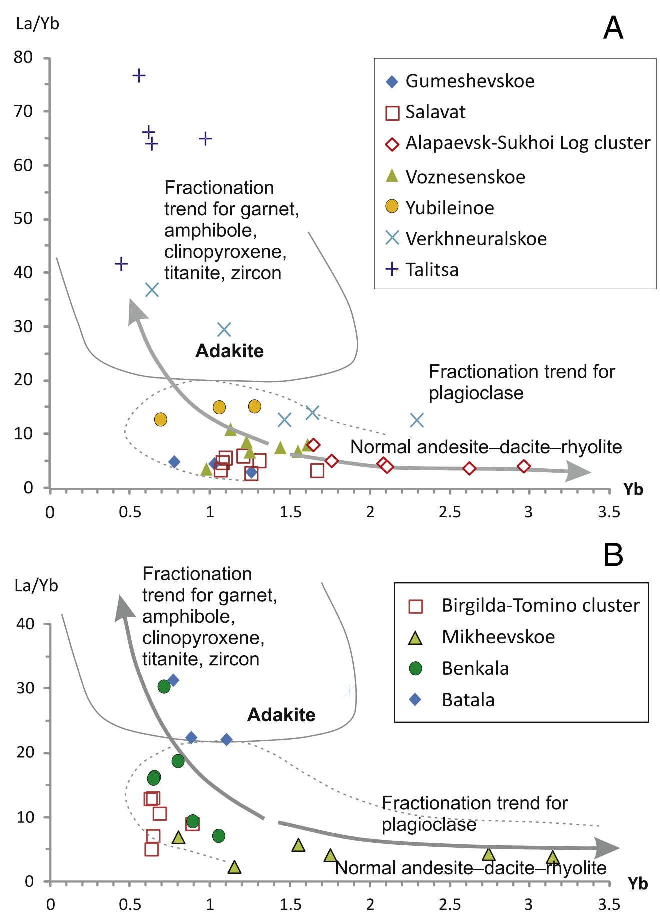

Fig. 15. La/Yb versus Yb diagram showing fields for adakite and island-arc andesite-dacite-rhyolite lavas. Typical differentiation paths resulting from fractionation of various minerals shown schematically (modified after Castillo et al., 1999; Richards and Kerrich, 2007). For intrusions associated with porphyry mineralization from Magnitogorsk megaterrane (A) and East- and Trans-Uralian megaterranes (B).

profiles (Fig. 13A). Those are relatively flat with the mean La_n/Yb_n ratios 2.80 for Gumeshevskoe and 2.97 for Salavat. There are low mean La_n/Sm_n ratios (1.95 for Gumeshevskoe and 1.97 for Salavat) and Dy_n/Yb_n ratios (0.93 for Gumeshevskoe and 0.99 for Salavat) which indicate that LREE to medium REE (MREE) enrichment is greater than MREE to heavy REE (HREE) enrichment. Salavat is characterized by a small mean Eu anomalies (0.88, calculated as $Eu^* = Eu_n / (Sm_n \times Gd_n)^{1/2}$). REE patterns for the Voznesenskoe deposit are, in general, similar to those of Salavat. There is a moderate Eu anomaly (mean = 0.85) and flat MREE to HREE profiles (mean Dy_n/Yb_n = 0.85). LREE to MREE profile is remarkably steep with a mean La_n/Sm_n = 3.36) and thus general LREE enrichment is higher (La_n/Yb_n = 5.06).

Occurrences of the Alapaevsk-Sukhoi Log trend exhibit REE patterns similar to Voznesenskoe (La_n/Yb_n = 3.16, La_n/Sm_n = 2.35, Dy_n/Yb_n = 0.86, Eu^* = 0.72) but with slightly higher HREE contents (usually above 10 ppm). Certain samples are characterized by a strong negative Eu anomaly (0.12 to 0.15) which is most likely to be the result of hydrothermal alteration. The Late Devonian Yubileinoe Au-porphyry and Carboniferous Mo-porphyry Verkhneuralskoe and Talitsa deposits have remarkably steep REE profiles (mean La_n/Yb_n = 9.69, 14.29 and 42.01 respectively) compared to those of the Early to Late Devonian Cu-porphyry deposits. Both LREE to MREE enrichment (mean La_n/Sm_n = 2.64, 3.51 and 4.99 respectively) as well as MREE to HREE enrichment (mean Dy_n/Yb_n = 1.56, 1.33 and 1.73 respectively) are also higher. A small negative Eu anomaly was noted only for the Yubileinoe deposit (mean 0.80). LREE contents are generally one order of magnitude higher than for Cu-porphyry deposits while HREE are remarkably low.

