



# Metamorphism of volcanogenic massive sulphide deposits in the Urals.

## Ore geology



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### ABSTRACT

The Urals VMS province comprises a broad spectrum of variably metamorphosed deposits, from unmetamorphosed to those without any primary ore textures, which are the results of high-grade metamorphic processes. *Contact metamorphism* near large granite and granodiorite plutons caused the most significant changes of ores, with coarse-grained to pegmatoidal ores with magnetite closest to its contact with the intrusion, followed by pyrrhotite-enriched copper ores, and more distal zinc ( $\pm$ Pb  $\pm$  Ag) mineralisation. Koktau, Tarnyer and Vesennye deposits are metamorphosed to the hornblende-hornfels and pyroxene-hornfels facies ( $t = 400$ – $800$  °C,  $P = 1$ – $6$  kbar). Metamorphism of Tash-Yar, Dzhusinskoe and Krasnogvardeiskoe deposits corresponds to the greenschist and albite-epidote-hornfels facies ( $t = 250$ – $450$  °C,  $P = 1$ – $4$  kbar).

The *regional metamorphism* of VMS ores varies from prehnite-pumpellyite facies ( $t = 150$ – $300$  °C,  $P = 0.5$ – $4$  kbar) in the South Urals to the epidote-amphibolite and amphibolite facies ( $t = 400$ – $600$  °C (up to  $700$  °C),  $P = 1$ – $6$  kbar) in the Karabash area in the Middle Urals. In the Magnitogorsk zone, the metamorphism of host rocks and VMS bodies increases to the north, reaching its peak near the Ufa promontory of the East European platform. With increased metamorphism, the morphology of orebodies evolves from gently dipping thick lenses (Alexandrinskoe and Uzelga fields), to subvertical and folded (Uchaly and Novo-Uchaly deposits) and pseudomonoclinally steeply-dipping vein-like bodies (Karabash district).

The massive sulphide transformation in PTX-gradient fields led to partial redistribution of ore material. An enrichment in Cu, Zn, Ag and Au,  $\pm$ Pb occur in the uppermost parts of large steeply-dipping massive sulphide lenses in wide tectonic zones (e.g., Gai deposit) or as gold-sulphide disseminated bodies near large metamorphosed VMS lenses, distal to a granite pluton (Tarnyer deposit). Partial melting probably occurred in some highly metamorphosed deposits (Tarnyer, Koktau and Mauk). Redeposition of base metals sulphides (chalcopyrite, tennantite, sphalerite,  $\pm$  bornite, galena), as well as the presence of “visible” gold and tellurides, took place during retrograde metamorphism, which produced a transfer of ore matter towards the low stress areas, such as the outer parts of shear zones, the uppermost parts of steeply-dipping ore lenses, pressure shadows, hinge zones of small folds, and small extension fractures (i.e., Alpine-type veins) in deformed ore body or its immediate surroundings.

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## 1. Introduction

The Urals are host to the world's largest belt of volcanogenic massive sulphides (VMS), containing about 2.3 Gt of ore with about 70 Mt of base metals (Zaykov et al., 1998; Prokin and Buslaev, 1999; Franklin et al., 2005; Kontar', 2013). The structural setting of these deposits, the timing of their formation in relation to the geodynamic evolution of the region, as well as the interpretation of their geochemical, mineralogical and lithological features remain the subject of debate (e.g.,

Herrington et al., 2005b; Nimis et al., 2010; Ryazantsev et al., 2012; Seravkin, 2013; Maslennikov et al., 2014; Safina et al., 2015a,b). Most of the deposits occurs in the Tagil and Magnitogorsk zones of the Main Greenstone Belt of the Urals (Kuznetsov, 1939), with its submarine arc-related Ordovician to Early Carboniferous assemblages.

In general, VMS deposits are closely associated with the simultaneously deposited volcanic and sedimentary rocks. Therefore, the majority of VMS deposits has an obvious geological (stratigraphic) age that coincides with the age of the host sequence (Allen et al., 1997; Franklin et al., 2005; Herrington et al., 2005a; Galley et al., 2007; Hannington, 2014; Shanks and Thurston, 2012). The effects of metamorphism on VMS deposits were first studied for deposits in the

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Appalachian and Scandinavian Caledonides (Emmons, 1909; Stanton, 1959; Vokes, 1963, 1969, 1971; Cook, 1993, 1996). Most researchers (Betekhtin et al., 1958; McDonald, 1967; Mookherjee, 1979; Spry et al., 2000; de Roo and van Staal, 2003 and references therein) suggest that the lens-like and banded orebodies with linearly oriented mineral textures were formed as a result of metamorphic differentiation and ductile deformations of primary massive or clastic ores, whereby their transformation was caused either by tectonic movements under high-grade metamorphic conditions or by the thermal effect of large younger plutons.

Many VMS deposits, which were modified by regional metamorphism and deformation, were accompanied by changes in ore mineralogy and textures largely as a result of isochemical processes (Lindgren and Irving, 1911; Vokes, 1966; Stanton, 1972; Sarcar and Deb, 1974; Marshall and Gilligan, 1987; Spry et al., 2000; Corriveau and Spry, 2014). The effects of regional metamorphism is more common for VMS deposits than the effects of contact metamorphism, which are less well documented (Vokes, 2000; Franklin et al., 2005; Mosier et al., 2009; Shanks and Thurston, 2012; Kozlov, 2015).

Volcanic complexes in the Urals that host the VMS deposits were relatively weakly tectonically reworked. So, they have served as a basis for numerous paleo-geodynamic reconstructions (Ivanov et al., 1975; Seravkin et al., 1992; Koroteev et al., 1997; Puchkov, 1997, 2017; Brown et al., 2001; Herrington et al., 2005b). A broad range of host rock compositions from basalt and rhyolite-basalt to basalt-andesite-dacite-rhyolite series, of Late Ordovician to Middle Devonian, is spatially related to the Uralian VMS deposits (Prokin and Buslaev, 1999; Herrington et al., 2005a; Seravkin, 2013). VMS deposits in the Urals range from Cu-rich (Co-Cu and Zn-Cu) to Zn-rich (Cu-Zn) and polymetallic (Pb-Cu-Zn), but also include Au-rich VMS deposits (Smirnov, 1988; Ivanov and Prokin, 1992; Herrington et al., 2005a; Zaykov, 2006; Seravkin, 2013).

Approximately, half of about 120 VMS deposits in the Urals have been mined out whereas others were developed to a significant extent (Khokhryakov, 2000). In 1990, only nine VMS deposits, including four large ones, were mined in the Urals. In 2015, twenty-four VMS deposits were in production, including six large deposits. Some new deposits were discovered as a result of exploration both in brownfield and greenfield terranes. Mineralogical and technological characteristics of ore types for the new deposits are of great importance as metal recovery from Cu and Zn concentrates is basically predetermined by the degree of the ore recrystallisation (Kreiter, 1948; Vikent'ev et al., 2006a; cf. Marshall et al., 2000). Only Urals-type Cu-Zn deposits were in operation until 1990 and only gold was extracted from the uppermost oxide zones of the Baimak-type deposits at that time.

The Uralian VMS deposits are relatively well preserved, with metamorphism of volcanic and volcano-sedimentary rocks mostly limited to the prehnite-pumpellyite facies, much lower than deposits of other Paleozoic VMS provinces. The ore fields even host well-preserved remnants of feeding channels and hydrothermal vent chimneys of “black smokers” (Zaykov and Maslennikov, 1987; Zaykov et al., 1995; Maslennikov, 2006; Maslennikova and Maslennikov, 2007; Maslennikov et al., 2009, 2013, 2017; Safina and Maslennikov, 2009), as well as unique relics of vent fauna (Shadlun, 1964; Zaykov et al., 1995; Little et al., 1998; Maslennikov, 1999; Ayupova et al., 2017; Maslennikov et al., 2016). Less attention has been paid to the metamorphic changes of Uralian VMS deposits. Most relevant works were carried out long ago, with the notable exception of the recently published study by Safina et al. (2015a,b).

Obruchev (1929) was the first to mention the affects of dynamic metamorphism on some Uralian VMS deposits. Features of dynamic metamorphism in the ores were subsequently described by Zamyatin (1929) and Vakhromeyev (1935), although detailed studies were undertaken later by Zavaritsky (1936, 1941, 1950a,b), Ivanov (1939, 1959), and Shadlun (1947, 1950). The influence of regional metamorphism on the Uralian VMS ores was later considered by several workers (Loginov, 1950; Zavaritsky et al., 1950; Rakcheev, 1962; Petrovskaya,

1963; Yarosh, 1973; Ivanov and Prokin, 1992; Vikent'ev, 1995b; Prokin and Buslaev, 1999), although the effects of contact metamorphism on sulphide ores has also been considered (Loginov et al., 1963; Starostin, 1964; Yarosh, 1973; Snachev, 1982; Vikent'ev et al., 2009; Belogub et al., 2011).

This paper describes geological setting and ore zoning of new, recently discovered VMS deposits (Tarnyer, Mauk, Tash-Yar, Letneye, Koktau), with the aim of evaluating the metamorphism-related changes and mineralisation. The results of previous studies (Shadlun, 1964; Loginov et al., 1963; Yarosh, 1973; Snachev, 1982; Maslennikov, 1999, 2006; Melekestseva et al., 2013; Maslennikova and Maslennikov, 2007), as well as our data on the well-known and long operated deposits, such as Gai, Uchaly, Degtyarsk, San-Donato and Karabash (Vikent'ev et al., 2000, 2006a, 2009; Moloshag et al., 2002, 2005; Belogub et al., 2003, 2010, 2011; Vikentyev, 2004, 2015), are summarised here to demonstrate the diversity of metamorphic processes.

For metamorphism types, the authors use the terminology of Bucher and Grapes (2011) which is very close to widely accepted modern terminology for the VMS deposits (Franklin et al., 2005; Giffkins et al., 2005; Shanks and Thurston, 2012). The authors follow the systematic approach taken by Vokes (2000) and Marshall et al. (2000) to describe the effects of metamorphism on sulphides. In particular, it is important to emphasise that metamorphism-related processes of metal transfer with subsequent redeposition is referred to as remobilisation (Marshall and Gilligan, 1987; Moralev et al., 1995; Yudovskaya et al., 1997; Cook et al., 1998; Corriveau and Spry, 2014). The mechanisms of ore mobilisation during metamorphism are summarised in Table 1. Ore remobilisation commonly occurs during the peak and retrograde post-peak phases of metamorphism (Yakovlev, 1978; Cook, 1993; Spry et al., 2000).

## 2. Tectonic setting and types of massive sulphide deposits in the Urals

VMS deposits of the Urals are subdivided into four types: Urals (dominant), Baimak, Dombarovskiy and Ivanovka types. Deposits of the *Urals type*, in turn, are subdivided into two subtypes with Cu  $\gg$  Zn and Zn  $\gg$  Cu (Table 2) and comprise nine world-class Cu + Zn deposits with 3–10 Mt metal endowment (Herrington et al., 2005a; Bortnikov and Vikentyev, 2013; Seravkin, 2013): Gai, Yubileynoe and Podolskoe are Cu-dominated deposits and Uchaly, Novo-Uchaly, Uzelga, Sibai, Degtyarsk and Safyanovka are Zn-dominated ones (Table 3). Eight of these deposits contain > 100 t Au and > 1000 t Ag (Vikentyev, 2006).

A few smaller deposits in the Magnitogorsk zone are classified as Au-pyritic or *Baimak type* (Bakrtau, Baltatau, Tashtau, Uvaryazh, Maiskoe, Dzhusinskoe and Barsuchiy Log) (Table 3). The ores of the Baimak-type deposits are enriched in Cu, Zn and, especially, in Pb, Ba, Au and Ag, in comparison with the typical deposits of the Urals type; they seem to be close analogues of the Kuroko-type VMS systems (Prokin and Buslaev, 1999; Glasby et al., 2007), and have been sometimes considered as a specific subtype of the Urals type (Eremin et al., 2000). The gold content commonly ranges from 1 to 1.5 g/t in the Urals-type ores to 2–5 g/t in the Baimak-type ores, with up to 15–90 g/t in zones of gold enrichment in both types (Vikentyev, 2006, 2015).

Some small deposits in the southern Urals are Cu-rich and slightly enriched in Co (Table 3), with typical bulk concentrations of 0.1 wt%

**Table 1**  
Modes of metal transfer during metamorphism.  
(Adopted from Marshall et al., 2000, with additions).

Mode of transfer	Mechanisms of metal transfer
Mechanical	Cataclasis, viscose-ductile flow, ductile flow
Diffusive	Solid state diffusion, hydrothermal-diffusive
Hydrothermal	In fluid (hydrothermal solution and gas), in brine
Melt	In sulphide melt, in polymetallic melt with the LMCE <sup>a</sup>

<sup>a</sup> LMCE - low-melting-point chalcophile elements (Frost et al., 2002).

**Table 2**  
Volcanogenic massive sulphide deposit types.  
(Adopted from Mosier et al., 2009) and systematics of VMS deposits of the Urals.

Hutchinson, 1973	Cox and Singer, 1986	Prokin and Buslaev, 1999	Franklin et al., 2005	Mosier et al., 2009	Final	Shanks and Thurston, 2012	VMS deposits in this study		Geodynamic setting <sup>a</sup>
							Transitional	Associated magmatic complexes	
Kuroko Zn-Pb-Cu-Ag	Kuroko	Baimak-type	Siliciclastic-felsic in a mature epicontinental arc	Siliciclastic-felsic in a mature epicontinental arc	Felsic to intermediate	Bimodal-felsic	-	-	
Noranda Zn-Cu	Urals-type	Urals-type	Bimodal-felsic in an epicontinental arc	Bimodal-felsic in an epicontinental arc	Bimodal-felsic	Bimodal-felsic	Baimak	Felsic-dominated (bimodal basalt-rhyolite)	Mature oceanic arc (subcontinent crust)
Cyprus Cu-pyrite	Besshi	Cyprus-type	Bimodal-mafic in an oceanic arc	Bimodal-mafic in an oceanic arc	Bimodal-mafic	Bimodal-mafic	Urals Cu >> Zn	Bimodal rhyolite-basalt	Primitive oceanic arc
	Cyprus		Bimodal-mafic in an epicontinental arc	Bimodal-mafic in an epicontinental arc	Pelite-mafic	Mafic-ultramafic	Urals Zn >> Cu	Bimodal basalt-rhyolite	Mature oceanic arc, backarc
			Pelite-mafic in a mature oceanic backarc	Pelite-mafic in a mature oceanic backarc	Mafic		-	Basalt	Primitive oceanic backarc
			Mafic in a primitive oceanic backarc	Mafic in a primitive oceanic backarc	Mafic		Dombrovsky	Serpentinite (minor basalt)	Forearc
			Mafic in a midoceanic ridge	Mafic in a midoceanic ridge			Ivanovka		

<sup>a</sup> After Vikentyev, 2004; Herrington et al., 2005a; Seravkin, 2013.

Co (up to 1–2 wt% Co) in comparison with 0.005–0.01 ppm Co, which is common for the Urals-type deposits. These Cu-pyritic (with minor Zn and Co) systems are locally classified as the *Dombrovsky-type* VMS deposits (Letneye, Osenneye, Levoberezhnoe, Vesenneye and Koktau) (Smirnov, 1988; Prokin and Buslaev, 1999; Seravkin, 2013), although they were also referred to as a subtype of the Urals type (Eremin et al., 2000; Dergachev et al., 2010). Some of the Cu-pyritic deposits (Ivanovka, Ishkinino, Mauk, and Pyshma-Klyuchevskoe) are equivalent to the Cyprus-type (Eremin, 1983; Kontar', 2013) or are a separate *Atlantic type* (Herrington et al., 2005a; Puchkov, 2017) or *Ivanovka Ni-Co-Cu type* (Melekestseva et al., 2013; Seravkin, 2013).

Most of the VMS deposits are located within the Tagil and Magnitogorsk zones of the Urals, which are composed of arc-related formations (Fig. 1). The zones extend for 2000 km roughly along 59–60°E, mainly to the east of the Main Uralian Fault (MUF) (Ivanov et al., 1975; Koroteev et al., 1997; Puchkov, 2010; Ivanov et al., 2013). At its surface, the MUF is exposed as a series of major tectonic sutures that are represented by schistose zones and serpentinite melange (e.g., Melekestseva et al., 2013). The Serov-Mauk serpentinite melange zone occurs along the suture in the eastern part of the Tagil zone (Petrov et al., 2010; Puchkov, 2017).

The Tagil zone extends from the southern to northern Urals (Fig. 1), and is predominantly filled with Ordovician to Silurian volcanic rocks (Karetin, 2000; Herrington et al., 2005b; Desiatnichenko et al., 2005; Petrov et al., 2010). Within the Tagil zone, VMS mineralisation is known in the northern (Tagil) and southern (Sakmara allochthon) segments (Ivanov and Prokin, 1992; Herrington et al., 2005a,b). The northern segment includes moderately to highly metamorphosed ore deposits and comprises small and medium-sized VMS-bearing clusters, arranged along the western margin of the Tagil zone (Shemur, Valentor, Kaban, Levikha-Karpushikha ore districts; Fig. 1; Table 5). A few moderate- to high-grade metamorphosed VMS deposits of the Krasnouralsk ore district are arranged along the eastern margin of the Tagil zone. The rock succession of the Tagil zone was comprehensively investigated in the Uralian Super-Deep Drillhole (USDD) (Vikentyev et al., 1990; Bashta et al., 1991). The southern segment of the Tagil zone occurs in a small tectonic fragment to the west of the MUF (Herrington et al., 2005a, 2005b; Puchkov, 2017) and it corresponds to the Mednogorsk ore district (Fig. 1, Table 2). The latter includes low-grade metamorphosed Komsomolskoe, Blyava and Yaman-Kasy deposits (Fig. 1). The Mauk high-grade metamorphosed VMS deposit occurs in the transition zone between the Tagil and Magnitogorsk zones (Fig. 1).

The Magnitogorsk zone is mostly present in the southern Urals, and is predominantly composed of Middle Devonian to Early Carboniferous rocks and contains all world-class VMS deposits of the Urals, which belong to the Urals type (Fig. 1, Tables 2, 3). The VMS deposits mainly formed in the Magnitogorsk arc-backarc (Herrington et al., 2005b; Seravkin, 2013; Puchkov, 2017) during the Emsian and Eifelian (Table 4). The Late Ordovician to Early Silurian times ("Tagil level") were less endowed with VMS deposits, containing 14.6% of ore and 15.6% of Cu + Zn + Pb metals of the total VMS reserves of the Urals (Table 5). The Urals type of VMS mineralisation is dominant and comprises 95% of ore and metal (Cu + Zn + Pb) (Kontar', 2013). Data on ore reserves for most deposits can be found in several overviews (Zaykov et al., 1998; Prokin and Buslaev, 1999; Herrington et al., 2005a; Seravkin, 2013; Kontar', 2013).

### 3. Types of metamorphism of pyrite-bearing volcanic complexes

The volcanic complexes, hosting VMS deposits, were almost completely reworked by regional metamorphism, commonly low-grade, during orogenesis in the Urals (Ivanov et al., 1975; Puchkov, 2017). This type of metamorphism is the dominant type for VMS deposits. The local areas of higher grade metamorphism occur in the southernmost part of the Middle Urals (Karabash area) and near granite intrusions (Rakcheev, 1962; Yarosh, 1973; Vikentyev, 1996). Correspondingly,

**Table 3**  
Features of VMS deposits of the Urals and correlation with global VMS deposit types.

Barrie and Hannington, 1999; Franklin et al., 2005 Type	Prokin and Buslaev, 1999	Herrington et al., 2005a	Seravkin, 2013	This study				
				Type	Age <sup>a</sup>	Host rocks	Geochemical type	Examples <sup>b</sup>
<b>Mafic</b> in ocean ridge, in a primitive oceanic backarc	Cyprus	Atlantic	Ivanovka (Ni-Co) Cu	Ivanovka	Late Silurian– Early Devonian	Serpentinite, metabasalt Serpentinite, gabbro, metabasalt Basalt, metabasalt	Ni-Co- <b>Cu</b> Ni-Co-Cu-(Au) <b>Cu</b> (Zn,Co)	<b>Mauk</b> , Ivanovka, Dergamysh, Ishkinino Pyshminsk-Klyuchevskoe
			Dombarovsk	Dombarovka Cu	Dombarovsky	Emsian		
<b>Bimodal-mafic</b> in an oceanic arc	Urals	Urals	Ural Cu-Zn	Urals	Late Ordovician – Early Llandoveryian	Bimodal rhyolite-basalt (with rare andesite and dacite)	1) <b>Cu-Zn</b> (Au)	<b>San-Donato</b> , <b>Tarnyer</b> , <b>Krasnogvardeiskoe</b> , Valentor, Kaban, Levikha
					Emsian	Bimodal rhyolite-basalt	2) <b>Cu-Zn</b> (Au) 3) Zn- <b>Cu</b> (Au, Ag)	Komsomolskoe, Blyava, Yaman-Kasy <b>Gai</b> , Podolskoe, Yubileinoe, Oktyabrskoe, Priorskoe, Kundyzydy, Limannoe
					Eifelian Mid-Eifelian	Bimodal basalt-rhyolite (with minor chert, limestone, andesite and dacite)	4) <b>Cu-Zn</b> (Au) 5) <b>Cu-Zn</b> (Au, Ag)	<b>Karabash group</b> , <b>Kuznechikha</b> <b>Uchalay</b> , Novo-Uchalay, <b>Sibai</b> , <b>Degtyarsk</b> , Safyanovskoe
					Late Eifelian – Early Givetian Givetian – Early Frasnian			<b>Uzelga</b> , Talgan, Molodezhnoe West-Ozerno, XIX Parts'ezda
<b>Bimodal-felsic</b> in an epicontinental arc	Baimak	Baimak	Baimak Au-Ba-Pb-Cu-Zn	Baimak	Late Ordovician – Early Llandoveryian	Bimodal basalt-rhyolite, felsic-dominated (with minor andesite and dacite)	1) <b>Zn</b> -(Cu-Pb-Ag-Au)	Galkinskoe
					Emsian		2) <b>Cu-Zn</b> -(Pb-Au) 3) <b>Au</b> -polymetallic	Vishnevskoe Maiskoe, Bakrtau, Baltatau, Uvaryazh
					Early Eifelian		4) <b>Au-Cu</b> -(Zn) 5) <b>Pb-Zn-Cu</b> -(Au) 6) <b>Cu-Zn</b> -(Pb-Au)	Tashtau <b>Dzhusinskoe</b> Barsuchiy Log
					Late Eifelian Mid-Eifelian		7) <b>Zn</b> -(Cu)	<b>Alexandrinskoe</b> <b>Tash-Yar</b>

<sup>a</sup> Geological age of host volcano-sedimentary horizon.

<sup>b</sup> Key deposits for this study – in bold.

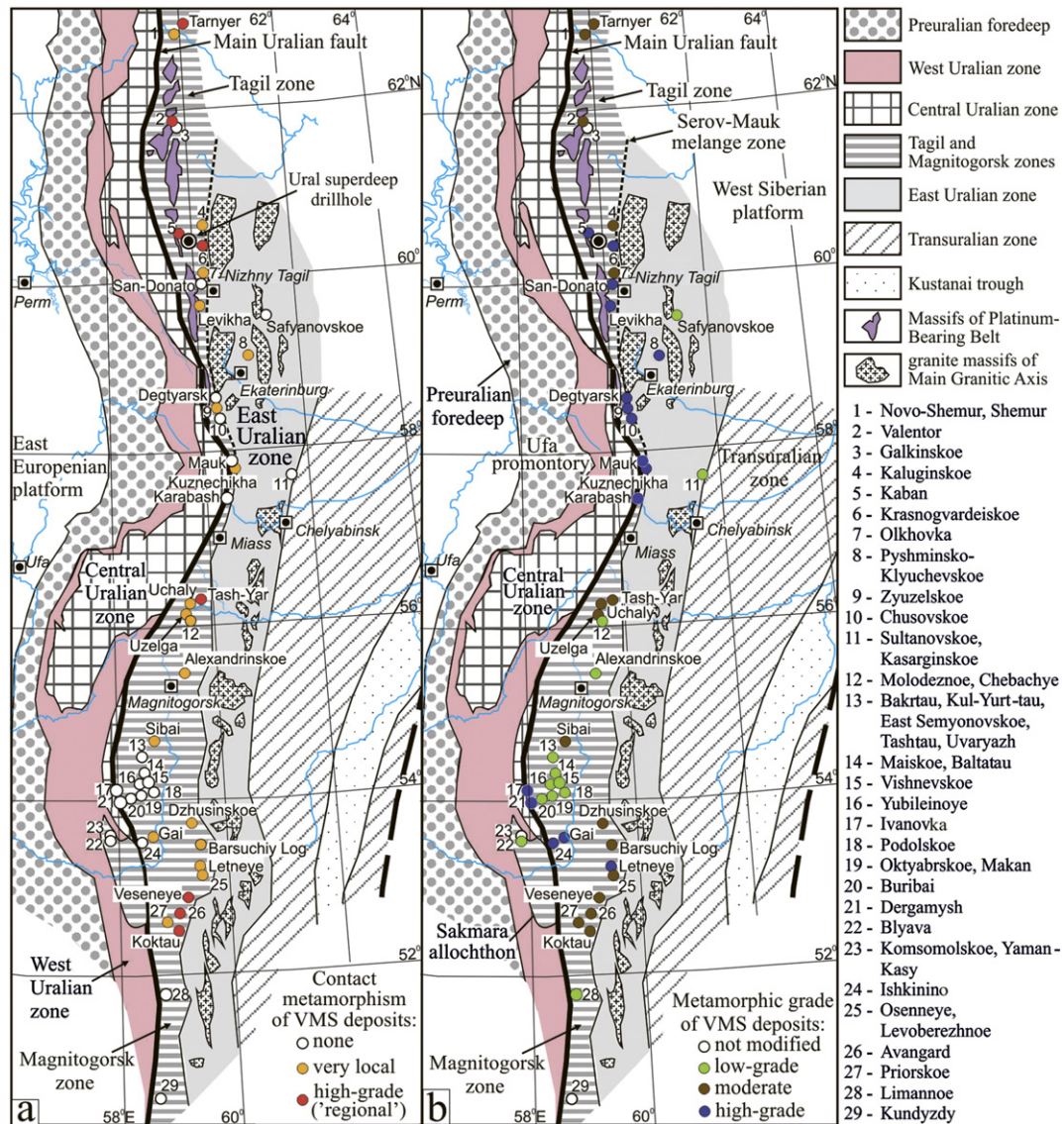


Fig. 1. VMS deposits of the Urals and their metamorphism (structural zones are modified after Puchkov (2010)). a – Contact metamorphism of VMS deposits, b – regional metamorphism of VMS deposits. The numbers correspond to the VMS deposits (from the north to south).

regional (burial and orogenic) and contact types of metamorphism affected other VMS fields in the Urals.

The T-P range of the regional metamorphism is broad in the Urals (Table 6, Fig. 2). This led to a unique (for VMS provinces) coexistence of unmetamorphosed deposits with those affected by low- to high-grade metamorphism. The mineral assemblages of slightly deformed Silurian and Devonian volcano-sedimentary rocks are essentially represented by quartz, albite, sericite, chlorite, carbonate ± prehnite, pumpellyite and epidote, indicative of prehnite-pumpellyite to lower greenschist facies of burial metamorphism. The low-grade metamorphosed volcanic rocks, which are rare in the Middle Urals, occur in the northern part of the Middle Urals (in the USDD area), near the axial part of the Tagil zone, and in the North Urals as well as in the central and southern parts of the Magnitogorsk zone.

It is necessary to emphasise that zeolite and prehnite-pumpellyite facies of metamorphism are not easily detectable for the VMS fields because it is difficult to distinguish syngenetic alteration of the deposit versus subsequent superimposed metamorphism since the temperature of the ore-forming fluid was likely to be 250° to ~400 °C (as based on vent temperatures from active forming deposits on the sea floor), i.e., the upper temperature estimation of conditions of primary

VMS formation was even higher than the temperature of the low-grade metamorphism. That the metamorphic conditions of host rocks were subjected to low-grade metamorphism is suggested by the following (see also Vikentyev et al., 2016): (1) the occurrence of zeolites, R1 ordered illite-smectite (rectorite) and some other clay minerals (see Table 6) in slightly altered host rocks, especially in the hanging wall of massive ore; (2) occurrence of dispersed amorphous organic matter, sub-graphitic material; (3) preservation of framboidal and globular pyrite in ore or its immediate surroundings; (4) well-preserved remnants of feeding channels, hydrothermal vent chimneys, and relics of vent fauna (see Introduction for references) in many VMS deposits of the Urals; and (5) common manifestation of such low-grade metamorphism in ore-bearing volcanic complexes outside VMS deposits.

Regional metamorphism reaches its highest grade (epidote-amphibolite and amphibolite facies) in the Karabash ore district, due to regional compression, related to the Ufa promontory of the East European platform (Fig. 1).

Burial metamorphism in the Tagil zone was systematically studied in the USDD, which was drilled in the Middle Urals. Effusive, subvolcanic and volcano-sedimentary rocks in the 6 km deep USDD were subject to low-grade metamorphism (Vikentyev et al., 1990; Vikentyev,

**Table 4**

Major ore-bearing levels, VMS districts and deposits of the Urals and their metamorphism.

Regional level	Local level	Formation	Age	Ore district	Deposit
Lower Silurian	Upper Ordovician – Lower Silurian	Baulus	Upper Caradocian – Lower Llandoveryan	Mednogorsk (Blyava) <sup>2</sup>	Komsomolskoe, Blyava <sup>a</sup> , Yaman-Kasy, Razumovskoe
		Lower Shemur	Upper Ordovician – Lower Llandoveryan	Shemur <sup>3</sup>	<b>Tarnyer</b> , Shemur <sup>a</sup>
		Kaban		Kaban <sup>1</sup>	<b>Kaban</b> (Kaban group)
		Kirovgrad		Levikha-Karpushikha <sup>1</sup>	<b>Levikha</b> (Levikha group), <b>Shaitanskoe</b> , <b>Karpushikha</b> , <b>Lomovka</b> , <b>Ezhovskoe</b> , <b>Kalata</b>
	Lower Silurian	Upper Shemur Krasnouralsk		Valentor <sup>3</sup> Tagil-Krasnouralsk <sup>1</sup>	Valentor <sup>a</sup> , Galkinskoe <b>San-Donato</b> , <b>Olkhovka</b> , <b>Krasnogvardeiskoe</b> , <b>Kaluginskoe</b> , <b>Andreyevskoe</b> , <b>Zavodinskoe</b> <b>Yuluk</b>
Lower Devonian – Eifelian	Lower Devonian	Karamalinsk	Upper Silurian– Lower Devonian	Yuluk <sup>1</sup>	
		Sakmara	Lower Devonian	Ivanovsky <sup>1</sup> Karabash <sup>1</sup>	<b>Ivanovka</b> , <b>Dergamysh</b> , <b>Ishkinino</b> <b>Mauk</b>
		Kungurkov	Lower Devonian	Pyshminsk <sup>1</sup>	<b>Pyshminsk-Klyuchevskoe</b>
		Baimak–Buribai	Emsian	Gaisky <sup>1</sup> Buribai <sup>3</sup> Baimak <sup>2</sup>	<b>Gai</b> Yubileinoe <sup>a</sup> , Buribai, Makan <sup>a</sup> , Oktyabrskoe <sup>a</sup> , Bakrtau, Tashtau, Baltatau, Maisk, Uvryazh <sup>a</sup> , East-Semyonovskoe <sup>a</sup> , Vishnevskoe, Kul-Yurt-tau
		Kiembraevo		Dombrovsky <sup>3</sup>	<b>Letneye</b> , Levoberezhnoe <sup>a</sup> , Osenneye <sup>a</sup> , <b>Vesenneye</b>
		Mugodzhary		Mid-Orsk <sup>3</sup> Upper-Orsk <sup>3</sup> Kundyzdy <sup>2</sup>	<b>Koktau</b> , Priorskoe <sup>a</sup> , <b>Avangard</b> Limannoe <sup>a</sup> Kundyzdy
Eifelian – Givetian	Lower Devonian–Eifelian	Irendyk	Emsian	Podolsk ore field <sup>2</sup>	Podolskoe <sup>a</sup> , East-Podolskoe
		Dzhusinsk	Lower Eifelian	Tarensai <sup>3</sup>	Barsuchiy Log <sup>a</sup> , <b>Dzhusinskoe</b>
	Eifelian	Karamalytash	Eifelian	Karabash <sup>1</sup>	<b>Karabash group</b> , <b>Kuznechikha</b> , <b>Sukhovyzovo</b>
			Mid-Eifelian	Sibai <sup>3</sup> Uchaly <sup>3</sup> Rezh <sup>2</sup>	Sibai <sup>a</sup> , Kamagan Uchaly <sup>a</sup> , Novo-Uchaly <sup>a</sup> , <b>Tash-Yar</b> Safyanovskoe
	Givetian	Lower Ulutau	Upper Eifelian Upper Eifelian – Lower Givetian Givetian – Lower Francian	Polevskoi <sup>1</sup> Alexandrinsky <sup>3</sup> Verkhneuralsk <sup>3</sup>	<b>Degtyarsk</b> , <b>Chusovskoe</b> , <b>Zyuzelskoe</b> Alexandrinskoe <sup>a</sup> , Babaryk <sup>a</sup> Uzelga <sup>a</sup> , Talgan, <b>Ozerno</b> , Chebache <sup>a</sup> , Molodezhnoe <sup>a</sup> West-Ozerno, XIX Parts <sup>a</sup> ezd

After Smirnov (1985, 1988), Ivanov and Prokin (1992), Prokin and Buslaev (1999), Herrington et al. (2005a), Seravkin (2013), Kontar', (2013), with significant corrections and additions.

<sup>1</sup> VMS district with high-grade metamorphosed deposits.<sup>2</sup> VMS district with low-grade metamorphosed deposits.<sup>3</sup> district including both low- and high-grade metamorphosed ore bodies/deposits.<sup>a</sup> Metamorphism from low-grade to moderate (locally – up to high-grade); bold – high-grade metamorphosed deposits.

2004). The mineral assemblages within an interval of 0 to 5 km correspond to the prehnite-pumpellyite facies ( $t = 220\text{--}300\text{ }^{\circ}\text{C}$ ). The parageneses of metamorphic minerals below a depth of 5065 m correspond to the greenschist facies ( $t = 300\text{--}375\text{ }^{\circ}\text{C}$ ) (see T-P paths on Fig. 2).

Later *orogenic metamorphism*, commonly accompanied by dynamo-metamorphic conversions, was overprinted on low-grade burial metamorphism. At the same time, outside the major shear zones and granite-bearing belts, these complexes exhibit prehnite-pumpellyite burial metamorphism (Valentor, Kaban, Rezh, Baimak, Buribai, Mednogorsk, and Kundyzdy VMS districts). In shear zones, features of dynamic

metamorphism are dominant. It was essentially syn-collision (orogenic) metamorphism, using the terminology of Bucher and Grapes (2011). It corresponds to an intermediate P/T type of metamorphism (Spears, 1993).

In the Middle Urals, the VMS deposits mostly occur inside of the NS-trending regional-scale shear zones. The steeply-dipping to vertical pseudo-monoclinical structure and widespread schistosity are the most characteristic features of the VMS deposits in these zones (Table 7). Routinely, massive sulphide plates and ribbons comprise few swells (up to 100–250 m wide; e.g., Degtyarsk) and pinches. Boudinaging at various scales, folded, sheet- and ribbon-like shapes of sulphide bodies

**Table 5**

Proved metal reserves of ore and metals (including mined ore) for the major VMS-bearing levels of the Urals.

VMS-bearing level	Reserves (proportion of the total for the Urals, %)					
	Ore, Mt (%)	Cu, Kt (%)	Zn, Kt (%)	Pb, Kt (%)	Au, t (%)	Ag, t (%)
Upper Ordovician – Lower Silurian	342.8 (14.6)	4662 (14.8)	5797 (16.4)	367 (16.3)	329.8 (13.8)	5537 (14.6)
Lower Devonian (mainly Emsian)	884.8 (37.6)	13,870 (44.0)	8833 (24.9)	560 (24.9)	1081.8 (45.4)	13,266 (35.0)
Eifelian – Givetian (mainly Eifelian)	1126.6 (47.9)	12,986 (41.2)	20,809 (58.7)	1322 (58.8)	973.7 (40.8)	19,121 (50.4)
Total	2354.1 (100)	31,517 (100)	35,439 (100)	2249 (100)	2385.3 (100)	37,924 (100)

Based on data of (Kontar', 2013), with corrections and additions of data for VMS deposits of West Kazakhstan.

**Table 6**  
Mineral parageneses and conditions of regional metamorphism of VMS deposits of the Urals.

Type of metamorphism	Facies	Key metamorphic minerals	<i>t</i> , °C	<i>P</i> , kb	Gradient, °C/km	Deposit
Burial	Zeolite	Ill, Ill-Sme, HSer (1M) ± Zeo, Kln, Mnt, Chl	100–180	0.1–0.5	15–25	Komsomolskoe, Yaman-Kasy, Galkinskoe, Kundyzdy
	± dynamic metamorphism (up to low greenschist)	Prh, Pmp, Ab, Q, Chl, Ttn ± Ser (1M ≫ 2M <sub>1</sub> ), Ep, Ank	150–300 200–400	0.5–4	25–50	Yubileynoe, Sibai, Safyanovskoe, Blyava, Alexandrinskoe, Talgan, Sultanovskoe Uchaly, Novo-Uchaly, Uzelga, Barsuchiy Log, Priorskoe, Valentor
Orogenic + dynamic metamorphism	Greenschist	Ab, Q, Ser (1M + 2M <sub>1</sub> ), Chl, Ep ± Act, Cc, Dol, Rt	250–450	1–5	25–50 (up to 100)	Gai, Degtyarsk, Levikha, San-Donato (III International), Krasnouralsk group (Krasnogvardeiskoe etc.), Kaban
	Epidote-amphibolite (up to amphibolite)	Olg, Mus (2M <sub>1</sub> ), Act, Bt, Ep, ± Hb, And, Ky, St, Grt, Tur, Ap, Rt, garnite	400–600 (350–700)	1–6	25–100	Karabash group, Mauk, Kuznechikha

Abbreviations of key metamorphic minerals (for Tables 6, 9, 10): Ab – albite, Act – actinolite, And – andalusite, Ands – andesine, Ank – ankerite, Ap – apatite, Ath – anthophyllite, BaFs – barium feldspar (zelsian, hyalophane), Bt – biotite, Cc – calcite, Chl – chlorite, Crd – cordierite, Dol – dolomite, Ep – epidote, Grt – garnet, Hb – hornblende, HSer – hydrosericite, Ill – illite, Kfs – K-feldspar, Kln – kaolinite, Ky – kyanite, Mnt – montmorillonite, Mus – muscovite, Olg – oligoclase, Pmp – pumpellyite, Prh – prehnite, Q – quartz, Rt – rutile, Ser – sericite, Sil – sillimanite, Sme – smectite, Spl – spinel, St – staurolite, Ttn – titanite (sphene), Tur – tourmaline, Zeo – zeolite.

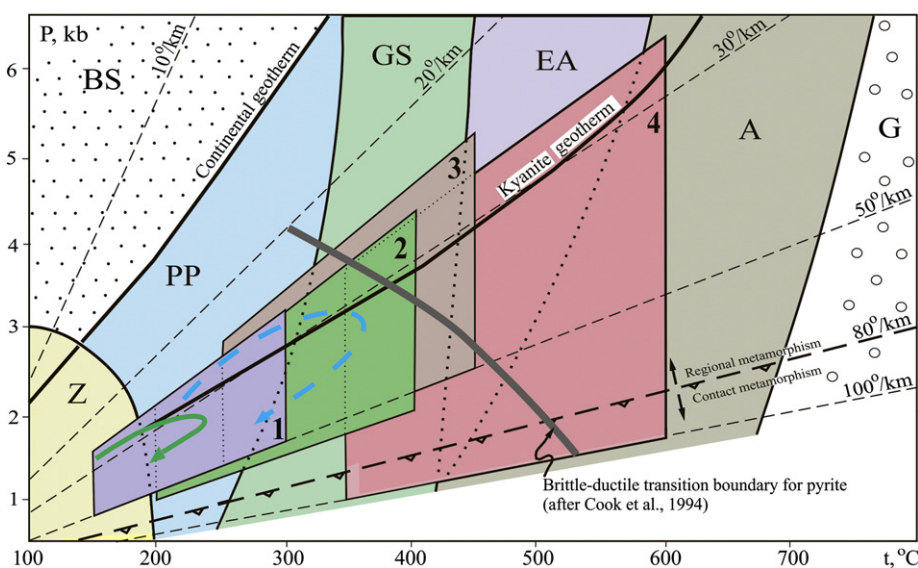
and Alpine-type veins (i.e., sulphide-bearing veins, routinely quartz-dominant, which has a metamorphic/hydrothermal, late-orogenic origin; see e.g. Vokes, 2000; Marshall et al., 2000) are common for the VMS deposits located inside the shear zones. The ore lenses were locally disintegrated into fragments and surrounded by more plastic quartz-sericite-chlorite aggregates. Rims of small inclusions of host rocks in massive ores and pressure shadows of microquartzite and massive pyrite boudins are generally composed of chalcopyrite.

The MUF zone, up to a few kilometres wide, is usually characterised by epidote-amphibolite and amphibolite facies metamorphism (Table 6). The Serov-Mauk melange zone (Puchkov, 2010) is similar to the MUF in terms of the metamorphic grade, which also rises up to amphibolite facies in the Karabash area, as exemplified by the Mauk deposit.

Contact metamorphism near granite intrusions or regional-contact metamorphism (Shanks and Thurston, 2012) results in complete recrystallisation and significant remobilisation of synvolcanic sulphides due to the thermal influence of the spatially related granite (Yarosh, 1973; Prokin and Buslaev, 1999; Snachev, 1982; Vikent'ev et al., 2009; Belogub et al., 2011). Large plagiogranite, granite and granodiorite

plutons or plagiogranite-gabbro polyphase massifs crystallised within a half million to a few million year time period and have had a strong impact on VMS ores and host volcanic rocks, 1–2 km from the granite massif (Tables 8 and 9). The contact-remobilised deposits (Tash-Yar, Tarnyer and Koktau) occur in the same ore fields together with the weakly and moderately metamorphosed VMS deposits. Plagiogranite and gabbro-plagiogranite synvolcanic massifs intruded during Late Silurian to Early Devonian in the Tagil zone (Fershtater, 2013). Granite emplacement was mainly induced by collisional process near the Devonian/Carboniferous (ca. 360 Ma) and Carboniferous/Permian (ca. 300 Ma) boundaries for the Magnitogorsk zone (Puchkov, 2017) (see Section 6.5).

Local contact metamorphism accompanied intrusion of dykes of intermediate to mafic compositions in many ore fields (e.g., Dzhusinskoe, Levikha, Letneye and Uzelga) (Tables 8). Contact metamorphism operated even very locally, in the narrow (0.1–1 m wide) dyke exocontacts (e.g., Uzelga and Uchaly). It resulted in development of late quartz-sulphide veinlets (galena, tennantite-tetrahedrite, native gold, magnetite, cubanite and bornite) inside the dykes and sulphide remobilisation in



**Fig. 2.** Regional metamorphism of VMS deposits in the Urals, modified after Vikentyev, 2004. Metamorphic facies: Z – zeolite, BS – blue schist, PP – prehnite-pumpellyite, GS – greenschist, EA – epidote-amphibolite, A – amphibolite, G – granulite. Kyanite geotherm after Bucher and Grapes (2011). The green arrow shows a T-P path for the upper parts of the USDD, and blue arrow shows a T-P path for the deepest parts of the USDD. Brittle-ductile transition boundary for pyrite – after Cook et al., 1994. T-P-condition of fields of metamorphism of VMS deposits (see Table 3): 1 – Yubileynoe, Safyanovskoe, Blyava, Alexandrinskoe, Talganskoe, Sultanovskoe; 2 – Uchaly, Novo-Uchaly, Uzelga, Sibai, Barsuchiy Log, Priorskoe, Valentor; 3 – Gai, Degtyarsk, Levikha, San-Donato, Krasnogvardeiskoe, Kaban; 4 – Karabash group, Mauk, Kuznechikha. Geotherm 80°/km is approximate boundary of contact metamorphism field.

**Table 7**  
Ore-bearing structures of regional-metamorphosed VMS deposits (after Vikentyev, 2004, with additions).

Metamorphism grade	Very low	Low	Moderate to high
Metamorphic facies	Zeolite and prehnite-pumpellyite	Greenschist	Epidote-amphibolite, amphibolite
Dominant ore-host structures	Gentle doms and trenches	Steeply-dipping to vertical Pseudomonoclinical	
General form of deposit	Lenoid, podiform, biclinal, mushroom-like, medusa-like	Lenoid, podiform, antiform	Platelike, podiform
Shape of ore bodies	Nondeformed Lense, layer, podiform dome, ellipsoidal, isometric, irregular; vein stockwork (in foot wall)	Deformed, greatly deformed and regenerated Plate-like, ribbon-like, rod-shaped, podiform, saddle reef, trench-like; vein	

polymetallic ore xenoliths captured the dykes (Uchaly, Gai and Alexandrinskoe; Starostin, 1964; Novoselov, 2002; Vikentyev et al., 2016).

The regional-scale transition from weakly to intensely dynamo-metamorphosed or contact-metamorphosed deposits can be observed in some ore fields, such as Uchaly, Shemur and Sredne-Orsk districts (Fig. 1, Table 5). For example, the deformation of host rocks and massive sulphide bodies within the Uchaly ore district increases towards the north, approaching the Ufa promontory (Vikent'ev et al., 2000). The metamorphic grade also increases from south to north from the zeolite facies in the Alexandrinskoe ore field to the prehnite-pumpellyite facies in the Uchaly ore field.

Significant variations between the VMS deposits of Tagil and Magnitogorsk zones are mostly the result of higher-grade dynamothermal metamorphism of the orebodies of Tagil zone (Zavaritsky, 1941; Kreiter, 1948; Shadlun, 1950), whereas contact metamorphism near granite plutons rarely occurs in both Tagil and Magnitogorsk zones. It was found for deposits of Kaban, Krasnouralsk and Levikha ore fields, Karabash group, Tarnyer, Zyuzelskoe and Kuznechikha deposits in the Middle Urals that dynamic metamorphism follows contact-thermal metamorphism associated with formation of large Late Paleozoic granitoid massifs.

#### 4. Regional metamorphism of massive sulphide deposits

The VMS clusters with linear morphology of the intensely deformed orebodies are located in the middle and southern segments of the Tagil part of the Tagil-Sakmara VMS zone (Tagil-Krasnouralsk and Levikha-Karpushikha districts), in the northern part of the western Magnitogorsk VMS zone (Degtyarsk, Karabash and Uchaly districts), in some parts of the eastern Magnitogorsk VMS zone (Dzhusinskoe deposit), and are somewhat represented in the Kamenskoe ore field (Sultanovskoe and Kasarginskoe deposits) (Fig. 1, Table 5).