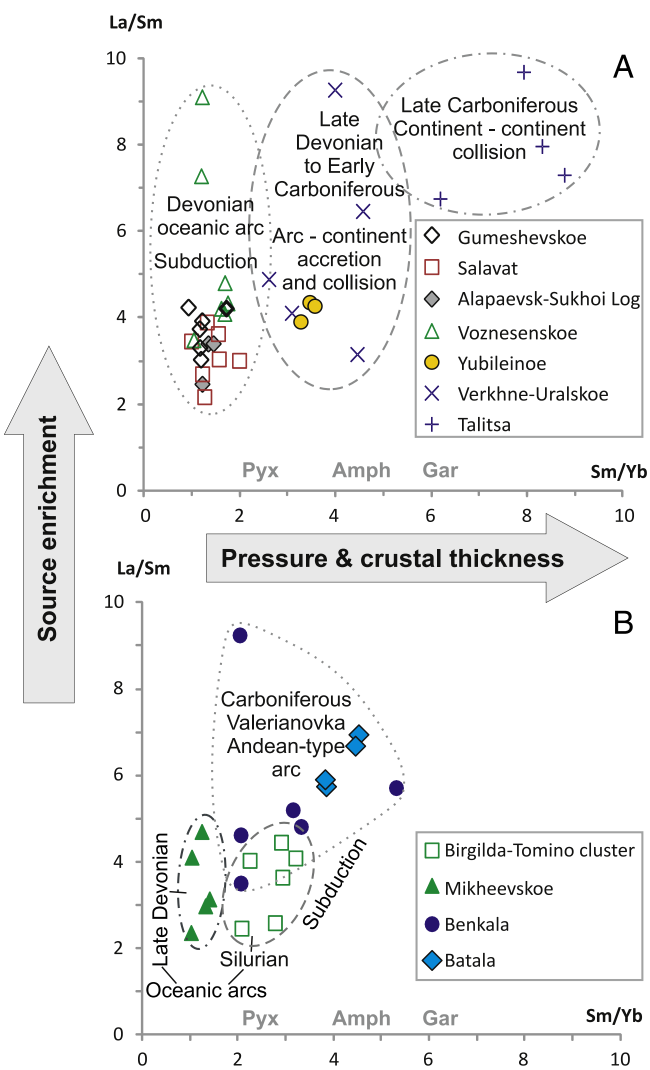

Fig. 16. La/Sm versus Sm/Yb diagram for intrusions associated with porphyry mineralization from Magnitogorsk megaterrane (A) and East- and Trans-Uralian megaterranes (B).
Modified from Kay and Mpodozis (2001); Zarasvandi et al. (2016).

Deposits of the Trans-Uralian megaterrane also display variable REE patterns. The REE patterns of the Mikheevskoe Late Devonian-Early Carboniferous Cu-porphyry deposit are similar to those of the Voznesenskoe deposit (La_n/Yb_n = 3.10, La_n/Sm_n = 2.38, Dy_n/Yb_n = 1.02). Benkala and Bataly Carboniferous Cu-porphyry deposits are characterized by significant LREE enrichment (La_n/Yb_n = 11.01 and 17.01, La_n/Sm_n = 3.47 and 3.98, Dy_n/Yb_n = 1.19 and 1.32 respectively). All three deposits lack a Eu anomaly.

The Tomino Cu-porphyry deposit of the East-Uralian Volcanic terrane exhibits REE patterns steeper than those of Cu-porphyry deposits from other terranes (La_n/Yb_n = 6.50, La_n/Sm_n = 2.23, Dy_n/Yb_n = 1.00).