##### 4.1. Strongly regionally-metamorphosed VMS deposits

###### 4.1.1. Amphibolite facies

The Mauk deposit is located in the Serov-Mauk melange zone where it is contiguous with the MUF zone at the junction of Tagil and Magnitogorsk zones directly opposite the Ufa promontory (Fig. 1). Here, the processes of dynamic metamorphism were manifested most intensely, and the rock experienced the most intense tectonic

movements (Fig. 3). The Upper Silurian to Lower Devonian host rocks are quartzite-like rocks intercalated with phyllites, amphibolites (metabasalts), marbles and lenticular ultramafic bodies (Buslaev et al., 1988a; Safina et al., 2015a,b) (Fig. 4). These rocks were metamorphosed to albite-epidote-actinolite ± biotite ± chlorite ± carbonate ± graphite-quartz schists and serpentinite (Buslaev et al., 1988a). The metamorphic changes correspond to the epidote-amphibolite and amphibolite facies ( $t \sim 500\text{--}700\text{ }^{\circ}\text{C}$ ,  $P = 1\text{--}5\text{ kbar}$ ) (Table 6).

The deposit is of the Cyprus-type (Smirnov, 1988; Eremin et al., 2000; Kontar', 2013), and contains massive copper ores (on average, 2.3 wt% Cu) with low amounts of zinc (0.2 wt% Zn) and precious metals (0.43 g/t Au and 10.8 g/t Ag). The elevated cobalt (~0.05 wt% Co) and nickel (~0.02 wt% Ni) concentrations in the Mauk ores are uncommon for the Uralian VMS deposits. The ores and host rocks underwent intense metamorphic recrystallisation in relation to strike-slip and thrust deformations. Contacts of the sheet-like orebodies are usually sharp (Fig. 4). This small deposit comprises nine sheet-like orebodies, with the three largest being the Central, Second and Third Eastern orebodies. The Central orebody is 1500 m long with an average thickness of ~5 m (up to 12 m maximum).

The metamorphic fabrics (banded, lenticular, gneissic and folded) and textures (porphyroblastic and crystalloblastic) dominate in chalcopyrite-pyrite, chalcopyrite-pyrrhotite-pyrite, chalcopyrite-pyrite-pyrrhotite ± magnetite, and sphalerite-magnetite-chalcopyrite-pyrite ores (Yarosh, 1973; Buslaev et al., 1988a; Safina et al., 2015a,b). Clinopyroxenes of clinoferrosilite-augite series are the most abundant gangue minerals in the ores; orthopyroxenes, siderite and biotite are minor.

Magnetite (up to 35 vol% at deeper levels of the Central orebody) replaced pyrite and less commonly chalcopyrite and pyrrhotite. Arsenopyrite, tennantite, marcasite, cubanite, valleriite, galena, mackinawite, greigite, hematite and Mn-ilmenite (~10 wt% Mn) are minor, whereas rucklidgeite, tellurobismuthite, native gold, native silver, hessite, stützite, uraninite and molybdenite are rare. Cubanite, tellurides and native gold are usually enclosed in metacrysts of pyrite.

The rare Pb-, Bi-, Te- and Ag-minerals occur in pressure shadows of pyrite and ilmenite crystals and as polymineral drop-like inclusions in pyrite (Moloshag et al., 2002; Safina et al., 2015a,b; Vikentyev et al., 2016). These rare minerals contain 'chalcophile elements with low melting temperature' (LMCE; Frost et al., 2002; Tomkins et al., 2007), i.e. elements, which characterise low melting temperature minerals. The chalcopyrite-galena eutectic has a relatively low melting point

**Table 8**  
Geological settings and nature of the contact metamorphism of VMS deposits of the Urals.

Subtype of contact metamorphism	The nature of the contact metamorphism	Deposits
Regional contact metamorphism (granite-related)	Ore fields in thermal halo, associated with Platinum-Bearing Belt massifs and related tectonic zones	Valentor, Kaban ore field
	Ore fields in thermal halo of large granitoid plutons and associated with regional shear zones	Krasnouralsk ore field; Zyuzelskoe, Olkhovka, Tash-Yar
	Ore fields in thermal halo of large granitoid plutons	Koktau, Tarnyer, Vesenneye, Avangard
Local contact metamorphism (dyke-related)	The contact of single dikes of basic and intermediate composition, including thick ones	Blyava, Uchaly, Novo-Uchaly, Molodezhnoe, Levikha, Alexandrinskoe, Oktyabrskoe, Sultanovskoe, Galkinskoe
	Suits of dikes of basic and intermediate composition	Gai, Sibai, Uzelga, Podolskoe, Degtyarsk, Novo-Shemur, Shemur, Ozerno, Letneye, Osenneye, Priorskoe, Dzhusinskoe, Barsuchiy Log

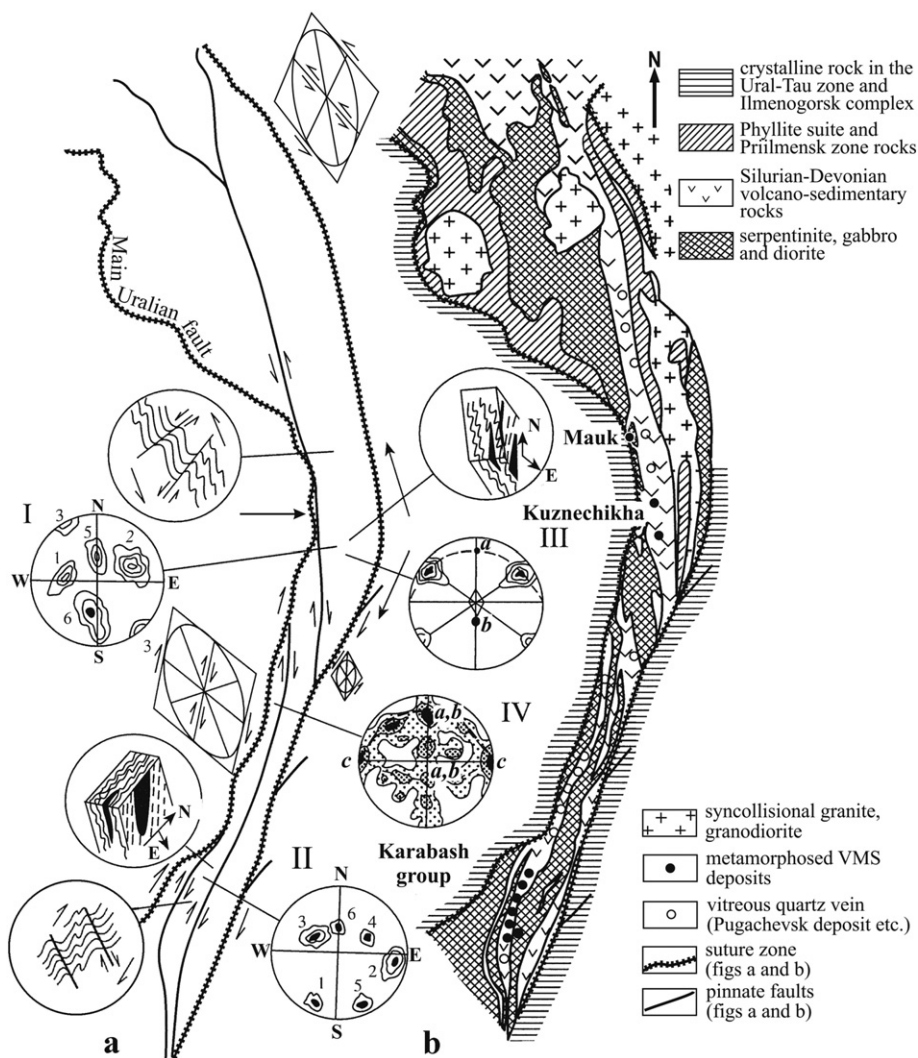
**Table 9**  
Mineral parageneses and PT-conditions of the contact metamorphism of VMS deposits of the Urals.

Facies	Key metamorphic minerals	<i>t</i> , °C	<i>P</i> , kb	Gradient, °C/km	Deposit
Albite-epidote hornfels (greenschist)	Ab, Q, Ser (2M <sub>1</sub> ), Chl, Ep ± Bi, Act, Rt	250–450	1–4	30–100	Tash-Yar, Kaban, Krasnouralsk field, Dzhusinskoe, Valentor; <i>in the local zones</i> : Uchaly, Alexandrinskoe, Uzelga, Sibai, Gai, Ozernoe, Oktyabrskoe
Hornblende-hornfels (epidote-amphibolite)	Olg, Mus (2M <sub>1</sub> ), Act, Bi, Ep, ± Grt, Hb,	300–550 (up to 700)	1–4	40–250	Letneye, Vesennyey; <i>in the local zones</i> : Tarnyer, Koktau
Pyroxene-hornfels (amphibolites)	Olg-Ands, Ath, Mus (2M <sub>1</sub> ), Crd, Grt, Spl, Hb, Ky, Sil, St, granite, ± Ap, Kfs	400–700 (up to 850)	1–6	35–300	Tarnyer, Koktau

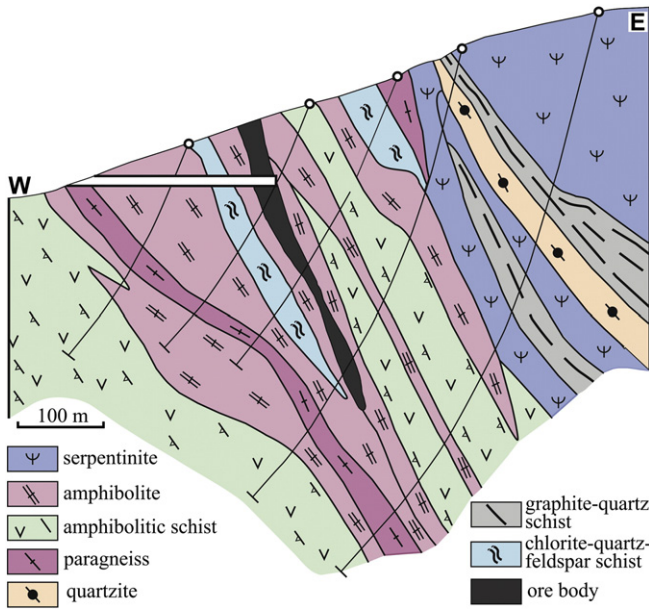
(~700 °C). The mechanism of formation of Bi-melt (including other LMCE) under hydrothermal conditions (Liquid Bismuth Collector Model; Douglas et al., 2000) is currently being considered as a possible way to scavenge minor metals (Ciobanu et al., 2006; Tooth et al., 2008; Tomkins, 2013). This mechanism probably operated during sulphide remobilisation of some VMS deposits of the Urals, which likely experienced partial melting (see below examples of the Tarnyer, Koktau and Alexandrinskoe deposits in the Section 5 and discussion in Section 6.4). Indications of partial melting of sulphide ore are not always

obvious (see Table 10), but its reality is very high for some high-grade metamorphosed VMS deposits of the Urals because evaluation of the peak metamorphism temperature by silicate minerals (Buslaev et al., 1988a,b) indicates values between 550° and 850 °C which exceed the melting point of many ore minerals (Tomkins et al., 2007).

Metamorphism resulted in recrystallisation of ore minerals, replacement of early sulphides by pyrrhotite and magnetite, as well as the formation of small lenses and clusters of gangue minerals (augite, enstatite, actinolite, biotite and celsian). Strike-slip and thrust faulting



**Fig. 3.** The location map of metamorphosed VMS deposits in the Karabash ore district, based on Rakcheev, 1962, with slight modifications. (a) – Microstructural data: I, II – diagrams of orientation of fissure joints (projection on the upper hemisphere), 1–6 maxima corresponding to the shear fractures (1–4) and the rupture fractures (5, 6); III – diagram of the orientation of 150 cleavage poles of hornblende from the amphibole gneiss; IV – diagram of 167 quartz axis orientations in quartz-sericite schist; directions of movement of tectonic blocks are shown by arrows; (b) – regional geological-structural scheme.



**Fig. 4.** Geological cross-section of the Mauk deposit. (Based on the Mauk Exploration Crew, Buslaev et al., 1988a).

were responsible for the fracturing of large recrystallised pyrites. This was followed by crystallisation of the regressive mineral assemblages and chalcopyrite “tails” in the pressure shadows around large recrystallised pyrite and Mn-ilmenite.

**4.1.2. Epidote-amphibolite facies**

The Karabash group of small Cu-Zn deposits is located at the transition between the Magnitogorsk and Tagil zones (Fig. 1), just south of the narrowest part of the linear occurrence of the Silurian-Devonian island-arc volcanic rocks (Fig. 3). The 6–8 km wide NS-trending band of volcanic rocks is characterised by a strong slaty and crenulation cleavage and a lens-block structure (Stickney, 1915; Rakcheev, 1977). The Eifelian metavolcanic rocks that host the deposits are also cross-cut by slaty cleavage. The deposits are confined to a zone of quartz-sericite schist,

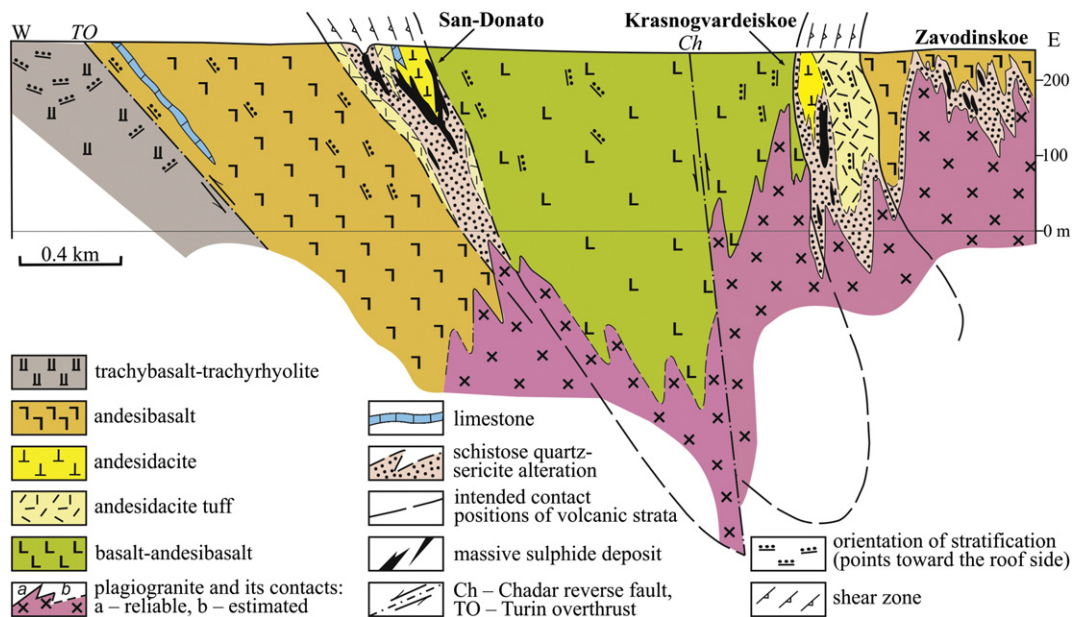
which dips 60–70° to the east. The N-S trending ultramafic bodies are related to normal faults. Schist, pyroclastics and metabasalt occur in the footwall of the orebodies, whereas siliceous and quartz-chlorite schists and metabasalt compose the hanging wall, which are overlain by limestone. The massive sulphide deposits form a narrow N-S trending 8 km long chain (Fig. 3), that includes the Pioneer, Stalinskoe, Pervomayskoe, Voroshilovskoe and Dzerzhinskoe deposits.

The massive sulphide lodes have flat-lenticular, vein-like or ribbon-like morphologies, dipping sub-vertically. En echelon-like orebodies, up to 10–15 m thick and 30–300 m long, are traceable for over 100–500 m up to 600–800 m down plunge, dipping to the east at 60–85°. Pyritic, Cu-pyritic and Cu-Zn-pyritic ore types are dominant. Typically, copper prevails over zinc, and copper ore gradually changes into pyritic type ore at depth. Within the ore field, the average copper and zinc concentrations increase from the southern to the central (3.9% Cu, 2.5% Zn, 4.4 g/t Au and 47 g/t Ag) and northern (2.3% Cu, 2.6% Zn) parts of the fields. A bornite-tennantite vein-like orebody, up to 2 m thick, contains ca. 2.9% Cu and 3.9% Zn. Baryte-sulphide veins, rich in gold, occur on the flanks of the Karabash field. Bornite-tennantite ore, as well as massive sphalerite veins in amphibolite, are likely products of ore remobilisation.

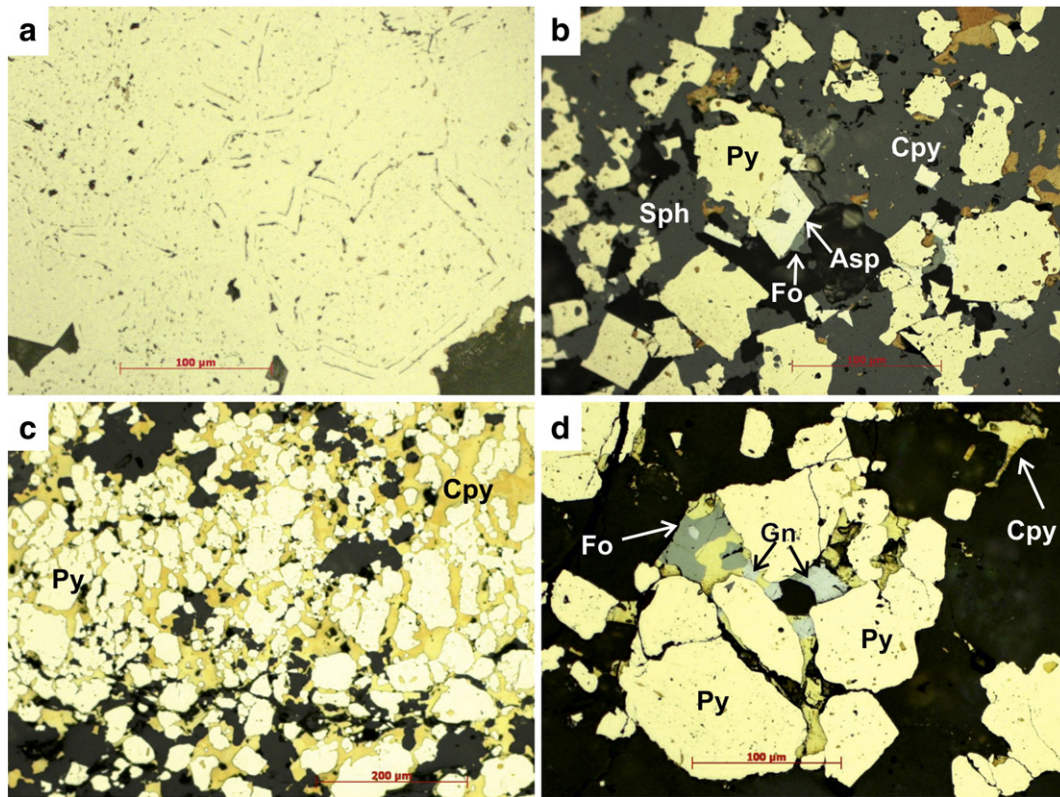
**4.1.3. Greenschist facies**

The medium-sized San-Donato Zn-Cu deposit is located in the southern part of the Tagil zone. Three ore zones, Western zone with 13 pyritic lenses, Eastern and Middle zones with Zn-Cu ore, were mined as a part of the Third International Mine operations (Zavaritsky, 1950a,b). Thirty-four NS-trending steeply-dipping Zn-Cu massive sulphide orebodies of the Eastern and Middle zones (Fig. 5) were deformed into en echelon folds from the south to the north, i.e., each body occurs to the east and deeper than the previous body. The Eastern ore lenses dip to the east at 75–85°, and the Middle zone dips to the east at 60–70°. The ore zones steeply plunge to the north.

The massive copper sulphide orebodies are relatively small. The ore lenses are 1–35 m thick and extend for 100–200 m along strike and for 300–600 m down dip, and are sheared and slightly folded. They are lenticular (ribbon-like) and vein-like or irregularly shaped. A sharp increase in thickness is confined to the pressure shadows of rigid rock blocks (megaboudins). The long axis of the orebodies, the elongated wallrock blocks rimmed by stringer ore, the linear rock structures and elongation of rock fragments in tectonic breccia, as well as grains of



**Fig. 5.** A generalised cross-section of the Krasnoyarsk ore district and position of main VMS deposits. (Modified after Smirnov, 1979).

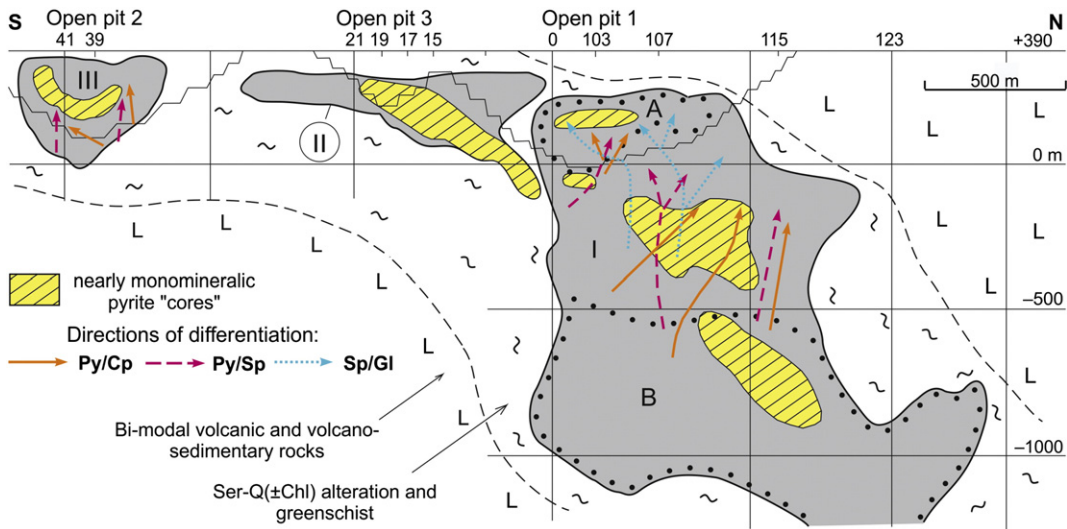


**Fig. 6.** Dynamo-metamorphosed and recrystallised VMS ore of the San-Donato deposit (reflected-light micrographs): a - the pocket of recrystallised fine-grained pyrite; b - massive zinc-rich ore: pyrite, chalcopyrite (slightly oxidized) and arsenopyrite with minor tennantite in the bulk sphalerite; c - numerous veinlets of chalcopyrite in granulated and fragmented pyrite in copper-rich ore; d - veinlets of galena-chalcopyrite-tennantite in the fractured pyrite in the impregnated (semi-massive) copper ore. Abbreviations of minerals (here and in Figs. 7 and 16): (Py) pyrite, (Cpy) chalcopyrite, (Sph) sphalerite, (Po) pyrrhotite, (Asp) arsenopyrite, (Ilm) ilmenite, (Mo) molybdenite, (Gn) galena, (Fo) tennantite-tetraedrite.

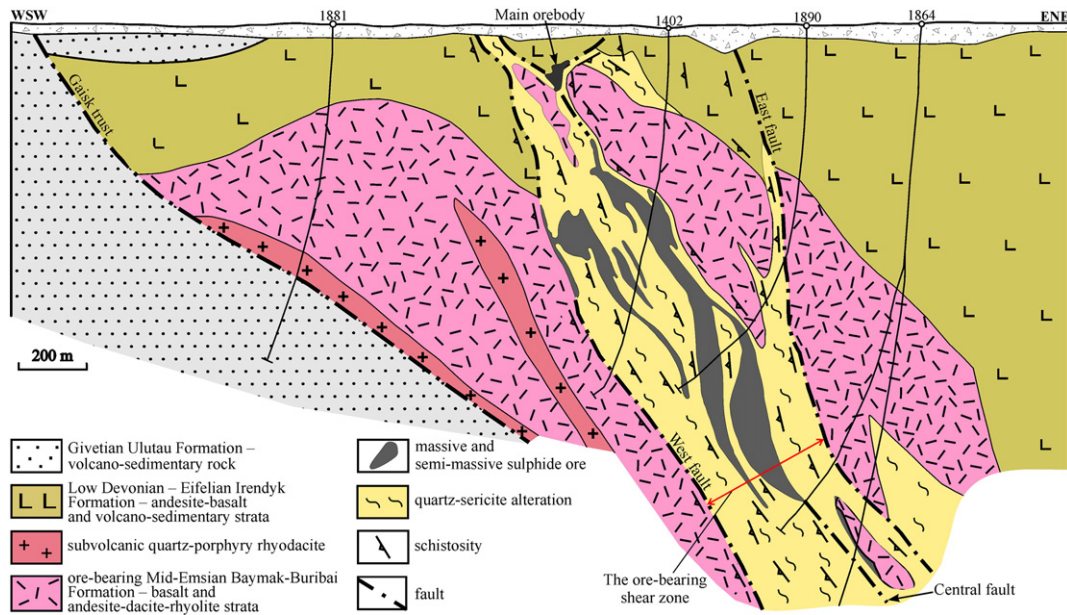
pyrite commonly have the same orientation (Smirnov, 1988). The host rock schistosity is oriented parallel to the contacts of the orebodies, which pinch out at 550–800 m depth below surface.

The massive and less abundant veinlet-disseminated Cu-Zn ores are polymetallic (100 g/t Ag, 5 g/t Au, 40 wt% Fe, 10–15 wt% Zn and 5 wt% Cu, with traces of Pb, Se, As, Sb, Te, Cd, Mo and Sn). The ore structures are massive, banded, streaky, patchy, porphyritic and breccia-like (Fig. 6); granoblastic textures are common. Sphalerite in the endocontacts

(i.e., internal contact zones) of the orebodies is characterised by thin banding, parallel to the contacts (Smirnov, 1988). The parallel banding is most prominent near the contact with the sulphide lenses. Metamorphic recrystallisation led to the formation of light-coloured sphalerite with inclusions of small crystals of pyrite. Based on the 335–350 Ma K-Ar age of sericite spatially associated with ore, the most substantial metamorphic transformations likely occurred during the Middle Devonian (Smirnov, 1988).



**Fig. 7.** Long vertical projection of ore-bearing zones and position of some large orebodies of Gai deposit. Hatched lines show an outline of alteration and greenschists. Ore-bearing zones: (I) northern (open pit 1), (II) middle (open pit 3), (III) southern (open pit 2). Separate orebodies (dotted contours): (A) main orebody, (B) eastern zone. Figures above the section represent numbers of exploration profiles. Pyrite "cores" in Zn–Cu orebodies and directions of differentiation (Py/Cp, Py/Sp and Sp/Gl) after Lapukhov (1975).



**Fig. 8.** Simplified cross-section of the Northern ore zone at the Gai VMS deposit, profile 107. (Modified after Seravkin and Skuratov, 2009).

In comparison with most of the Uralian deposits (except for the Alexandrinskoe and Valentor), the San-Donato ore is more enriched in chalcopyrite, bornite and sphalerite. Tennantite-tetrahedrite, arsenopyrite and galena are minor, with tennantite-tetrahedrite containing up to 0.45 wt% Ag. Chalcocite, enargite, cubanite, pyrrotite, marcasite, valleriite, magnetite, hematite, native gold, calaverite, tetradymite, stromeyerite, mawsonite, stannoidite, altaite, and hessite are rare minerals.

The giant deposit in the southern part of the Magnitogorsk zone is one of the world's largest VMS systems. Annual ore production from the underground mine (to a depth of 750–940 m) is 5 Mt. The ore reserves are explored to a depth of 1500 m (Prokin et al., 2004; Vikent'ev et al., 2006b) (Fig. 7). Massive ore constitute about 90% of total reserves.

Up to the present, 200 Mt. of ore were extracted from total reserves of 450 Mt ore @ 1.45 wt% Cu, 0.72 wt% Zn, 1.2 ppm Au and 14 ppm Ag. The richest ore was mined between 1961 and 1997, totalling 132 Mt. @ 3.5 wt% Cu. This deposit is underlain by felsic and mafic volcanics of the bimodal rhyolite-basalt series, belonging to the Emsian-Eifelien Baimak-Buribai Formation (Seravkin and Skuratov, 2009; Seravkin, 2013). The volcanic rocks of the Gai ore field are cut by numerous steeply microgabbro dykes, 0.2 to 5 m thick.

The NS fractures cut across the Gai ore field (Fig. 8), which is bounded by the Gai thrust fault, in the west, and by the Kalinovsk fault, in the east. The ore-bearing block is intersected by faults, dipping 50–60° to the east, the largest of which are the Western, Central and Eastern faults (Prokin et al., 2004; Seravkin and Skuratov, 2009). The mineralised zone is bordered by the Western and Eastern faults and consists of sericite-quartz and sericite-chlorite-quartz metasomatic volcanic rocks and schists with sulphide mineralisation. The zone stretches for about 5 km along strike and 2 km down dip. Its thickness varies from a few dozen metres to 800 m. This metasomatic zone hosts lenses of massive and disseminated ores, varying from a few metres to 1300 m in size, with their thickness ranging from 2 to 150 m. The wall-rock alteration halo at the Gai deposit is characterised by the following mineral facies: (1) silicification; (2) sericite-quartz; (3) sericite-chlorite-quartz; and (4) quartz-sericite-diaspore-pyrophyllite. The zone of sericite-chlorite-quartz alteration, 40 to 300 m thick, surrounds a zone of sericite-quartz rock. Chlorite in the altered rocks consists of clinocllore or prochlorite. The mixed-layered minerals are sericite (Buslaev, 1969; Grabezhev et

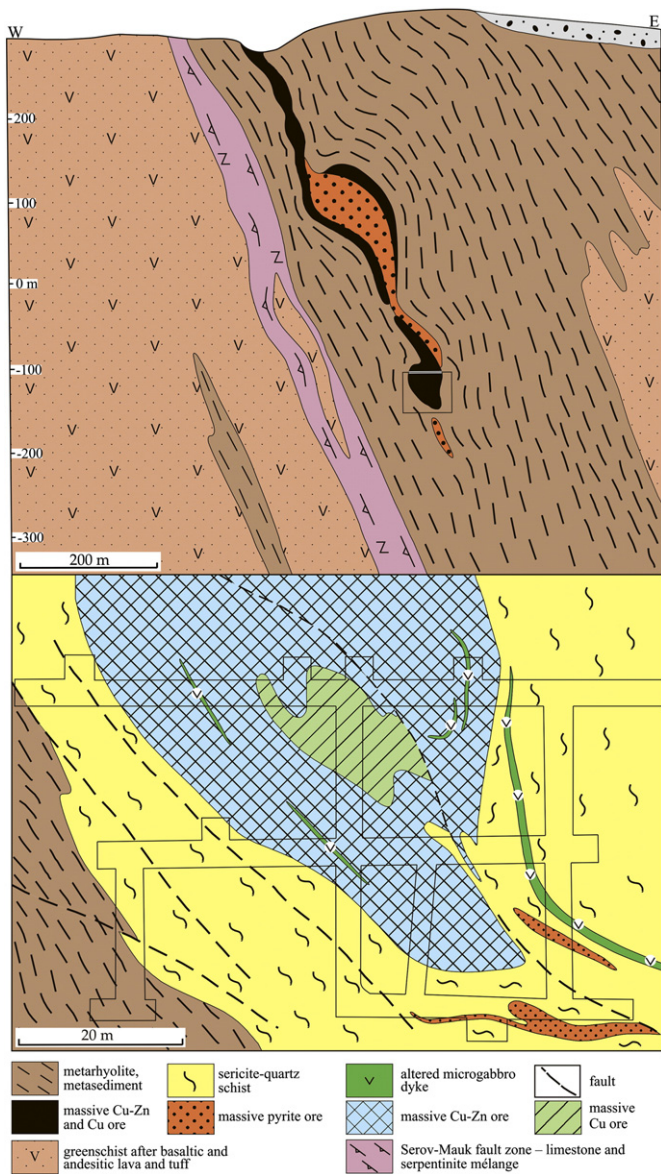
al., 1998) and pyrophyllite; diaspore was found as 0.02–0.1 mm sized crystals.

The K-Ar isochron ages for sericite from the Gai deposit are  $363 \pm 9$  Ma and  $347 \pm 10$  Ma, and mark periods of shear deformation of the deposit and its host rocks (Prokin and Buslaev, 1999). A younger age of  $288 \pm 2$  Ma corresponds to the time of main collision of the East European platform and the Kazakh Paleozoic terrane (see Discussion), and is considered as the time of thrusting and formation of the present structure of the deposit.

The Gai deposit is subdivided into Northern, Central and Southern ore zones (Prokin and Buslaev, 1999; Seravkin and Skuratov, 2009). The majority of ore reserves, including high-grade ore, are located in the Northern zone (Fig. 7), which has a strike length of 1600 m. Its downdip plunge exceeds 1700 m, whereas the total thickness of the orebodies reaches 200 m. The Main orebody has the highest copper and gold grades (Vikentyev et al., 2016). The massive sulphides are poor in pyrite and rich in bornite and tennantite, and are considered to be remobilised (Prokin et al., 2004). The orebody occurs in a pressure shadow zone of the mega-scale boudin of massive metabasalt (Fig. 8).

The ore and its host rocks were affected by extensive strike-slip faulting and thrusting for over a few hundred metres, which resulted in boudinage of the orebodies and an echelon arrangement of the ore lenses and blocks. The following ore types are distinguished: pyrite, chalcopyrite-pyrite, chalcopyrite-sphalerite-pyrite, and bornite-bearing (Pshenichny, 1975). Pyrite is the dominant mineral of the ores (60–90 vol%). Chalcopyrite and sphalerite are the major economic minerals (1–10 vol%), and tennantite-tetrahedrite (usually close to tennantite end-member) are common.

The orebodies are lens- or ribbon-shaped with high-angle terminations (Fig. 8). The maximum thickness of the orebodies ranges from few metres to 80 m for the upper lenses and up to 150 m for the lower ones. The zinc-copper ore is the dominant type, with 0.5–4 wt% Cu, 0.5–2 wt% Zn, 15–35 wt% S, 0.7–2 g/t Au, and 10–30 g/t Ag. The average contents of trace elements (in g/t) are: 470 As, 130 Co, 38 Se, 30 Te, 8 Ga, 5 Ge, 2 In. The highest gold grades (~2–5 g/t and locally higher) occur in the peripheral and uppermost parts of the major ore lenses and small vein-like orebodies, located in the hanging wall and footwall of the major ore zone. The pyrite ore contains 0.1–0.2 wt% Cu, 0.1–0.15 wt% Zn, 45–55 wt% S, 0.5–1 g/t Au and 10–20 g/t Ag, with average (in g/t) 460 As, 260 Co, 66 Se and 30 Te.



**Fig. 9.** Cross-section of the Degtyarsk deposit. (Based on data of the Degtyarsk Mine).

The presence of bornite-bearing ore is a characteristic feature of the Gai deposit, and is widespread in the upper part of the Northern zone within the Main orebody (Starostin, 1963; Nesterenko, 1978). This orebody has an internal mineral zoning, with bornite in the outer zone, followed by bornite-chalcopyrite-pyrite zone inwards, then to the sphalerite-chalcopyrite zone and finally to the pyrite zone, which makes up the central portion of the orebody (see Fig. 22 in Prokin and Buslaev, 1999). Chalcopyrite was almost completely replaced by bornite. Mineralisation also contains tennantite, native gold and uncommon rare minerals, such as germanite, mawsonite, stannoidite and betchertinite; but typically no tellurides. Individual native gold segregations in the bornite ore reach 1–2 cm in length, with largest one up to 10 cm (P.Ya. Yarosh, pers. comm.). The silver content in bornite ranges from 0.2–0.6 wt% Ag, which is 2–3 times higher than in the coexisting tennantite.

The massive ore is most common but brecciated and spotted textures are also present, along with rare layered and colloform fabrics. Banded structures are widespread in the outer parts of the ore lenses near the contacts with wall-rocks and consist of alternating bands (0.5 to 2.0 mm wide) of pyrite, chalcopyrite, sphalerite ( $\pm$  bornite) (Pshenichny and Shadlun, 1962). The sulphide bands are parallel the

contacts of the orebodies or their tectonic fragments. Cataclastic and foliated textures are rare in the ores and are constrained to the narrow zones controlled by the younger steep normal faults. All these textures likely resulted from dynamic metamorphism.

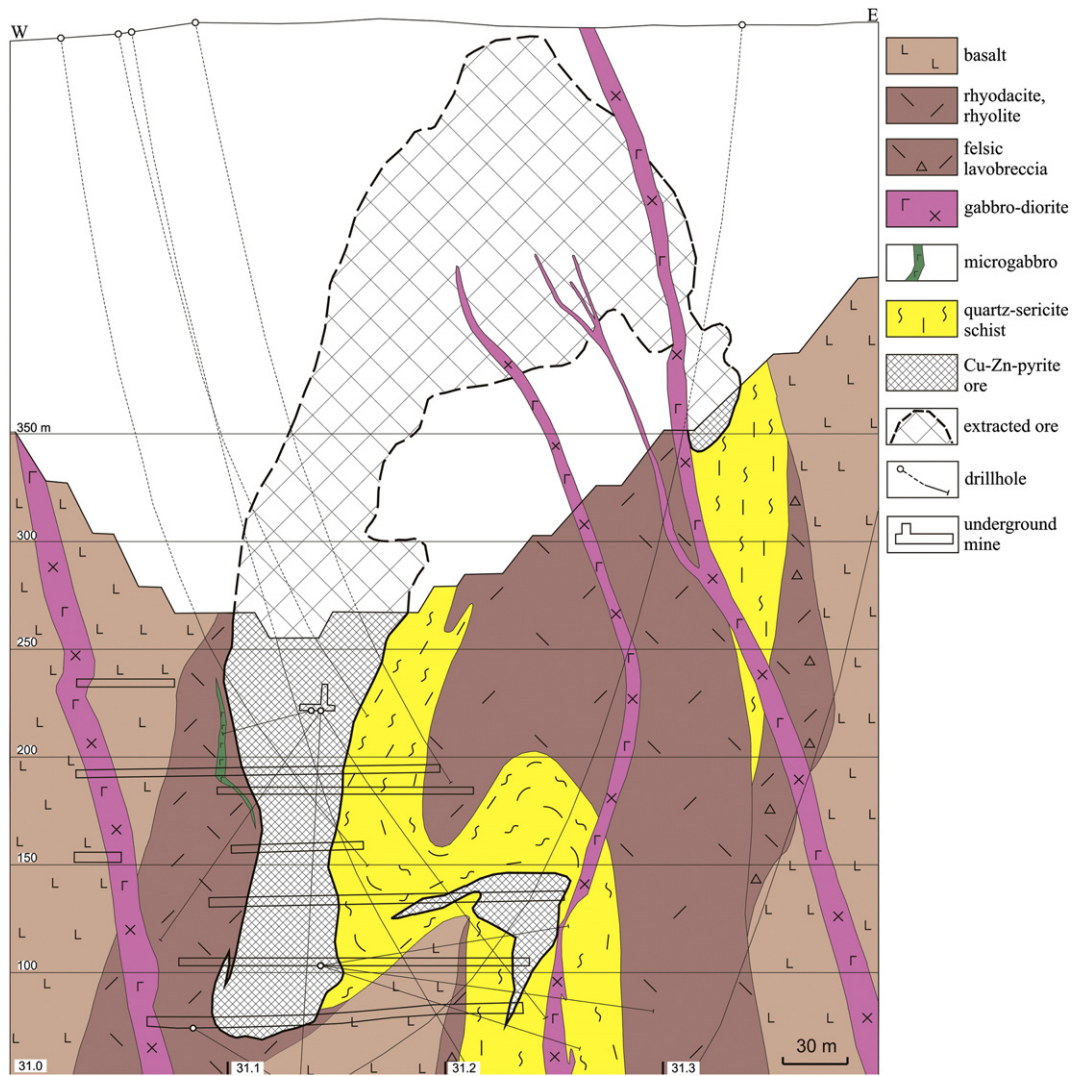
Based on mineral geothermometry and fluid inclusion data, the temperature of ore deposition varied from 270 to 445 °C (Vikent'ev et al., 2006a,b). According to the fluid inclusion study (Andriyanova et al., 1978), the fluid pressure was 660–685 bar. We conclude that the tectono-metamorphic transformations of the Gai deposit gave rise to schistosity in the host rocks and the breakup of large sulphide lodes into lensoid fragments, accompanied by migration of ore material up to hundreds metres, ore recrystallisation, formation of remobilised bornite-bearing Cu-Zn ore and accessory Au, Ag, Bi, Te, Ge, Sn, V, Co, Ni minerals.

The Degtyarsk deposit (130 Mt ore, 4 Mt. Cu + Zn) was the biggest underground mine in the USSR in the 1930–80s, with an annual production totalling 1.5 to 2 Mt of ore. It is located in the Serov-Mauk melange zone, which has a thickness of ~500 m in the Degtyarsk ore field. Folds, flexures, pinch and swell structures are common for the single sheet-like orebody that dips steeply to the east at ~70–85° and strikes over 5 km, with ~650 m vertical extent of mineralisation (Ivanov and Merkulov, 1937). The tectonic planar structures are widespread in the orebody and in the endocontacts of orebodies, in particular, as well as in the host rocks, which were metamorphosed to the greenschist facies. The morphology of the massive sulphide sheet is complicated by a few bulges, up to 100–250 m thick. The pyritic ore occurs in the thickest part of the central zone of the orebody, and minor pyritic mineralisation occurs in the deepest parts of the deposit (Fig. 9). Pyrite is a dominant mineral (60–90 vol%); chalcopyrite and sphalerite are the major ones (1–10 vol% in sum). The base metal grades average to ~1.3 wt% Cu and ~2.7 wt% Zn. The gold grade commonly ranges from 1 to 1.5 g/t and from 1.5 to 3 g/t at the deeper horizons, with average 25–50 g/t Ag (up to 100 g/t). The pyrite-content decreases, whereas the contents of sphalerite, chalcopyrite, quartz and baryte, as well as gold and silver grades, increase towards the flanks and with depth below the central pyrite “core”. As a result of a large scale remobilisation, the sulphides are located in the curves of drag folds and pressure shadows of boudins. The ores at the deepest horizons near the lower pinch-out of the main ore lode at a depth of ~600 m are enriched in Zn, Au, Ag and Sb. Based on mineral geothermometry and fluid inclusion data, the deposit was metamorphosed to  $t = 150\text{--}300$  °C and  $P = 0.5\text{--}2$  kbar (Vikent'ev, 1995b, 2004).

#### 4.2. Weakly metamorphosed VMS deposit (prehnite-pumpellyite facies)

The Uchaly Cu-Zn deposit is one of the largest (115 Mt. ore reserves) and best-studied Urals-type deposits (Smirnov, 1988; Seravkin, 1994). The deposit is localized in the contact zone between felsic volcanic/volcano-sedimentary rocks and basalt unit (Fig. 10). The felsic rocks are quartz-sericite and quartz-sericite-chlorite altered over a 200 m width. This alteration also affects the overlapping volcano-sedimentary rocks. The thin chloritisation zone occurs along the contact of the orebody. The host rocks together with sulphide bodies and overlying volcanics of the Karamalytash and Ultau Formations are deformed into a complex fold and are displaced along the steeply-dipping faults.

The complex lenticular orebody extends for 1300 m in a N–S direction and 400–500 m down subvertical dip, reaching 100–150 m in thickness (Fig. 10). It is folded in some parts (Figs. 10, 11). The major ore types include massive Cu-Zn ore (1 wt% Cu, 4 wt% Zn, 38 wt% S), disseminated Cu-Zn ore (0.6 wt% Cu, 1.6 wt% Zn, 20 wt% S), and subeconomic disseminated Cu ore (0.4 wt% Cu, 0.9 wt% Zn, 10 wt% S). In addition to gold and silver by-products, copper-zinc ore contains 1 wt% As, 0.5 wt% Pb, 3.3 wt% Ba, as well recoverable (in ppm) 50 Se, 70 Te, 14 In and 150 Cd (Seravkin, 1994). High concentration of mercury, up to 37 ppm (with an average of 9.3 ppm Hg), is typical for zinc ores (Pirozhok, 1998).



**Fig. 10.** Complex folds of the Uchalny deposit along profile 14. (Based on data of the Uchalny Mine).

Almost 90 minerals have been identified in the ore with pyrite, sphalerite and chalcopryrite being the major minerals. Galena, hematite, magnetite, tennantite and tetrahedrite are minor minerals. Altaite, arsenopyrite, hessite, native gold, calaverite, marcasite, mowsonite, melnikovite, pyrrhotite, renierite, tellurobismutite and petrovskaita are rare. Baryte is commonly associated with quartz gangue. The ore lode demonstrates asymmetric zoning. The following ore types roughly replace each other from the footwall to the hanging wall: (1) veinlet-disseminated chalcopryrite-pyrite; (2) banded pyrite; (3) equigranular chalcopryrite-pyrite; (4) inequigranular and thin-banded chalcopryrite-sphalerite-pyrite; (5) colloform, banded and breccia-like chalcopryrite-sphalerite-pyrite and galena-bearing sphalerite-pyrite; and (6) breccia-like and lenticular chalcopryrite-pyrite and pyrite.

Only a small number of VMS deposits of the Urals can be classified as unmetamorphosed or metamorphosed to the zeolite facies (Yaman-Kasy, Komsomolskoe, Kundzydy and Galkinskoe). They are all located at a distance of 500 km and more from the most metamorphosed Karabash area.

### 5. Contact metamorphism of the VMS deposits

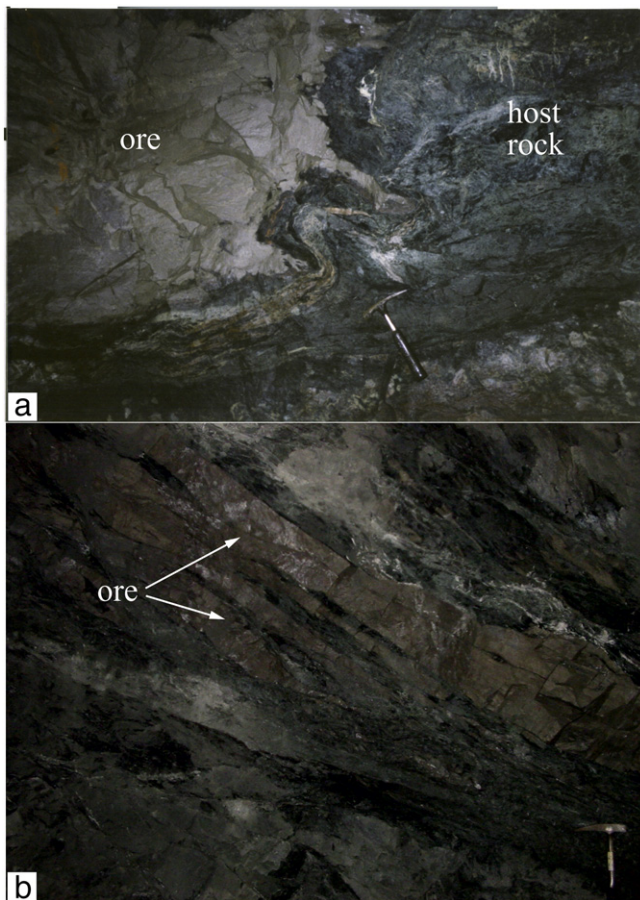
The group of the contact-metamorphosed deposits (Tables 5 and 6, Fig. 12) includes those that experienced significant thermal influence by large intrusions of granite, plagiogranite, granodiorite, and diorite

(Taryer, Kaban, Krasnogvardeiskoe, Levikha, Shaitanskoe, Zyuzelskoe, Tash-Yar, Sibai, Vesenneye, Avangard, Priorsk and Koktau). In addition to these, regional contact metamorphosed deposits (Shanks and Thurston, 2012), VMS bodies commonly show very local affects from mafic dykes over a distance of only decimetres (Levikha, Uchalny, Uzelga, Sibai, Dzhusinskoe, Barsuchiy Log, Letneye and Gai deposits).