4. Discussion

On Rb vs. (Y + Nb) and Ta vs. Yb diagrams (Pearce et al., 1984), all the igneous rocks investigated fall within the volcanic arc field (Fig. 14A and B). The only exceptions are some analyses of the Yubileinoe, Verkhneuralskoe and Talitsa deposits on the Ta vs. Yb diagram (Fig. 14B). This confirms the conclusion that all the copper-porphyry occurrences described are related to subduction processes of various ages. Au- and Mo-porphyry deposits, in turn, were formed at the beginning of the collision of the Magnitogorsk arc with the East European platform in the Famennian (Puchkov, 2013, 2017 and references therein) which roughly corresponds to the age of the Yubileinoe Au-porphyry deposit (374 ± 3 Ma). This is also in agreement with the idea that the Au- and Mo-porphyry deposits were formed during the latest stages of subduction.

4.1. Porphyry deposits related to Magnitogorsk subduction

The earliest (Middle Devonian) porphyry mineralization of the Magnitogorsk megaterrane is characterized by high Cu/Mo ratios (approx. 600) and by the dominance of propylitic alteration, e.g. the Karaksak and Salavat occurrences, and Gumeshevskoe skarn-porphyry deposit (Table 1). They are related to gabbro-diorite-quartz diorite porphyry intrusions of the Na calc-alkaline series. Intrusions exhibit flat chondrite-normalized REE patterns with low LREE to MREE enrichment (La_n/Sm_n ration near 2) and insignificant MREE to HREE enrichment Dy_n/Yb_n near 1). Middle to Late Devonian deposits and occurrences (e.g. Voznesenskoe and occurrences of the Alapaevsk-Sukhoi Log cluster) display lower Cu/Mo ratios (approx. 250 in the Voznesenskoe deposit). Deposits of this group are linked to intrusions evolving from gabbro-diorite to granodiorite in the K-Na calc-alkaline series. These rocks are slightly more enriched in LREE compared to the Salavat and Gumeshevskoe deposits but in general have similar REE patterns. The Late-Devonian Yubileinoe deposit is related to much more felsic rocks (granodiorite to granite) but also belonging to the K-Na calc-alkaline series. In the La/Yb versus Yb diagram all the aforementioned deposits fall in the normal andesite-dacite-rhyolite field (Fig. 15A).

The Carboniferous Verkhneuralskoe and Talitsa deposits are characterized by high Mo contents and predominantly of phyllic and potassic alteration and are related to subalkaline rocks. These two deposits have remarkably steep chondrite-normalized REE-patterns due to both LREE/MREE and MREE/HREE enrichment. This usually indicates garnet fractionation or separation from melt in a restite (Richards and Kerrich, 2007 and references therein). In the La/Yb–Yb diagram the Talitsa deposit plots in the adakite-like field while the Verkhneuralskoe deposit falls in the both the volcanic arc and adakite field (Fig. 15A). A general increase in Sm/Yb ratios from Yubileinoe (mean = 3.42) to Verkhneuralskoe (mean = 3.73) and to Talitsa (mean = 7.8) mostly reflects pressure-dependent changes from clinopyroxene to amphibole to garnet in the mineral residue in equilibrium with the evolving magmas (Kay and Mpodozis, 2001 and references therein) as shown in Fig. 16A.

Thus deposits of the Magnitogorsk megaterrane evolve from Cu-porphyry related to the Devonian volcanic arc to Au- and Mo-porphyry related to accretion and subsequent arc-continent collision during the Late Devonian.