#### 5.1. Regional contact metamorphism (in the halo of large granitoid massifs)

The Taryer deposit, which belongs to the Ivdel' VMS group (northern Sverdlovsk region), is hosted by Upper Ordovician rocks of the basalt-rhyolite association and is overlain by Lower Silurian (Llandoveryan) volcanics of the basalt-andesite-dacite-rhyolite association. The deposit is medium-sized, containing 144 Kt of Cu at 1.5% Cu and 375 Kt of Zn at 4.01% Zn (Kontar' and Libarova, 1997).

The Taryer deposit is located within the thermal aureole of the Pomurskiy Intrusive Complex (Fig. 13). Its setting is controlled by the contact zone between the intrusive complex and its host volcanic rocks. The mineralised zone strikes 115°-SE over 1500 m and dips to the southwest under the intrusive body, subparallel to its contact at high angles (Fig. 27 in Prokin and Buslaev, 1999). The deposit comprises five steeply-dipping orebodies with the largest ones being referred to as the Orebodies 1, 2 and 5 (Kuskov and Kulikov, 1967; Buslaev et al., 1988b).



**Fig. 11.** Details of the Uchaly deposit at its northern flank (a) and in the lower pinching of the Main Orebody (b). a - Two loop-like folds in the footwall of the Uchaly deposit; contact of host schist and ore "apophysis", which goes into the western (hanging wall) side of the orebody near its northern pinching; uniform gray field in the upper left part of the image and in the core of the folds is rich Cu-Zn ore; right and bottom parts of the image are the enclosing banded quartz-sericite-chlorite schist. Level -350 m, ort 17/20, western wall (2000). b - sheared orebody at the transition from the Main Orebody to the "superdeep apophysis": gentle, plate- and ribbon-like sulphide lenses (brown, in the centre of the photograph), with local pinch and swell structures, dip  $55^\circ < 25\text{--}30^\circ$ , level -460 m, boring ort 3/4, looking north (2006).

The stratigraphic section of the host volcanic rocks consists of a basal amygdaloidal basalt and andesite at the top. The basalt is locally altered into a pyroxene-garnet-epidote  $\pm$  magnetite skarn. The volcanic sequence also includes subvolcanic quartz-plagioclase dacite porphyry, which hosts the deposit. The pyrite-bearing sericite-quartz-plagioclase rocks in the footwall parts of the ore zone are similar to sericite-quartz altered rocks in the footwall of the other VMS deposits in the Urals.

The deposit is restricted to the roof of the polyphase Late Silurian to Early Devonian Pomurskiy diorite intrusion, ~ 16 km in diameter, which occurs south of the mineralised zone and affected the fabrics and mineralogy of ores and their host rocks. The older phase consists of gabbro, microgabbro and gabbro-diorite, which give way to diorite porphyry in the peripheral part of the intrusion. The younger phases consist of holocrystalline amphibole-biotite and biotite diorite, whereas its marginal parts consist of quartz diorite and plagiogranite. The intrusive rocks are thought to be derivatives of the same magmatic chamber (Kuskov and Nesterov, 1970). Mentioned intrusive rocks and youngest quartz-feldspar pegmatite dykes are related to the same intrusive complex.

The contact metamorphic processes produced widespread hornfels, which formed after the formation of both volcanic rocks and the older-phase diorite of the Pomurskiy intrusion. All hornfels types have

characteristic textures and generally display relict porphyritic textures. The major hornfels minerals are plagioclase, quartz, hornblende, biotite and hypersthene, with minor diopside, anthophyllite, spinel, and cordierite. The protoliths of hornfels were mafic and intermediate rocks, and hornfels are rich in mafic minerals (amphibole, biotite and hypersthene) with low quartz content. Quartzite-like hornfels with muscovite and sodic plagioclase were also developed after the sericite-quartz alteration and felsic volcanic rocks. These rocks locally contain andalusite and sillimanite. Hornfels after subvolcanic acid porphyry contains quartz, plagioclase, hornblende and locally potassic feldspar, with minor biotite, cordierite, andalusite, sillimanite and hypersthene.

The wall-rock alteration includes, along with dominant sericite-quartz rocks, local domains of Fe-rich calcic and magnesian skarn. The Fe-rich calcic skarn consists of fine-grained grossular-andradite garnet, ferroaugite, and epidote, whereas magnesian skarn occurs as patches and veinlets of cummingtonite, anthophyllite, magnesian chlorite, highly magnesian biotite, serpentine, brucite, humite and cordierite, and is generally sulphide-bearing (Kuskov and Nesterov, 1970; Yarosh, 1973).

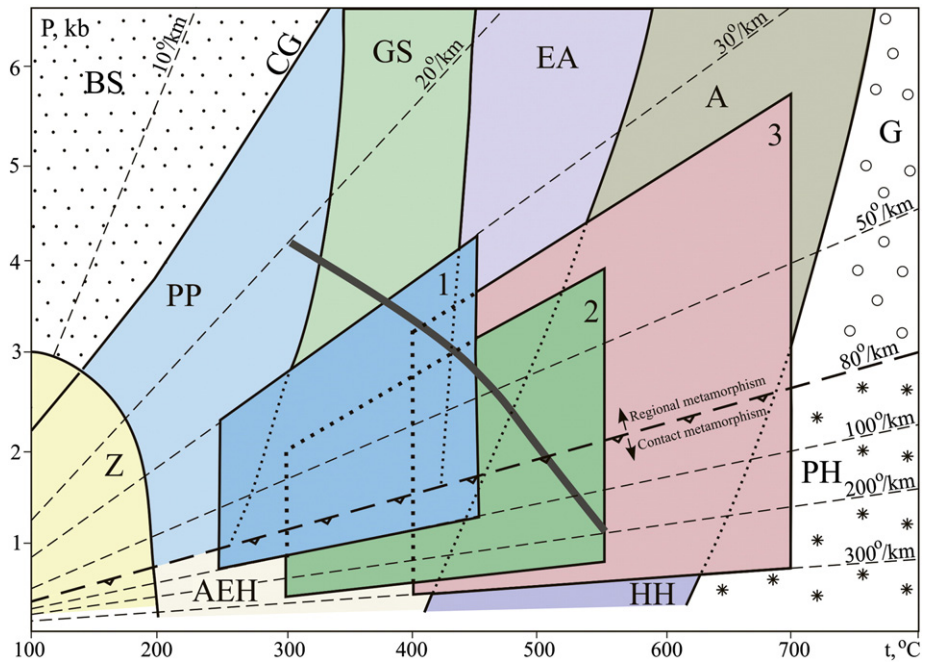
Tarnyer ores are classified, based on sulphide proportion, as massive (30%) and veinlet-disseminated (70%). In terms of ore types, there are zinc, copper-zinc (dominates), copper and pyritic ores. The veinlet-disseminated ores commonly rim massive orebodies. Zinc enriched sphalerite-chalcopyrite-pyrite ores tends to occur in the upper part of steeply-dipping ore lens, with zinc and copper grades decreasing with depth. They change into pyrrhotite  $\pm$  pyrite enriched and Cu, Zn-poor ores downdip. The precious metal grade of Cu, Cu-Zn, Zn and pyrite ore types are 1.0, 0.9, 0.7 and 0.3 g/t Au and 13.3, 14.8, 16.66 and 3.9 g/t Ag, respectively (Kuskov and Nesterov, 1970). The veinlet-disseminated ores are more enriched in precious metals, up to 2.35 g/t Au and 22.05 g/t Ag. Gold-bearing silica alteration, tectonised and mineralised with sulphides, with up to 30 g/t Au, constitutes economic gold orebodies (0.5 g/t Au cut-off). Belogub et al. (2010) reported that gold is contained in diorite, granodiorite, and porphyritic diorite dykes and other intermediate rocks. Gold in Au-bearing rocks shows that >70% of it is in the native form and occurs as aggregates with other minerals, whereas in pyritic ores it does not exceed 40%.

Mineralisation of the upper and middle horizons is dominated by the massive ore varieties, with minor amounts of veinlet-disseminated ores. The major textural types of massive ores are coarse-grained porphyritic, banded and pegmatoidal. The porphyritic and banded massive sphalerite-chalcopyrite-pyrite ores, dominant in the Orebodies 1–3, likely formed during the recrystallisation of the primary, synvolcanic fine-grained sulphide ores. The pegmatoidal sphalerite-chalcopyrite-pyrrhotite ores were developed as veins in the contact parts of the massive orebodies, where they fill fractures in contact-metamorphosed intermediate-mafic dykes (Fig. 14). We believe that this ore type is younger than massive ores because it is remobilised. The stringer and veinlet-disseminated ores are hosted by silicate wall-rocks and vary in composition. Metamorphic ore fabrics of the Tarnyer deposits are discussed in more details in Vikentyev et al. (2016).

The ore mineralogy is complex, and is composed of pyrrhotite, sphalerite, pyrite, chalcopyrite with various tellurides, predominantly altaite, which occur as small equant inclusions in chalcopyrite and galena. Other minerals are native bismuth and gold, Ag-Au alloy (küstelite), tellurobismuthite, hessite, sylvanite and rarer petzite, calaverite, tetradymite and tsumoite (Vikentyev et al., 2016).

The tectonised zones locally host remobilised sulphide veins and veinlets, which are dominated by pyrite, chalcopyrite, pyrrhotite, galena and minor aforementioned rare Au-, Te- and Bi-minerals.

The Koktau copper deposit, previously named 50 Let Oktyabrya, is located to the east of the Khromtau, west Kazakhstan. The ore field is located in the Priorsk subzone of the eastern Magnitogorsk VMS zone, which is the southern continuation of the Dombarovsk subzone (Herrington et al., 2005a,b). The Priorsk subzone consists of arc volcanics, mostly basaltic complexes of the Emsian Mugodzhary Formation, which are crosscut by numerous intrusive and subvolcanic bodies.



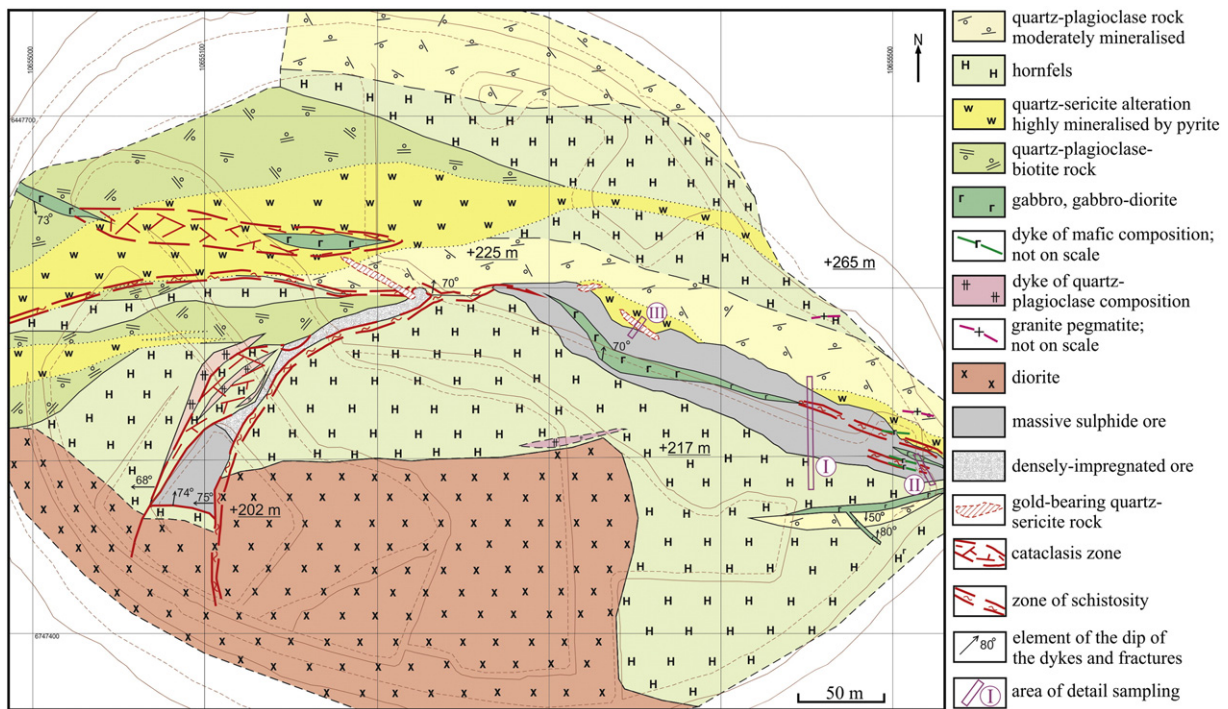
**Fig. 12.** T-P conditions of contact metamorphism in the VMS deposits of the Urals, in some cases coupled with regional-metamorphic transformations: 1 – Kaban, Krasnogvardeiskoe, Dzhusinskoe, Levikha, Uchaly, Uzelga, Gai, Sibai, Alexandrinskoe, Barsuchiy Log, Ozernoe, Oktyabrskoe; 2 – Tash-Yar, Vesenneye, Letneye; 3 – Koktau, Tarnyer (T-P data see Table 6); modified after Vikentyev, 2004. AEH – albite-epidote hornfels; HH – hornblende hornfels; PH – pyroxene hornfels. Other comments and abbreviations of metamorphic facies see in Fig. 2.

These bodies are dominated by Middle to Late Devonian granitoids of the Sredne-Orskiy Massif, which surrounds the ore field in the north, west and east (Vakhrushev, 1973). The deposit is confined to the eastern contact of the massif (Fig. 15).

The NE-, NW- and N-trending dykes, along with the small intrusions of variable composition (from basalt to rhyolite and from diorite to granite), are arranged along the faults. Their origin is related to both

the volcanic source and granitoid magmatism. The youngest granite porphyry and quartz porphyry dykes crosscut all of the aforementioned dykes and subvolcanic bodies.

Mafic volcanic rocks are amphibolised mostly by fluids derived from granite and granodiorite plutons with locally developed skarn. Two types of hornfels occur in the deposit (Vakhrushev, 1973): (1) anthophyllite-cordierite and biotite-cordierite, which replaced mafic



**Fig. 13.** Geological plan of the open pit at the Tarnyer deposit. Position of areas with detailed sampling: I – 225–230 mRL; II – 217–225 mRL (see Fig. 14); III – area with Bi-Te-Au-rich mineralisation, 217 mRL (see Vikentyev et al., 2016).

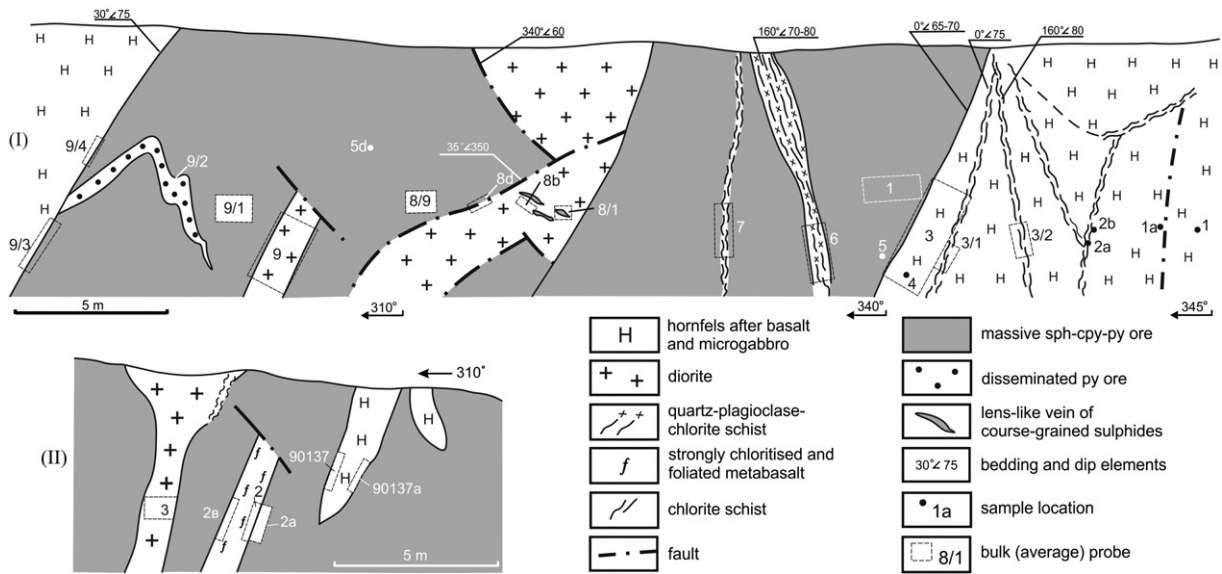


Fig. 14. Details of relationships between dykes and massive sulphide ore at the Tarnyer deposit (the open pit walls). For the position of areas (I) and (II) see the quarry map (Fig. 13).

rocks; and (2) anthophyllite-quartz-albite, biotite-quartz-albite and quartz hornfels with subordinate sericite, anthophyllite, andalusite and spinel after subvolcanic rhyodacite and genetically related lavas.

The NS-trending mineralised zone (approximately 2.5 km long) comprises three ore lodes: Northern, Central and Southern, with the last hosting 85% of the reserves, totalling 50 Mt of ore, grading 1.82 wt% Cu (0.9 Mt Cu), 0.47 wt% Zn, 0.031 wt% Co, 0.015% As, 73 g/t Se and 5.4 g/t Ag. The Central Lode, 10–12 m thick, unites two medium-sized ore-bodies and one small gently dipping orebodies with

high-angle terminations. The Northern Lode, which is 1.1 km north from the Central Lode, hosts a single steeply SE-dipping (70–85°) orebody, which consists of two lenses separated by pyritic ore. The thickness of the lode ranges from 10 to 80 m, and it splits into a few apophyses along its flanks.

None of the orebodies are exposed at the surface. Massive ore is mined by open pit methods at the Southern Lode. The top of the lode dips eastward at a low angle, conformable to the contact with the altered volcanic rocks (Fig. 15), and the base has a complex morphology

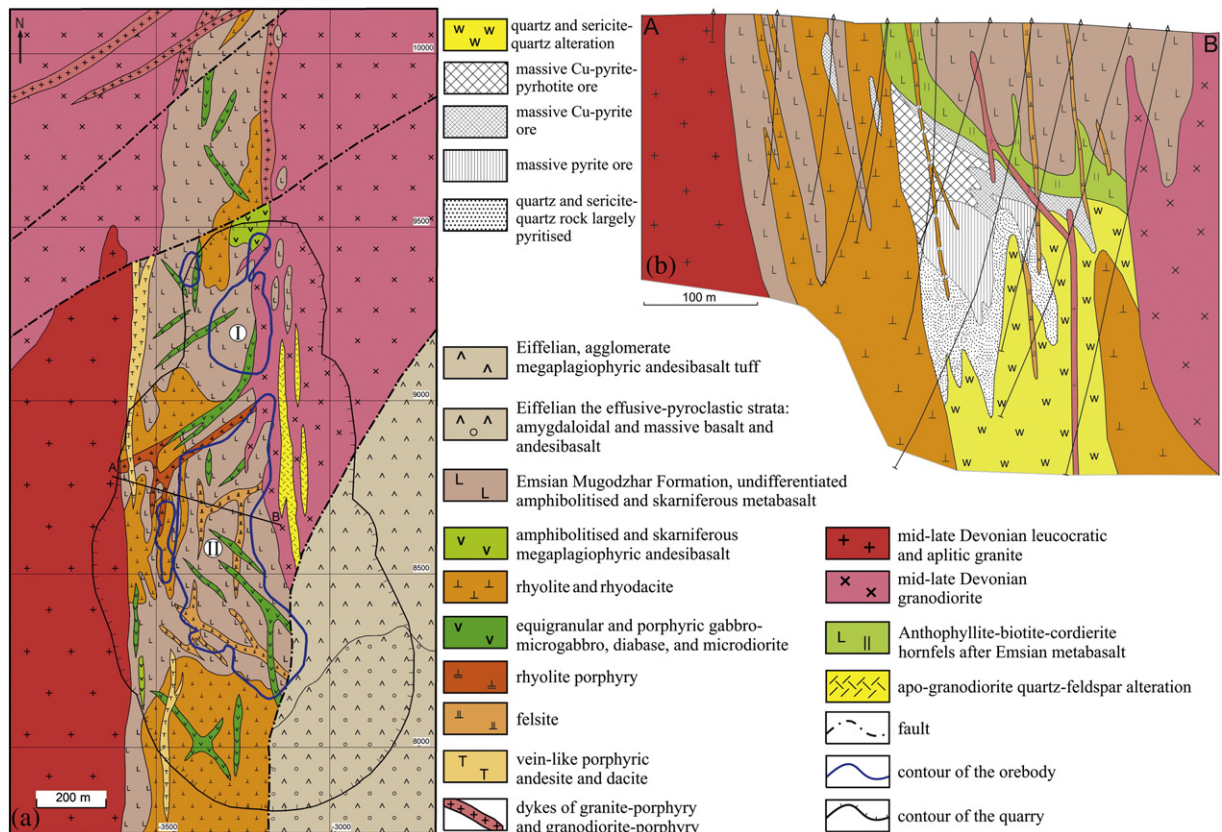


Fig. 15. Geological plan of the Central (I) and Southern (II) lodes (a) and geological section (b) of Koktau deposit (compiled using data of M.I.Vakhrushev and mine geologists).

with numerous apophyses. The Orebody 1 (940 × 350 m, and up to 150 m thick) contains 73% of the reserves of the ore deposit. A series of small lens- and vein-shaped ore offshoots on the western flank dip steeply (75–80°) to the east. These offshoots are either hosted by rhyolitic-dacite dykes or occur at the contacts with the sheet-like basalt layers, which separate the offshoots from the Orebody 1.

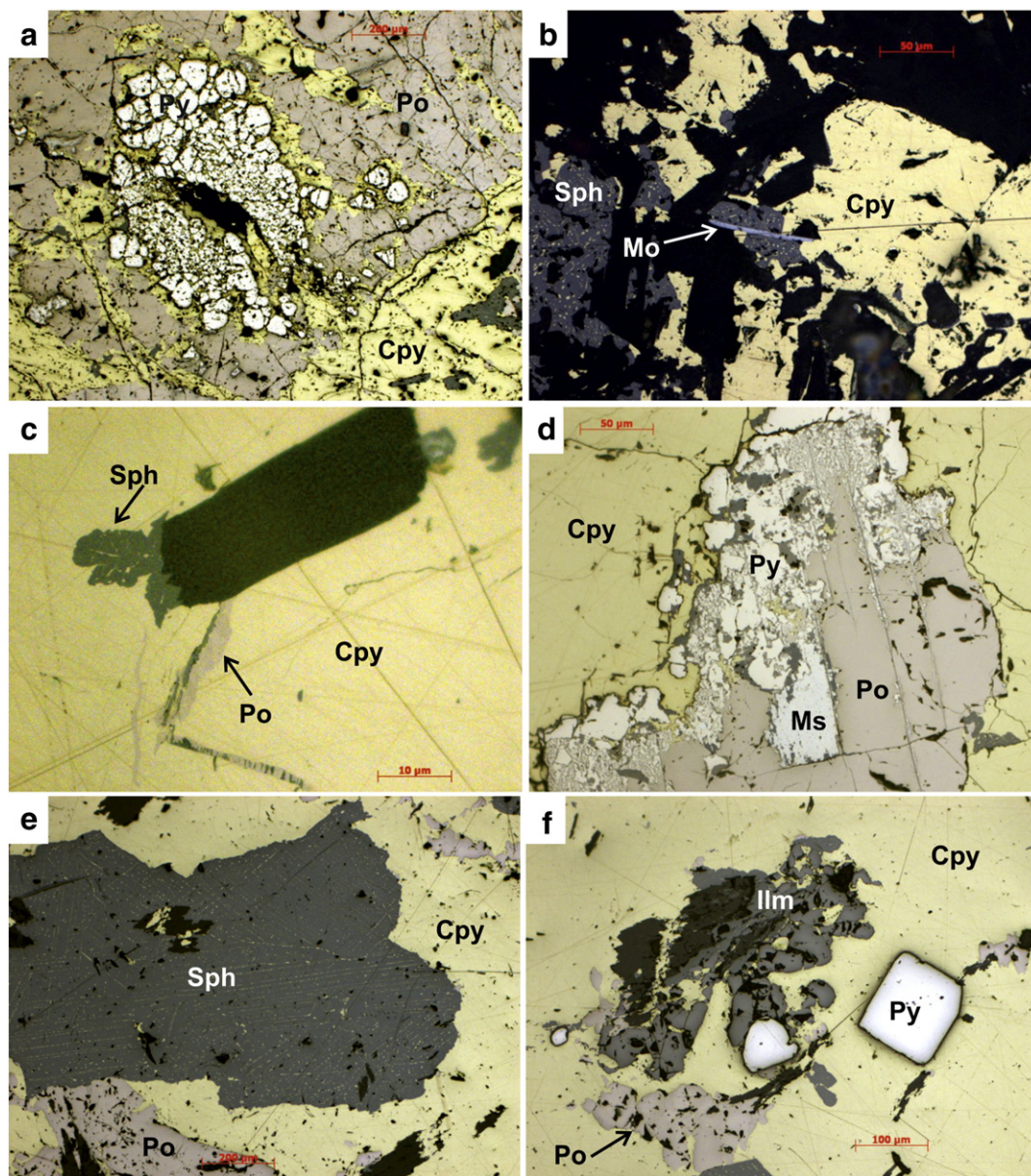
The massive sulphide ores, up to ~75% of the total reserves, contain 60–90 vol% of sulphides and contain relatively little gold (0.2 g/t), with its grade increasing to 0.84 g/t Au in stringer and veinlet-disseminated (<60 vol% sulphides) ores. Up to 1 g/t Re was detected in some ore samples. The major ore types are chalcopyrite-pyrite, chalcopyrite-pyrite-pyrrhotite and chalcopyrite-sphalerite-pyrite.

Ore mineralisation in the Southern Lode is distributed unevenly, which contains both massive and patchy-impregnated ores (Fig. 16). The ores are dominated by brecciated, porphyric, porphyroblastic and granular textures, with subordinate banded, lenticular, gneissic, spotted

and stringer fabrics. Gangue anthophyllite and cordierite replaced ore minerals. The ores are inequigranular, varying from medium- to coarse-grained, although fine- and giant-grained varieties are also present; pyrite porphyroblasts in these ores reach 2–4 cm across or even more.

Pyrite, chalcopyrite, sphalerite and pyrrhotite are major ore minerals. Magnetite, ilmenite, marcasite, molybdenite, cubanite and mackinawite are minor, with accessory galena, tennantite, arsenopyrite and bismuth minerals.

The earliest formed minerals are magnetite and ilmenite, which likely formed during pre-ore alteration after microgabbro with accessory titanomagnetite. Both magnetite and ilmenite are commonly found as inclusions in pyrite, chalcopyrite and pyrrhotite. The first (earliest) ore assemblage comprises fine-grained pyrite-1, which is generally found as brecciated fragments, 3–5 mm across, with corroded margins cemented by chalcopyrite, pyrrhotite and sphalerite, a common mineral



**Fig. 16.** Contact recrystallised high-grade copper ore of the Koktau deposit (reflected-light micrographs): a – older pyrite as xenolith (white, with a chalcopyrite rim) in a chalcopyrite-pyrrhotite aggregate; b – sphalerite grain is cut by a thin molybdenite veinlet (bluish) in the high-grade copper semi-massive ore; c – sphalerite (dark gray) and pyrrhotite (pinkish) at the terminations of a tabular cordierite grain (black) in chalcopyrite (yellow groundmass); d – pyrrhotite replaced by pyrite (white) and marcasite (bluish); e – chalcopyrite emulsion in sphalerite and coarse-crystalline chalcopyrite; f – ilmenite xenoliths in chalcopyrite. See Fig. 6 for abbreviations.

assemblage with the pyrite. Crystallisation of fine-grained pyrite-1 was followed by deposition of quartz together with equigranular pyrite, chalcopyrite, sphalerite (and likely pyrrhotite). Quartz forms segregations and veinlets that fill cataclastic fractures and cracks in the early pyrite. Quartz grains contain corroded fragments of earlier pyrite-1 as well as small chalcopyrite and sphalerite pockets and impregnations. Later pyrite-2 contains small inclusions of chalcopyrite, sphalerite and pyrrhotite. Both fine-grained pyrite-1 and later pyrite-chalcopyrite-quartz assemblages correspond to the synvolcanic stage of sulphide mineralisation. This stage of mineralisation preceded an emplacement of the earlier dykes, large granitoid intrusions and youngest granite porphyry, microgranite and microdiorite dykes.

Ore was significantly modified by recrystallisation and overprinted by anthophyllite and cordierite. Recrystallised ores constitute the bulk of Orebody 1. Recrystallisation was accompanied by redeposition of ore minerals and a likely input of additional Cu, Mo, Se, Re, Bi and Te during the final crystallisation of granodiorite magma. During the post-peak retrograde stage of contact metamorphism, the orebody was fractured. This stage was responsible for the formation of undulating cracks, which were filled with silicate fine-grained material. The peripheral parts of the separated ore lenses locally host segregations of fine-grained arsenopyrite and bismuth minerals.

High temperatures, based on mineral geothermometry and fluid inclusion data (500 °C and higher), the relatively common occurrence of segregations of native bismuth and As-minerals, and the presence of specific subgraphic eutectic sulphide intergrowths suggest the involvement of the process of partial melting in the ore reworking at the peak of metamorphism. The ore assemblages, including those with anthophyllite, are cross-cut by thin quartz-carbonate ± baryte veinlets with impregnated chalcopyrite, sphalerite, galena and tennantite.

The small Tash-Yar deposit is located in the eastern part of the Uchaly ore district in the northern Magnitogorsk zone, 250–900 m away from the Early Permian Akhunovo Massif, the largest granite intrusion in the area (Yashchinin, 1970; Ivanov and Prokin, 1992; Vikent'ev et al., 2009). Granites are surrounded by a contact aureole (up to 2500 m) of metamorphic hornfels (Snachev, 1982; Ivanov and Prokin, 1992).

The host rocks to ore consist of a basalt-rhyolite volcano-sedimentary sequence of the Eifelian-Early Givetian Karamalytash Formation, which is composed of dacite, rhyodacite, basalt, their tuff and mixed tuff, intruded by rhyolite, microdiorite and microgabbro bodies of the Middle Devonian age. Mineralisation is NNE-trending and follows the foliation zones. The ore zone is approximately 400 m wide and is traceable in a NE direction for 1 km. The orebodies occur in sericite-quartz alteration in felsic volcanic and volcano-sedimentary rocks. In the outer parts of the alteration haloes, mineral parageneses include chlorite and biotite; the latter mineral occurs at deep levels of the deposit and in its southeastern flank (Yashchinin, 1970; Snachev, 1982; Baranov, 1987; Vikent'ev et al., 2009).

The deposit comprises several steep lenses, dipping northwest, of low-grade veinlet-disseminated zinc ores that are up to 400 m long and up to 50 m thick (Fig. 17). The ore has an average grade of 1.3 wt% Zn, 0.1 wt% Cu, 0.1–0.6 g/t Au and 5–30 g/t Ag. Pyrite and sphalerite are major ore minerals in approximately equal proportions. Chalcopyrite is minor; galena, tennantite, bornite, chalcocite, pyrrhotite, magnetite and altaite are rare. Pyrite and sphalerite are generally brecciated and their detached fragments are enclosed by a ductile quartz-sericite-chlorite aggregate in impregnated ores and mineralised alteration, indicating pre-metamorphic precipitation of major sulphides. Pressure solution elongate pyrite grains with preferred pyrite crystal orientations are evidence of their dynamic recrystallisation. Synmetamorphic recrystallisation was accompanied by coarsening of sulphides (Vikentyev, 2004). At the same time, the superposition of subvertical sphalerite-bearing quartz-sulphide veins on the primary dispersed and layered pyritic mineralisation reflects a high amount of zinc remobilisation.

Geochemical haloes of base metals in altered rocks that host ore are characterised by lateral (for hundreds of metres) zoning relative to the granite massif: copper haloes are confined to the south-eastern flank of the deposit (closer to the massif), whereas lead (along with silver) haloes are typical of the north-western flank that is most distal to the granite (Yashchinin, 1970; Baranov, 1987).

The contribution of synmetamorphic processes to ore redistribution is also evident from the general arrangement of the quartz-sphalerite veins along the steeply-dipping foliation zones. Geometry of the separate sulphide accumulations (patches, small lenses and stringers) commonly follows cleavage, microfolds, foliation and primary bedding.

The Permian was marked by intense ductile deformation along the northern termination of the Akhunovo Massif that acted as a giant boudin under latitudinal compression as a result of the collision (Vikent'ev et al., 2009). It was accompanied by right-lateral displacement along the NNE-trending zone that borders the northern margin of the massif in the west. The development of the steeply-dipping northeastern extensional fractures induced migration of hydrothermal-metamorphic fluids with the formation of quartz-sphalerite veins. The Tash-Yar deposit formed as a result of two superimposed nearly-synchronous Early to Middle Permian phases of remobilisation: syn-magmatic thermal and syncollisional dynamo-thermal.

### 5.2. Local contact (dyke-related) metamorphism of VMS deposits

The small Letneye deposit is hosted in a basalt-dominated succession (Fig. 18). The volcanic-hosted orebodies are crosscut by little younger microgabbro dykes, as well as by rarer dykes of highly alkalic andesite and dacite (porphyritic amphibole-biotite lamprophyre, trachyandesite and trachydacite) (Poluekov et al., 1974; Gaskova et al., 2010). According to Le Maitre et al. (2005), rocks of the dyke complex belong to the normal alkalic and subalkalic series. Microscopy studies show microgabbro metamorphosed and altered in an analogous fashion to those of the host rocks, which include evidence of epidote, actinolite and chloritic alteration, with the feldspar being completely saussuritized and, in places, albitised. The lamprophyre, trachyandesite and trachydacite dykes are fresher and their alteration resulted in the development of metamorphic actinolite, which replaced hornblende and chlorite after primary amphibole and biotite. Feldspar in lamprophyre is relatively fresh (both plagioclase and occasional K-feldspar are present); K-feldspar of trachydacite is locally altered to clay. The amphibole-biotite lamprophyre dyke contains abundant amygdules, which suggest that the melt was rich in fluid.

The following ore varieties (on average 2.8 wt% Cu and 1.2 wt% Zn) are distinguished based on the ore fabrics in massive and stringer ores (Belogub et al., 2004; Belogub, 2006). *Massive ores* include: (1) brecciated magnetite ores (magnetite + pyrite ± hematite, with chalcopyrite in veinlets); (2) banded pyrite (up to 1.5 cm thick) and magnetite (up to 2 cm thick); (3) massive fine-grained chalcopyrite-pyrite ores (± sphalerite, magnetite, pyrrhotite); (4) massive or weakly banded sphalerite-pyrite-chalcopyrite ores with 0.5–2 cm thick bands (± magnetite, hematite, galena and rare pyrrhotite, with sphalerite occurring as lenses and veinlets); (5) patchy (“leopard spots”) pyrrhotite-pyrite-chalcopyrite ores with fabrics defined by the development of pyrite porphyroblasts (up to 1 cm across). Along with major sulphides, the ores contain marcasite, cobaltite, rare native gold and pyrrhotite with pentlandite exsolutions; and (6) patchy pyrite-chalcopyrite-pyrrhotite ores, where pyrite (0.5 mm across) occurs in the pyrrhotite matrix. The minor minerals are magnetite and pentlandite. *Stringer ores* are represented by chalcopyrite located at the contact with dykes and in pinches of the orebody. They contain pyrite, rarely sphalerite and gangue minerals, such as quartz, calcite and epidote, forming up to 6 cm thick veinlets.

The orebodies are dominated by massive, weakly banded, banded, and lenticular chalcopyrite-pyrite and sphalerite-chalcopyrite-pyrite ores. The patchy ores occur near contacts with the dykes, and their

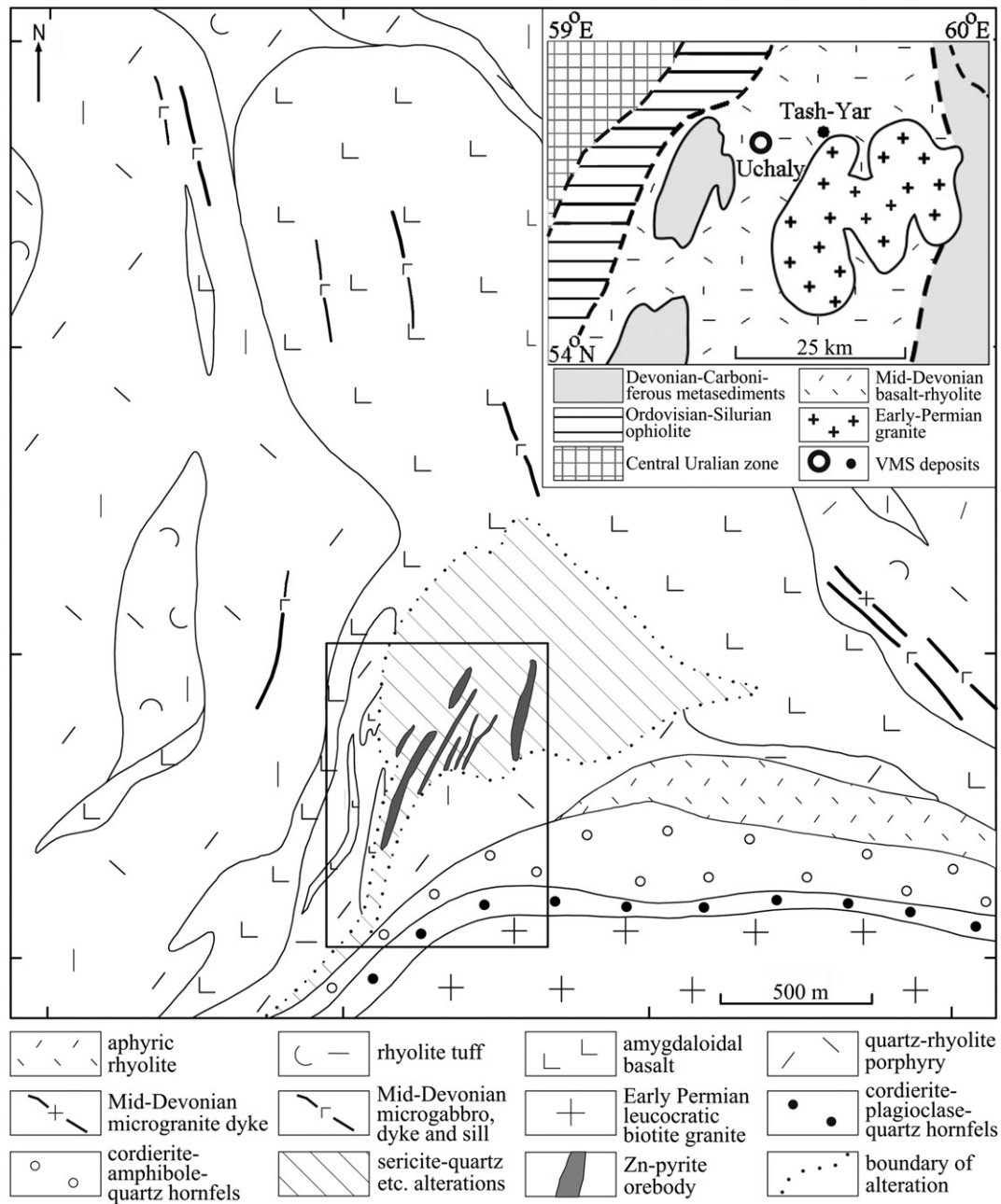


Fig. 17. Geological map of the Tash-Yar ore field. Box indicates approximate boundary of the Tash-Yar deposit.

volume is relatively insignificant. Magnetite-dominated ores are found in the lower parts of the orebody. Their contact with sulphide ores is relatively sharp. The stringer pyrite-chalcopyrite and chalcopyrite ores occur sporadically at pinching parts of the orebodies and at the contacts with the microgabbro dykes.

Our data confirm the fabric changes in ores, affected by the dykes (Ismagilov and Poluekov, 1978). We also found that remobilised mineralisation contains newly formed pyrrhotite, native gold, cobaltite and pentlandite and suggested that the scale of the contact transformations depends on the thickness of the dykes and the primary ore mineralogy (Belogub, 2006; Gaskova et al., 2010).

The small Dzhusinskoe (or Dzhusa) deposit is hosted by volcano-sedimentary rocks of the Lower Devonian (Emsian) rhyolite-dacite-andesite association metamorphosed to the greenschist facies. Late Devonian to Tournaisian porphyritic gabbro dykes and intrusive bodies of the Early Carboniferous microdiorite and quartz diorites are widespread in the ore field (Eremin and Kogan, 1964). Hundreds of dykes make up

approximately 20% of the area that is exposed in the open pit, which is 800 m in diameter. The variously oriented dykes have different thickness (from 0.3 to 20 m) (Fig. 19). The footwall and hanging walls of the mineralised zone consist petrographically similar rocks: irregularly sheared and sericitised andesidacite with more extensive alteration in the footwall.

The ore zone is 50–150 m thick and is traced to a depth of >800 m (Eremin and Shishakov, 1969; Glasby et al., 2007). The elongated lens-shaped and ribbon-like orebodies have a complex morphology and form numerous interfingering branches. In some places, the orebody is cross-cut by the diorite and gabbro dykes, which were subjected to quartz-albite-chlorite alteration. For example, Orebodies 1, 2 and 3 are fragments of a single large orebody, separated by altered gabbrodiorite dykes (Fig. 19). Some of the dykes preceded mineralisation and their xenoliths occur as inclusions in ore bodies (Eremin and Kogan, 1964; Eremin and Shishakov, 1969). Small shear zones occur near contacts of the orebodies, commonly outside the areas where the dykes occur.

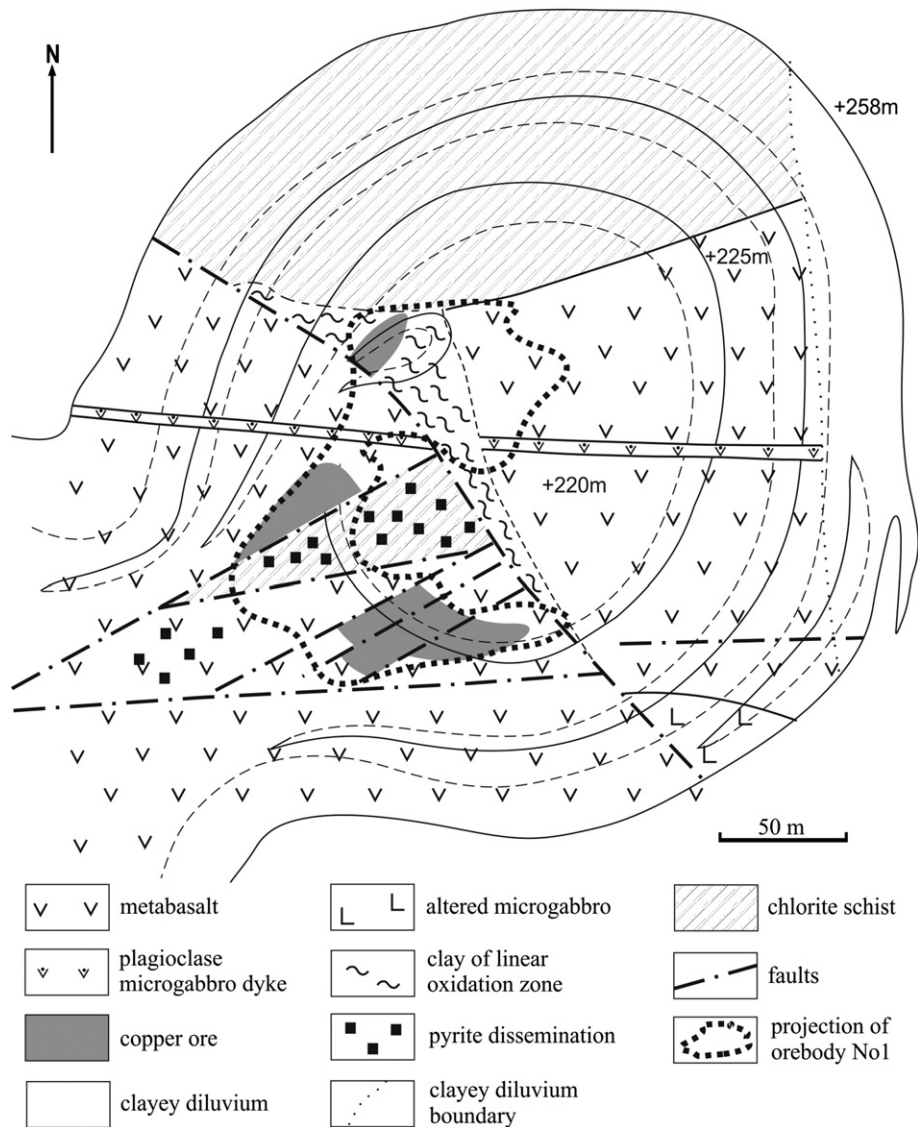


Fig. 18. Geological plan of open pit at the Letneye deposit (2003).

The orebodies, with an average grade of 3.34 wt% Cu, 2.13 wt% Zn, 0.77 wt% Pb, 1.1 g/t Au and 26 g/t Ag, consist of massive sulphide ores and are accompanied by minor veinlet-disseminated mineralisation. The great diversity of ore fabrics in massive ores was formed as a result of multiple brecciation of sulphide aggregates and their shear-related dynamic metamorphism and recrystallisation at the contacts with the dykes. The orebodies include pockets of coarse-grained quartz and baryte. All ore types are cataclased, with linear cataclasis affecting even the youngest mineral assemblages.

The thick (5–10 m) microdiorite dykes near the orebodies host low-angle polymineral Alpine-type veins, which are composed of quartz, feldspar, hematite, and chalcocopyrite (outside the orebodies) and of quartz, chlorite, and chalcocopyrite (within the orebodies). The quartz-feldspar-hematite-chalcocopyrite veins host variably-sized (from 15 to 20 mm) pockets with galena, whereas the quartz-chlorite-chalcocopyrite veins may contain cavities, crustified with large well-faceted quartz crystals, up to 3–10 cm across. Quartz displays features of distinct zoning and, when brecciated, deformational lamellae, parallel the cataclasis fractures. Mg-Fe chlorite is spatially associated with anatase crystals.