4.2. Porphyry deposits related to East- and Trans-Uralian subduction

Cu-porphyry deposits of the Birgilda-Tomino ore cluster (the East-Uralian volcanic zone) and Mikheevskoe Cu-porphyry deposit of the Trans-Uralian zone are both related to volcanic arcs of different age and have similar ore geochemistry (the Cu/Mo ratio is approx. 150 in the Tomino deposit and 115–110 at Mikheevskoe). REE distributions for both deposits correspond to the normal volcanic arc andesite-dacite-rhyolite field following the plagioclase fractionation trend (Fig. 15B). However minor involvement of clinopyroxen fractionation cannot be ruled out for deposits of the Birgilda-Tomino cluster (Figs. 15B and 16B). Middle to Late Carboniferous deposits of the Trans-Uralian terrane (i.e. Benkala, Batala and others) have Cu/Mo ratios mainly in the range from 100 to 200, i.e. similar to the Mikheevskoe deposit. They are linked to intrusions ranging from diorite to granodiorite and granite of the K-Na sub-alkaline series. In contrast to the Mikheevskoe deposit (related to an intra-oceanic arc), Benkala and Batala are characterized by steep chondrite-normalized REE patterns due to clinopyroxene and amphibole fractionation (Figs. 15B and 16B) and in the La/Yb–Yb diagram (Fig. 15B) these deposits deposit plot in the adakite-like field.

Thus from the Late Devonian to Early Carboniferous the tectonic setting of mineralization evolved from the Mikheevskoe deposit linked to an oceanic island arc to the Benkala deposit in the Carboniferous linked to an Andean-type margin marked by involvement of clinopyroxene and amphibole fractionation with a crust thickening in an eastward direction.

4.3. General remarks

It is commonly observed that Cu-porphyry deposits exhibit a temporal and geochemical evolution from sub-economic to economic. This trend correlates with increase in La/Sm and Sm/Yb ratios in associating intrusions, due to crustal assimilation and crustal thickening. This was noted in the Central Andes (Kay and Mpodozis, 2001), and in the Urumieh–Dokhtar Magmatic Arc, Iran (Zarasvandi et al., 2016) and some other settings. In the Urals however the lack of proven resources for most porphyry-style occurrences of the group related to the Magnitogorsk subduction (i.e. Salavat, Voznesenskoe, Verkhneuralskoe etc.) prevents this trend from being tested. Despite this, the presence of elevated contents Au and Mo in porphyry ores (the Yubileinoe deposit) can be correlated with involvement of amphibole fractionation and minor garnet fractionation (the Talitsa Mo-porphyry deposit). The East and Trans- Uralian Tomino and Mikheevskoe deposits (each containing approx. 1.5 Mt Cu) are related to oceanic arc-derived magmas with little REE enrichment but are roughly of the same size as the Benkala deposit (1.56 Mt Cu) located in an Andean-type continental margin where amphibole fractionation and crustal thickening were significant.

5. Conclusions

Most of the Cu (±Mo,Au) porphyry and porphyry-related deposits of the Urals are located in the Tagil-Magnitogorsk, East-Uralian Volcanic and Trans-Uralian volcanic arc megaterranes:. They are related to subduction zones of different ages:

(1) Silurian westward subduction: deposits of the Birgilda-Tomino ore cluster and the Zeleny Dol deposit East Uralian volcanic terrane;
(2) Devonian Magnitogorsk eastward subduction and to the subsequent collision between the Magnitogorsk arc and the East European plate: deposits and occurrences located in the Voikar, Tagil and Magnitogorsk terranes and, probably in the Alapaevsk-Techa terrane;
(3) Carboniferous subduction: deposits located in the Trans-Uralian megaterrane: Mikheevskoe in the Late Devonoan to Early Carboniferous intra-oceanic volcanic arc, Benkala and others in the Early Carboniferous Valeryanovka Andean-type margin of the Kazakh continent.
(4) Talitsa Mo-porphyry deposit related to the Carboniferous continent-continent collision and located on the East Uralian megaterrane.

Porphyry mineralization of the Magnitogorsk megaterrane shows an evolving relationship from gabbro-diorite-quartz diorite in the Middle Devonian to granodiorite-plagiogranodiorite in the Late Devonian and finally to granodiorite in the Carboniferous with a progressive increase in total REE, Rb and Sr contents. This corresponds to the evolution of the Magnitogorsk terrane from a volcanic arc which gave place to an arc-continent collision in the Famennian. This trend correlates with a decrease in Cu/Mo ratio of Mo in ores from approx. 600 at Salavat to approx. 2 at Talitsa.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.oregeorev.2016.07.002.

Conflict of interest

We confirm that there are no known conflicts of interest associated with this publication.

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