The ore consists of pyrite (10–90%), chalcocopyrite (10–90%), sphalerite (5–40%), galena (0.5–10%) and tennantite-tetrahedrite (0.5–5%). The subordinate minerals are arsenopyrite, magnetite, pyrrhotite, bornite, and hematite, whereas mackinawite, As-cobaltpentlandite, hessite,

native gold, native silver and native tin are rare. The dominant gangue minerals are quartz and baryte, whereas carbonates, chlorite and sericite are minor. The high content of galena and baryte in the Dzhusinskoe deposit contrasts with what is typical for most deposits in the Urals (cf., Glasby et al., 2007). The ores commonly have brecciated or banded structures along orebody contacts.

The massive ores consist of fine-grained pyrite aggregates, with oval pyrite domains, up to 10 cm in size, which are distinct in colour. Oval botryoidal segregations consist of pyrite with relics of colloform-zoned or radiating texture, whereas the fine-grained matrix is composed of recrystallised pyrite, although some crystals are not completely recrystallised and contain relics of the primary colloform texture. The mineral assemblage of quartz with chalcocopyrite, sphalerite, bornite, tennantite-tetrahedrite and pyrite replaced and cemented the earlier pyrite, and produced a brecciated structure. The quartz-bearing veins, bands and veinlets are abundant in the microgabbro dykes and along the contacts of the dykes with sulphide ore. The widespread sulphide-free quartz segregations intersect botryoidal pyrite aggregates, fill cataclasis fractures and occur along colloform zones, which displaced and deformed some layers of pyrite. Quartz in the selvages of the lenses is chalcocopyrite-like and has a dark gray colour.

The content of chalcocopyrite varies from 10 to 50 vol% in the massive sulphide ores and up to 90–95 vol% in ladder veins in the microgabbro

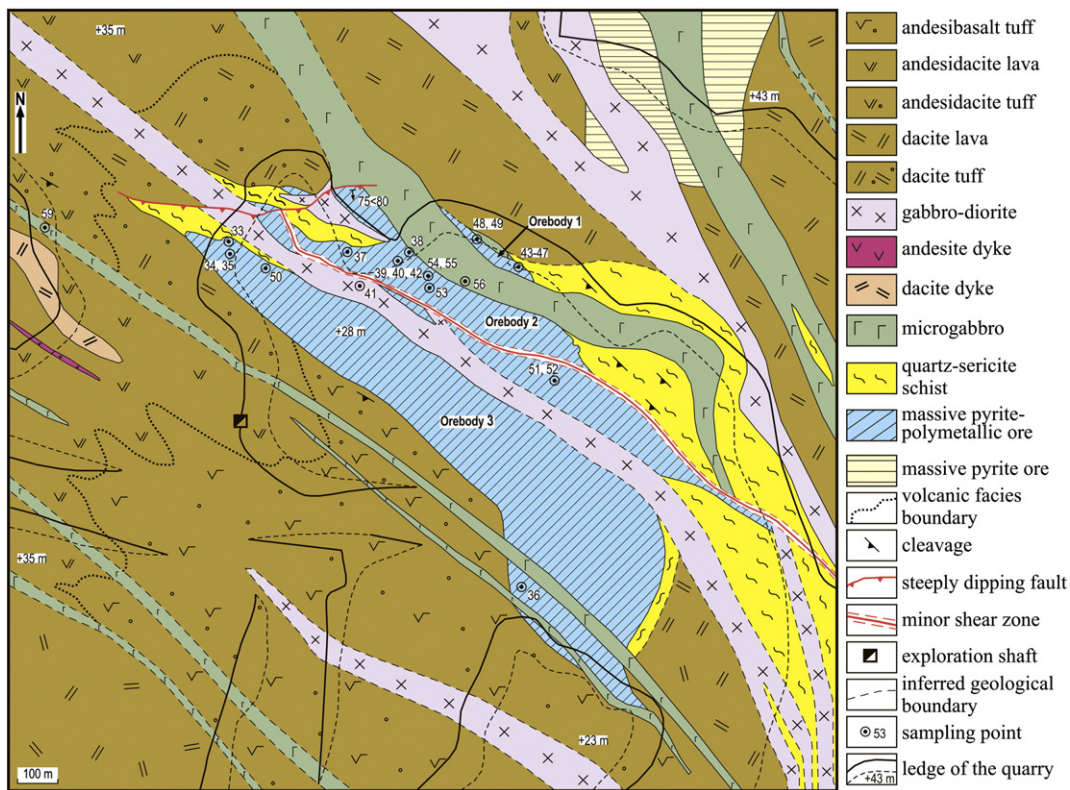


Fig. 19. Geological plan of the Dzhusinskoe open pit (2007), showing complex relationships between orebodies and dykes of two phases.

dykes or along dyke contacts with sulphide ores. The chalcopyrite generally cements pyrite, replaced its botryoidal aggregates, accentuating their primary colloform-zonal or radiating inner texture, and occurs as pockets and segregations in quartz. Chalcopyrite in the veins is massive, where it locally contains sphalerite (with chalcopyrite tiny inclusions), galena and bornite. The last mineral shows exsolution textures with chalcopyrite. Quartz at the contact with chalcopyrite contains pyrite and arsenopyrite crystals (up to 1–1.5 mm). Sphalerite is associated with galena and contains inclusions of fine-grained pyrite and magnetite.

Small Alexandrinskoe Cu–Zn deposit is located in the eastern Magnitogorsk VMS zone. The ore-bearing sequence is hosted in two Middle Devonian formations: the Lower Karamalytash Formation of felsic lavas, lava-breccia and tuffs, and the Upper Ulutau Formation of bimodal volcanic rocks, which are interbedded felsic and mafic lavas and lava-breccia with horizons of mixed tuff and limestone (Tesalina et al., 1998; Vikent'ev et al., 2000). The host rocks are metamorphosed from the zeolite to low prehnite-pumpellyite facies. Well-preserved phenocrysts of clinopyroxene, relict orthopyroxene as well as metamorphic albite, quartz, chlorite, sericite and carbonate are common minerals. Some orebodies, 3–8 m thick, occur within the shear zone and are hosted by sericite-quartz schist. Orebodies, 3–20 m thick, are composed of massive and semi-massive (impregnated) sulphides, with an average grade of 4.4 wt% Cu, 5.48 wt% Zn, 0.52 wt% Pb, 1.3 g/t Au and 49 g/t Ag. Four ore types are distinguished based on mineral composition: 1) pyritic; 2) copper (chalcopyrite-pyrite and bornite-pyrite); 3) copper-zinc (chalcopyrite-sphalerite-pyrite and bornite-sphalerite-pyrite); and 4) zinc (sphalerite-pyrite). The second and third types are dominant. Copper-rich (Cu and Zn-Cu) massive lenticular and breccia-like ores are most abundant in the deposit. Spherulitic, radial and framboidal textures are widespread in massive ores that confirms the ore was subjected to low grade regional metamorphism.

The copper-zinc ore dominates within the Main Orebody 1. Some prevalence of copper ore ( $Zn/Cu = 1-1.5$ ) is observed in its central and western parts with Cu-rich ores tending to occur towards the

hanging wall, whereas they change downdip to copper-zinc and eventually, in places, to zinc ores. This reversed zoning is very uncommon for VMS deposits in the Urals (Prokin and Buslaev, 1999). The proportion of copper and copper-zinc ores is almost equal in the eastern part of the orebody. Here, the copper ores occur in the axial zone, and copper-zinc ores occur in upper and lower parts of the body. The northern part of the Main Orebody comprises very rich massive copper-zinc ores, whereas the southern part contains bornite-bearing mineralisation with upward zoning from the chalcopyrite-pyrite ( $\pm$  baryte) to bornite-pyrite (+ chalcopyrite) and to bornite-sphalerite-pyrite (+ chalcopyrite) assemblages.

The unusual sulphide-bearing mineral assemblages occur in the endocontacts of 10–12 m thick pyroxene microgabbro dyke. Mineralisation occurs where the dyke intersects footwall alteration (Novoselov, 2002) and as rare sulphide inclusions (up to 0.4 m) in the dyke (Fig. 9 in Vikent'ev et al., 2000). The amount of sulphides at the dyke endocontacts reaches ~5–10 vol% and they were distributed over 1 m from the contact. The sulphide segregations display two textural types: (1) nodule-like rounded segregations and (2) fine-grained impregnation of sulphides.

The *sulphide nodules* are usually rounded or amoeboid, with a maximum dimension of 2–4 mm. As a rule, fine-grained quartz rims the nodules along the margins, with sulphides forming micro-apophyses in the interstices of the quartz grains. The boundary between the rim of quartz and microgabbro matrix is sharp. Galena and chalcopyrite are dominant in the nodules, and tennantite is minor. Baryte occurs at the contact with silicate matrix as euhedral crystals, 2–5  $\mu$ m in size. Galena and chalcopyrite regularly form complex intergrowths with a subgraphic pattern, resembling a eutectic texture. The average ratio of chalcopyrite to galena in the nodules is ~3.8. Tennantite is observed as small particles, ~0.01 mm in size, at the contact between chalcopyrite and quartz rim.

Another type of mineralisation in the dyke is sulphide microimpregnation with abundant rutile. The intergrowths of sulphides and rutile reveal an exsolution texture, with rutile lamellae in the

sulphide matrix. The xenomorphic sulphides, including galena, chalcopyrite, bornite, chalcocite and covellite, form impregnations and fill the interstices between silicates, forming the sideronitic texture (Moorhouse, 1959). Galena is the most abundant sulphide and occurs either as small monomineral intergrowths of anhedral grains in the silicate matrix or, more commonly, in association with bornite, chalcocite and tennantite. Bornite, chalcocite and tennantite overgrew skeletal galena along its margins.

The sulphide nodules are viewed as a product of melting of sulphide xenoliths, which were incorporated in the dyke during emplacement. Additional process of sulphide liquid segregation likely occurred and was followed by sulphide crystallisation. This is in agreement with the rounded drop-like shape of the nodules and subgraphic eutectic texture of the chalcopyrite–galena intergrowths. Such textures are not typical for primary VMS ore and indicate near simultaneous crystallisation of sulphides in the dyke, probably from a melt.

## 6. Discussion

The influence of metamorphism on the VMS deposits, in general, is significant and variable. Analysis of metamorphic grades, reported by Mosier et al. (2009) for 1090 VMS deposits throughout the world, indicates that among the 819 deposits only 3% are unmetamorphosed. According to their statistics, deposits were metamorphosed in zeolite (1.5%), sub-greenschist, prehnite–pumpellyite or pumpellyite–actinolite (7%), greenschist (62%), amphibolite (11%), blueschist or eclogite (2%), granulite facies (0.5%) and contact metamorphism (13%) (Mosier et al., 2009; cf., Shanks et al., 2009). Based on the data of Mosier et al. (2009), post-ore deformation occurred in 80% of VMS deposits, and post-ore intrusions occur in 60% of them. It is noteworthy that only a small proportion of the VMS deposits is considered to be subjected to high-grade metamorphism, probably, partly due to the fact that an identification of a primary sea-floor hydrothermal nature of some extremely metamorphosed sulphide occurrences is ambiguous. Primary features of the VMS deposits are often completely masked (Vokes, 1969, 2000; Cook et al., 1993; Dobretsov et al., 1987; Shanks and Thurston, 2012; Lobanov et al., 2014). The interpretation of the order of the ore-forming events can be also complicated because of the convergence of indicative features. It is not the case with the Uralian VMS deposits, which represent examples of different metamorphic grades, where regular metamorphic changes are traceable and identifiable. Most VMS deposits in the Urals were metamorphosed from the prehnite–pumpellyite to lower greenschist facies.

Probably, it is not a coincidence that two of the world's largest VMS provinces, the Urals and the Iberian Pyrite Belt, are characterised by a relatively low degree of metamorphism, unlike most other ore belts with smaller ore reserves and, as a rule, higher grade of metamorphism. Low grade metamorphism (prehnite–pumpellyite to lower greenschist facies) apparently contributes to a better preservation of the VMS bodies. Stronger metamorphism can lead to disintegration of the ore deposits and partial dispersion and remobilisation of sulphides.

### 6.1. Structural setting of the metamorphosed VMS deposits in the Urals

The steeply-dipping pseudomonoclinial shear-related structures are dominant in VMS deposits of the Middle Urals (Table 7), whereas gentle folding is typical of deposits in the South Urals, with local shear zones occurring in the fault-related areas, such as Gai and Podolskoe ore fields and the Alexandrinskoe, Sibai, East-Semyonovskoe, Bakrtau, Makan and Dzhusinskoe deposits (Smirnov, 1985, 1988; Prokin and Buslaev, 1999). Overall, the metamorphosed orebodies are steeply-dipping orthogonal to a tectonic stress direction and parallel to a plain of shear flow. A few large intensely deformed VMS deposits are composed of single elongated subvertical sheet-like lens with either prominent bulges (Degtyarsk and Priorskoe) or they occur in a large fold (Novo-Uchaly and Uchaly). Single large and thick orebodies are more typically located

in the South Urals, although many deposits also occur as a package of intensely deformed steeply-dipping large and thick lenses (e.g., Sibai and Gai deposits) with the Gai deposit comprising several dozen ore lodes. In the Middle Urals, mainly within the Tagil zone, deposits are composed of a much large number of small orebodies as exemplified by the Levikha–Karpushinsk group of 800 orebodies (Loginov et al., 1963; Smirnov, 1988; Kontar', 2013), or several dozens of orebodies forming the San-Donato deposit as well as Krasnouralsk and Karabash ore fields (Rakcheev, 1962; Smirnov, 1988; Kontar', 2013). The host volcanic complexes and lenticular orebodies are steeply-dipping in these ore districts, and similar orebody morphology occurs in the Degtyarsk, Uchaly, Dzhusinskoe, Limannoe and Priorskoe deposits of the Magnitogorsk zone.

The conformity of the planar and linear fabrics of the host rocks with the dip of lenses and with the elongation of ribbon-like orebodies is typical not only for the deposits of the Karabash group but for all deformed VMS fields of the Middle Urals hosted by quartz-sericite and quartz-sericite–chlorite schists (Rakcheev, 1962; Ivanov and Prokin, 1992). This setting is similar to that of massive sulphide deposits of the Rudny Altai, Finland, Norway, USA and northern Sweden (Vokes, 1969; Starostin et al., 1989; Marshall and Gilligan, 1993; Spry et al., 2000).

Intense ductile deformation is accompanied by reverse faulting in the Karabash area and, south of it, by right-lateral displacement along the NS-trending zone as indicated by steeply-dipping extension fractures (Fig. 4). This process produced migration of hydrothermal–metamorphic fluids, and the formation of quartz–sphalerite veins (Tash-Yar), sphalerite and gold-bearing sphalerite–bornite–chalcopyrite veins in the deposits of the Karabash group and Kuznechikha deposit. A series of deposits (Tash-Yar, Dzhusinskoe; deposits of Kaban, Krasnouralsk and Karabash groups) experienced two remobilisation processes (dynamic–thermal and synintrusive). The metamorphic nature of fluids that precipitated quartz–sulphide associations is indicated by fluid inclusion studies which yielded high fluid pressures estimates of 0.5–1.5 kbar (Vikentyev, 2004; Vikentyev et al., 2016).

Differences in the shapes of some VMS orebodies can be explained by the degree of syngenetic destruction of sulphide mounds (Maslennikov, 2006; Maslennikov et al., 2013). But the structure of VMS deposits, being conformable to the general direction of the Urals tectonic elements, suggests that the shape of the orebodies results from the superposition of metamorphic structures on the preceding primary ones. Increase of flatness of the orebodies is in accordance with the increasing degree of metamorphism (Table 7).

### 6.2. T-P conditions of the metamorphic transformations

Various types of metamorphism occurred in the Urals during collision and folding (Ivanov et al., 1975; Puchkov, 2017). It should be emphasised that the geological boundaries between the types of metamorphism are commonly uncertain due to different timing of contributing geological processes, and situations where their manifestations overlap each other. As a whole for the Urals, all types of metamorphism, including burial, dynamic and contact metamorphism are minor; they are subordinate to orogenic metamorphism. But, as for individual ore deposits, these “minor” types may be crucial, since they often completely modify the geological structure of the deposit, ores textures, and mineral composition. The dynamic and contact types of metamorphism of ore controlled important but relatively local transformation processes. Both are superimposed on each other in the Kaban, Krasnouralsk and Levikha ore fields, Karabash group, Tarnyer, Zyuzelskoe and Kuznechikha deposits in the Middle Urals, as well as in the Tash-Yar and Dzhusinskoe deposits in the South Urals (Table 10). The mineral assemblages of the VMS-hosting volcano–sedimentary complexes in those few ore regions, which have not experienced significant transformations (“VMS districts with low-grade metamorphosed deposits” in Table 5), mainly correspond to the prehnite–pumpellyite and lower greenschist facies of burial

**Table 10**  
Degree and nature of metamorphic alteration of VMS deposits of the Urals.

The degree of transformation of deposits	Facies	t, °C	Deposits	Re-crystal-lisation	Neoblasts (Po, Asp, Mt., Zn-Spl, Ba-Fs, Ab)	Redistri-bution of chemical elements in the ore	Pyrite porphyroblast	Tectonic planar fabrics	Partial melting signs
Non metamorphosed and very weakly metamorphosed	Zeolite	100–200	Komsomolskoe, Yaman-Kasy, Kyndyzdy, Galkinskoe	–	–	–	–	–	–
Weakly metamorphosed	Tectonically disturbed	Zeolite – prehnite-pumpellyite	150–300	Bakrtau, Tashtau, Baltatau, Maiskoe Blyava, XIX Parts”zd, Talgan, Buribai, Kamagan, Vishnevskoe, West-Semenovskoe, Kul-Yurt-tau	±	–	–	–	–
			150–350	Yubileinoe, Uvaryazh, Sultanovskoe, West-Ozerno	±	–	–	–	–
	Strongly tectonically disturbed	Prehnite-pumpellyite <sup>a</sup>	150–350 (400)	Safyanovskoe, Babaryk	±	±	–	–	–
			150–350 (400)	Uchaly, Novo-Uchaly, Molodezhnoe, Alexandrinskoe	±	±	–	–	±
Moderately metamorphosed	Tectonically disturbed; local contact metamorphism	Prehnite-pumpellyite to lower greenschist <sup>a</sup>	180–350 (450)	Uzelga, Podolskoe, Ozerno, Osenneye	+	+	±	±	–
			200–400	Novo-Shemur, Shemur, Oktyabrskoe	+	±	–	±	–
	Strongly tectonically disturbed; local contact metamorphism	In areas associated with MUF and PBB	200–400 (450)	Sibai, Priorskoe	+	++	+ RZ	+	±
			250–450	Barsuchiy Log, Makan, Buribai, Levoberezhnoe	+	+	+	+	±
Metam-m from moderate to high	Strongly tectonically disturbed, including regional shear zones	Greenschist	250–450 (500)	Gai, Degtyarsk, San-Donato (III International), Ezhovka, Kalata	++	+	++	++	±
				Dzhusinskoe, Kaban and Krasnouralsk ore fields, Zyuzelskoe, Olkhovka, Karpushikha, Shaitanskoe, Lomovka, Levikha group, Chusovskoe	++	++	++ RZ	+	++
Strongly regional metamorphosed; local contact and dynamic metamorphism	Upper greenschist – amphibolite	350–500	Letneye	++	++	+	++	+	–
Strongly metamorphosed in a regional shear zones; contact metamorphism			350–600 (700)	Karabash group, Yuluk	++	+	++ RZ	+	+
			350–700 (800)	Mauk, North and South Kuznechikha	++	++	++ RZ	++	++
Remobilized; contact metamorphism	Albite-epidote-hornfels – pyroxene-hornfels		350–550 (650)	Tash-Yar	++	+	++ RZ	+	±
			350–700 (850)	Koktau, Tarnyer, Vesenneye, Avangard	++	++	++ RZ	++	++

Mineralogical attributes: – none; ± insignificant; + noticeable, to significant; ++ characteristic, strongly developed.

MUF – Main Uralian Fault, PBB – Platinum-Bearing Belt, RZ – regenerated geochemical zoning.

Mineral abbreviations see Table 3 and Fig. 6.

<sup>a</sup> In local zones (usually in the lowest horizons) up to upper greenschist facies.

metamorphism with  $t = 150\text{--}300\text{ }^{\circ}\text{C}$  (up to  $400\text{ }^{\circ}\text{C}$ ) and  $P = 0.5\text{--}2\text{ kbar}$  (Table 6, Fig. 2).

Orogenic metamorphism occurs in shear zones as coupled dynamic and thermal effects and it commonly corresponds to greenschist facies. The metamorphic mineral assemblages mainly evolve correspondingly to  $25\text{--}50\text{ }^{\circ}\text{C}/\text{km}$  gradient (Fig. 2). The metamorphic grade ( $t = 250\text{--}450\text{ }^{\circ}\text{C}$  and  $P = 1\text{--}5\text{ kbar}$ ) is greater inside the major shear zones (Table 6, Fig. 2). The parageneses of actinolite, biotite, epidote, oligoclase and muscovite ( $\pm$  zoisite, andalusite, kyanite, garnet, staurolite, and spinel) occur in some shear zones, mainly in the Karabash area. The epidote-amphibolite (up to amphibolite facies) metamorphism took place at  $t = 400\text{--}600\text{ }^{\circ}\text{C}$  (up to  $700\text{ }^{\circ}\text{C}$ ) and  $P = 1\text{--}6\text{ kbar}$  (Vikentyev, 1995b). In the Middle Urals, most deposits are characterised by NS-trending steep to nearly vertical structures and some of them are hosted by the major shear zones (Krasnogvardeiskoe, San-Donato, Degtyarsk and many others deposits). In the South Urals, the deposits are hosted in low-grade metamorphosed rocks (most of the VMS deposits), located within the minor shear zones (Uchaly, Alexandrinskoe, Sibai, Uvaryazh, Makan, Gai, Dzhusinskoe and Priorskoe deposits), or in the minor shear zone near large granite pluton (Tash-Yar deposit as well as, in the North Urals, Tarnyer deposit).

Contact metamorphism mainly corresponds to the greenschist and albite-epidote-hornfels facies in the aureoles of medium-sized plagiogranite and gabbro-plagiogranite massifs (Krasnogvardeiskoe, Kaban and Zyuzelka deposits), with  $t = 250\text{--}450\text{ }^{\circ}\text{C}$ , gradient range of  $50\text{--}100\text{ }^{\circ}\text{C}/\text{km}$  and  $P = 1\text{--}4\text{ kb}$  (Fig. 12, Table 9). The hornblende-hornfels and pyroxene-hornfels facies metamorphism near large granite and granodiorite plutons (Koktau, Tarnyer, Tash-Yar and Vesenneye deposits) took place at  $t = 400\text{--}700\text{ }^{\circ}\text{C}$  (up to  $850\text{ }^{\circ}\text{C}$ ) and  $P = 1\text{--}6\text{ kbar}$ . Massive and semi-massive ores were changed into coarse-grained and pegmatoidal, as well as coarse porphyroblastic ones, although relics of primary textures may survive locally even under high-grade thermal metamorphism (e.g., Koktau and Tash-Yar). The massive and semi-massive sulphide orebodies are zoned in relation to the granitoid massif: the magnetite-pyrite mineralisation occurs near the contact, changing into pyrrhotite/pyrite and copper-rich ores, whereas zinc ( $\pm$  Pb, Ag) mineralisation is located distal to the granite pluton (Prokin and Buslaev, 1999).

Very local, dyke-related contact metamorphism was documented for the Dzhusinskoe, Levikha, Letneye, Uzelga, Sibai and Uchaly deposits (Yakovlev, 1959; Eremin and Kogan, 1964; Borodaevskaya et al., 1967; Pshenichny and Kulagina, 1968; Ismagilov and Poluekov, 1978; Pshenichny, 1984; Seravkin, 1994; Vikentyev et al., 2004). The local contact processes took place at  $t = 250\text{--}500\text{ }^{\circ}\text{C}$  (up to  $700\text{ }^{\circ}\text{C}$ ) and  $P = 1\text{--}4\text{ kbar}$  (Fig. 12; Table 10). The local thermal effects of gabbroic dykes on massive sulphide ores resulted in partial melting of sulphides (Stevenson, 1937; Brett and Kullerud, 1967; Mookherjee, 1970; Kovalev, 1975; Demin and Sergeeva, 1981; Sakiya et al., 1983; Eremin et al., 1987). Ore xenoliths were reported in some dykes, although the most common contact influence of the dykes is expressed by sulphide recrystallisation and the appearance of atypical assemblages of magnetite, pyrrhotite, cubanite and, sometimes, hematite.

### 6.3. Metamorphogenic geochemical zoning

The differential remobilisation of sulphides in deformed and metamorphosed orebodies has been described in the literature (Lawrence, 1967; McDonald, 1967; Vokes, 1971; Pedersen, 1980; Marshall et al., 2000). Metamorphic redistribution of ore-bearing components manifested itself at different scales (Table 1): from mineral grains, expressed as recrystallisation or segregation, redistribution of trace elements in sulphides and sulphosalts, appearance of neoblasts of ore and gangue minerals in ore, and the formation of banded and gneissic structures of tectonic flow through to the deposit and regional scales (Vikentyev et al., 2016).

Remobilisation takes place in response to mechanical and chemical disequilibria, which have been established as a result of nonhydrostatic stress during deformation of the orebody at elevated temperatures (Stephansson, 1974). The ore material in most cases is transferred from high-pressure to low-pressure areas, resulting in formation of characteristic structures, such as coarse-grained sulphides in pressure shadows between boundins, thickened fold hinges and sulphide infillings in tension fractures (Pedersen, 1980; De Lorraine and Dill, 1982; Vikentyev, 1987; Marshall et al., 2000). As a rule, the metal grades of VMS ores increase from weakly to highly dynamo-metamorphosed deposits, because of a decrease in the amount of gangue quartz and carbonates and almost complete removal of baryte due to their preferential dissolution under pressure in the zones of compression and intense shear deformation (Vikentyev, 1987; Starostin et al., 1989).

Primary and imposed geochemical zoning can be still distinguished in the orebodies in shear zones (Krivtsov et al., 1979; Baranov, 1987; Smirnov, 1988). The primary (syngenetic) zoning is preserved in the weakly affected VMS deposits and is expressed as a decrease in the Cu/Zn ratio (or  $\text{Cu}/(\text{Pb}+\text{Zn})$ ) from the base to the top of the orebody (Baranov, 1987; Vikentyev, 2004). This is the case for the Yubileynoe, Podolskoe, Molodeznoe and Shemur deposits. These gently dipping orebodies are characterised by pyrite enrichment at the base, whereas pyrite ore is replaced by chalcopyrite-pyrite and sphalerite-chalcopyrite-pyrite ores upward and towards the flanks (Smirnov, 1988). This type of zoning is common in other VMS deposits worldwide (Large, 1977; Franklin et al., 1981, 2005). However, this type of zoning is absent in the most low-grade metamorphosed Galkinskoe, Komsomolskoe and Kundyzy deposits (Smirnov, 1988; Vikentyev, 2015), and the reasons for this are unclear. The pyrite ore comprises the top and flanks of the weakly-metamorphosed Chebache orebody (Smirnov, 1988), whereas polymetallic geochemical halos can be traced in the hanging wall for  $200\text{--}300\text{ m}$  above the orebody that is also typical for many other weakly and moderately deformed deposits of the Urals type (Ivanov and Prokin, 1992).

Secondary (newly formed) zoning is expressed by a change of chemical composition in vertical section through the steeply-dipping orebodies (Loginov, 1974; Baranov, 1987; Smirnov, 1988). The redistribution of metals inside the orebody occurred under subvertical temperature gradient simultaneously with deformation. It resulted in reduction of base metal (Zn, Cu  $\pm$  Pb) grades and increase of the copper proportion ( $\text{Cu}/(\text{Zn} + \text{Pb})$ ) with depth for steeply-dipping small to medium-sized ore lenses and sheets (Ovchinnikov and Zhabin, 1977; Krivtsov et al., 1979; Prokin and Buslaev, 1999; Prokin et al., 2004). The zoning in the vertical section is typical of steeply-dipping deposits, located in the shear zones, such as San-Donato, Andreyevskoe (Krasnouralsk group), Ezhovskoe and Olkhovka deposits of the Middle Urals. During metamorphism Zn, Pb, Ag and, in part, Cu were transferred from the lower parts of the steeply-dipping bodies towards the uppermost part of the shear zones; Mo and Co were immobile elements (Ivanov and Prokin, 1992). The final transverse zoning of the steeply-dipping bodies showed a near symmetric pattern. Redeposition of ore minerals also may occur in sheared host rocks, as, for example, at the Degtyarsk and Olkhovka deposits (Ivanov and Prokin, 1992).

Metamorphic redistribution of base metals is well documented for the Novo-Sibai orebody of the Sibai deposit, one of the largest single massive sulphide bodies in the Urals (112 Mt ore with  $\sim 2.9\text{ Mt}$  Cu + Zn). The Central pyrite-rich part of the lenticular orebody was found to be significantly depleted in base metals with respect to the upper and lower parts, as well as the marginal parts, enriched in re-deposited Cu and Zn (Fig. 20) (Ivanov and Prokin, 1992; Prokin and Buslaev, 1999). The contact zones of the Cu-pyrite Letneye deposit are enriched in sphalerite (Smirnov, 1988).

The regional scale metamorphic zoning is most prominent in the northern part of the Magnitogorsk zone. The intensity of deformation in massive sulphide bodies and their host rocks increases northwards within the Uchaly-Alexandrinskoe ore zone, approaching the latitudinal

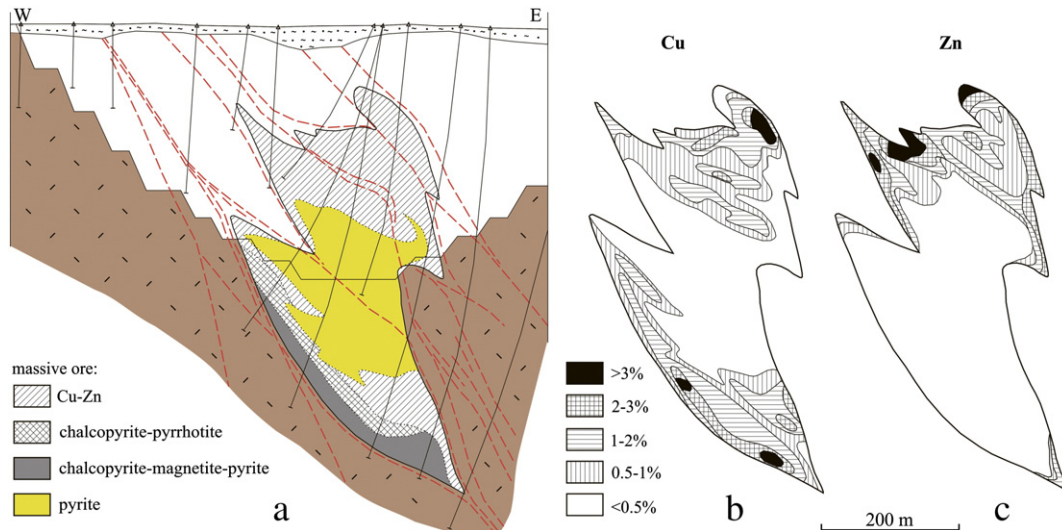


Fig. 20. Cross-section of the Sibai deposit: New Sibai orebody (a) and distribution of Cu (b) and Zn (c) (simplified after Smirnov, 1988; Prokin and Buslaev, 1999).

transform zone of the regional compression, with the highest grade of metamorphism near the Ufa promontory. The metamorphic grade increases from south to north up to the greenschist and higher facies. The morphology of the orebodies evolves in the same direction from the gentle thick lenses (Alexandrinskoe deposit and ones of the Uzelga ore field) to subvertical lenses (Uchaly and Novo-Uchaly) and to pseudomonoclinally steeply-dipping sheets in the Karabash area. This correlates with an increase in the proportions of sulphides in ores from zeolite to amphibolite facies, as well as in the total ore reserves from the zeolite to greenschist facies, although large accumulations of sulphide are absent in areas metamorphosed to the epidote-amphibolite and amphibolite facies.

Concentrations of Cu and, especially, Ag, Pb and Ba relative to Zn in the ores decrease as metamorphic grade increases from south to north in this region; it also correlates with a decrease in the Sb/As ratio (Vikent'ev et al., 2000). It was probably caused by the differential mobility of elements during dynamo-thermal metamorphism, with Pb, Ba, Cu, Sb and Ag being relatively mobile, whereas Zn and As were essentially immobile (Vikent'ev, 1995a,b; cf., Pedersen, 1980). It looks like that the mobility of the ore elements closely correlates with the relative

ductility of their host minerals under strain following the order from least mobile pyrite to sphalerite and chalcopyrite and up to most mobile galena and tennantite-tetrahedrite (Ramdohr, 1928; Clark and Kelly, 1973). The irregular patterns of the geochemical zoning, such as that in the Main orebody of the Uchaly deposit (Seravkin, 1994; Ivanov and Prokin, 1992), can be a consequence of the complex history of hydrothermal redeposition and metamorphic recrystallisation.

The vertical metamorphic ore zoning is well expressed in the steeply-dipping Krasnogvardeiskoe deposit, the largest in the Krasnouralsk ore field (Minina and Tryakina, 1979; Prokin and Buslaev, 1999). The upper part of the sheet-like orebody is composed of Cu and Cu-Zn ores, whereas at a depth of 450–700 m the ore is mainly pyritic, whereas pyrrhotite and magnetite ores occur in the deepest parts of the deposit at depths of 700 to 920 m (Fig. 21). The individual ore lenses are also zoned: the upper parts of the ore lenses and ribbons are enriched in Cu and Zn, but with increasing depth, the grade of these metals decreases and Cu-Zn ore gives way to pyrite ore. Upward, synmetamorphic redeposition of metals is highlighted in replacement of chalcopyrite and sphalerite by gangue minerals in the deepest parts of the orebodies and the replacement of host rocks by these sulphides in their upper parts (Prokin and Buslaev,

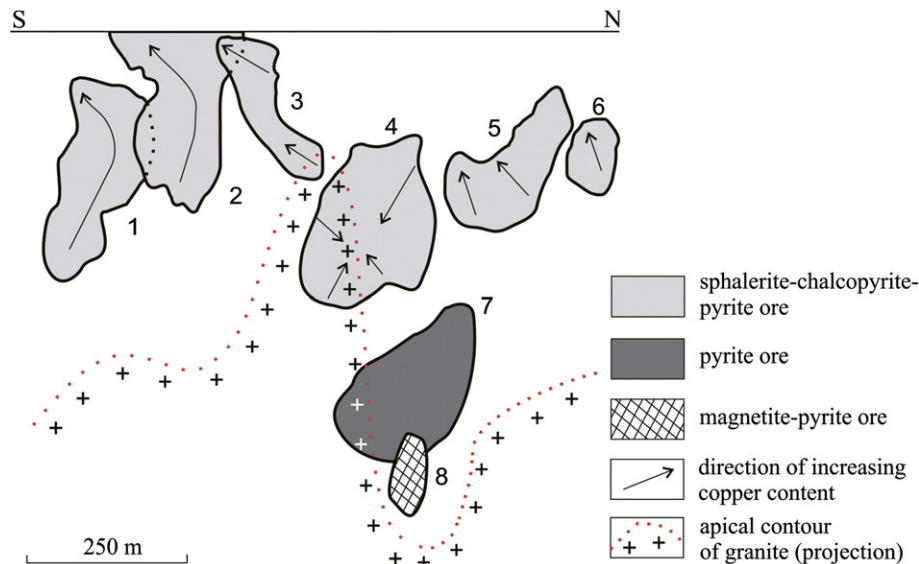


Fig. 21. Long vertical projection of the Krasnogvardeiskoe deposit (after Minina and Tryakina, 1979). Hatched line shows an outline of plagiogranite. Orebodies: (1) Second Southern, (2) Main, (3) Large Northern, (4) First Northern, (5) Second Northern, (6) Third Northern, (7) Lower Pyritic, (8) Magnetitic.

1999). The geochemical halo of the Krasnogvardeiskoe deposit has a rather symmetrical pattern relative to the orebodies (Ivanov and Prokin, 1992), whereas the geochemical haloes are commonly asymmetrical in the low-grade metamorphosed deposits of the South Urals (Baranov et al., 1988). It was suggested that part of the mobilised base metals together with gold was redeposited in the gold-polymetallic veins and lenses of disseminated sulphides, forming the Bogomolovskoe gold deposit near the Krasnogvardeiskoe VMS deposit or similar small gold deposits in the north of the Uchaly ore field (Sazonov et al., 2001; Znamensky and Znamenskaya, 2009; Kisters et al., 1999).

Likely, gold and silver were also metamorphically redistributed, however this issue has not been well studied for VMS deposits in the Urals (Vikentyev, 2015). However, systematic sampling across the Gai deposit (Fig. 22) shows a dramatic zonation in Au and Ag across the strike and along the dip of the orebodies.

The redeposition of synvolcanic sulphides and redistribution of base metals near the granite intrusions or dykes occurred mainly in the Late Silurian to Early Devonian in the Tagil zone or in the Early Permian in the Magnitogorsk zone (Bea et al., 2002; Fershtater et al., 2007; Fershtater, 2013). These processes resulted in formation of extensive (over hundreds of metres) lateral geochemical zonation (Cu → Zn → Pb, Ag) relative to the contact in accordance with the palaeotemperature gradient.

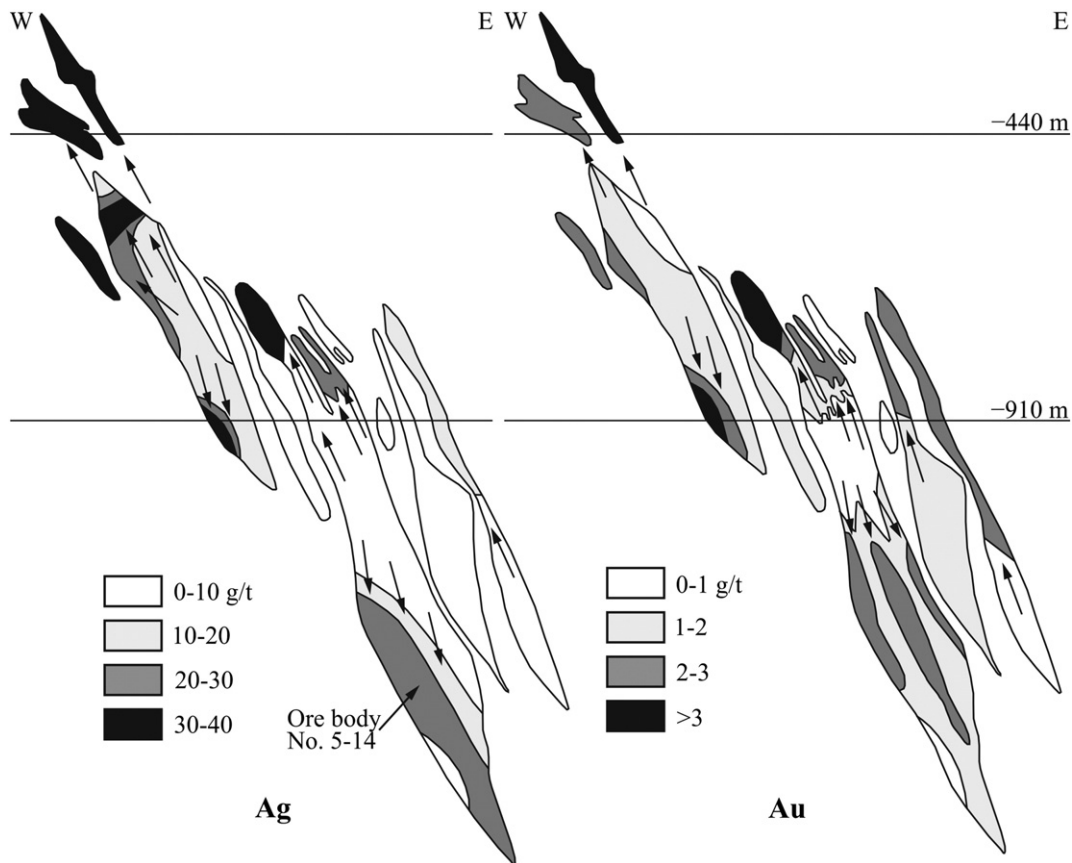
Lead, silver, and partly zinc were remobilised from ores and transported away from deep-seated granite to be redeposited in the upper parts of the steep orebodies (Ivanov and Prokin, 1992). Symmetric zonation was found in the schist zone-hosted massive sulphide deposits, strongly thermally affected by the plagiogranite intrusions as, for example, in the Krasnogvardeiskoe deposit. The geochemical haloes of anomalous Co, Bi, Ba, and Sn tend to be confined to the central part of the shear zone, whereas Mo, Zn, Pb, and Ag haloes occur in its periphery

(Ivanov and Prokin, 1992). In the Tarnyer deposit, Cu-rich ore occurs further away from the contact with the granite intrusion and sphalerite-pyrrhotite with minor chalcopyrite ores occupy the lowest part of ore body No 5 situated nearest with the diorite intrusion at South-West of the deposit (Smirnov, 1988).

#### 6.4. Synmetamorphic ore remobilisation

In the 1940s, Zavaritsky (1941, 1943) noticed a relative copper (and, occasionally, zinc) enrichment in the thin peripheral parts of the ore lenses in the Degtyarsk and other deposits in the Middle Urals, with proportions of sphalerite and chalcopyrite increasing towards the margins of the orebody (Fig. 9). He concluded that migration and redeposition of base metals during metamorphism led to the redistribution of metals in the orebody. Remobilisation of sulphide ores is commonly generated by metamorphic processes in the shear zones (cf., “daughter” orebodies, De Lorraine and Dill, 1982), and they are rarely associated with large magmatic intrusions. New ore mineralisation (“remobilisates”) is deposited in the uppermost parts of large steeply-dipping massive sulphide lenses within the tectonic zones (e.g., Gai deposit, Fig. 22) and may occur as disseminated gold-bearing sulphide bodies near large metamorphosed VMS lenses far away from the granite pluton, as in the Tarnyer deposit. They are formed at relatively moderate T-P conditions, commonly during the retrograde stage of the major tectonometamorphic event.

The large metamorphic veins in the Karabash area, as well as the large bornite-bearing Main orebody of the Gai deposit are metamorphogenic in origin (Smirnov, 1988). In both cases, Cu-rich and Au-rich massive sulphide ores are pyrite-poor and enriched in bornite and tennantite. The bornite ore type is confined to major tectonic zones in the Valentor and San-Donato deposits as well as in the South



**Fig. 22.** Geochemical zoning of ore bodies of the Gai deposit with Au and Ag distribution in section 115 (in g/t, based on data of Gai mine, redrawn from Vikent'ev et al., 2006b and Seravkin and Skuratov, 2009), position of this section see on Fig. 7. Arrows indicate probable direction of synmetamorphic migration of the metals, mainly upward, from synvolcanic sulphides. Apex parts of ore lenses are especially enriched in Au and Ag, thin-out and outer zones of ore bodies are commonly richer than their inner, central parts which are consist of mainly pyritic ores with low concentrations of precious metals. Please note that the biggest ore body No. 5–14 (40% of total Gai deposit reserves) is in the centre and bottom of the figure.

Urals, in the Molodezhnoe, Podolskoe, Blyava and Gai deposits (Moloshag et al., 2005; Ivanov and Prokin, 1992).

As for the South Urals, metamorphic redistribution of chemical elements is most obvious in the Gai and Tash-Yar deposits, but it still remains controversial for other VMS deposits (Baranov, 1987; Smirnov, 1988; Ivanov and Prokin, 1992). Alternative suggestions by Maslennikov (1999), consider the base metal enrichment at the thin margins of the orebodies was synvolcanic and mostly due to halmyrolysis, i.e., the interaction of sulphide mound material with sea water although the details of the process and the reasons for the directed migration of chemical elements are not explained.

Selective remobilisation of polymetallic sulphides left large amounts of pyrite as the restite, as appears to be the case for the formation of a thick centrally located large pyrite lens in the Degtyarsk deposit (Fig. 9), or a few such lenses inside of the large orebodies of the Gai deposit (Fig. 7). Other examples include the stratigraphic lowest lenses or lowest parts of a large lens, composed of pyrite and pyrrhotite in the Uzelga, Letneye and Krasnogvardeiskoe deposits, as well as pyrite and magnetite in the Letneye, Krasnogvardeiskoe, Priorskoe and Sibai deposits (Smirnov, 1985, 1988; Prokin and Buslaev, 1999; cf., Pedersen, 1980).

The metamorphogenic Kuznechikha Cu-Zn-Ba orebody is a vein, which generally follows the orientation of minor folds in the host schist, although in some places it is confined to a fault. Locally, the vein may cross-cut the hinges of the folds. However, in most places the contacts of the vein are conformable to the fold hinges, even if they display an overturned and drag fold morphology. The Cu-Zn-Ba vein is composed of breccia, with fragments of host schist, massive sulphide ore, quartz and rare fragments of garnet (cf., *Durchbewegung structure*, Vokes, 1969). It is thought that polymetallic mineralisation was formed during the retrograde stage of metamorphism, and the hydrothermal process terminated with the deposition of minor amounts of cinnabar (Rakcheev, 1956).

Under influence of the plagiogranite intrusion, Cu, Zn, Cd, As and Ag were remobilised from the root parts to the upper parts of the steeply-dipping ore lenses and formed monomineral chalcopryrite and sphalerite accumulations at the top in the Zavodinskoe deposit in the Krasnouralsk ore field (Ivanov and Prokin, 1992). Gold was also remobilised from the massive sulphide orebodies and redeposited as Au-sulphide disseminated bodies near these lenses, away from a granite pluton (Tarnyer deposit, Fig. 13).

Partial melting of sulphide material, containing As, Sb, Pb, Te, Se, Bi and Au, occurred in the zones of the highest-grade dynamic metamorphism (Mauk and Kuznechikha) and in cases of extensive thermal influence of large granite massifs (Koktau, Tarnyer, and Kaban deposits) (Vikentyev et al., 2016) or thick dykes (Gai, Sibai, Uchaly, and Alexandrinskoe deposits; Starostin, 1964; Vorobyov, 1995, Novoselov, 2002; Vikentyev, 2015). Partial melting of sulphides in these deposits seems likely in view of the relatively high temperatures attained during the metamorphism. The thermal peak was estimated to be 600° to 850 °C, which is near or above the experimentally eutectic temperature of the system Fe-Pb-S (716 °C; Brett and Kullerud, 1967). The melting began in the Fe-Cu-Pb sulphide system at 508 °C (Craig and Kullerud, 1968, for discussion see Stevens et al., 2005).

Probability of partial melting for some mentioned extremely metamorphosed VMS deposits of the Urals is suggested by the following:

- (1) evaluation of the peak metamorphism temperature by silicate minerals indicates values between 550° and 850 °C (Buslaev et al., 1988a,b; Tables 6, 9, 10) that exceed the melting point of Bi, Au, and Te minerals and some sulphides (Tomkins et al., 2007);
- (2) Lead-, Bi-, Te- and Ag-minerals occur as polymineral ( $\pm$  chalcopryrite,  $\pm$  sphalerite,  $\pm$  pyrrhotite) drop-like inclusions (up to 100  $\mu$ m) in pyrite, droplets consist of 1 to 5 minerals (Safina et al., 2015a,b; Vikentyev et al., 2016). The presence of the assemblages of bismuth minerals and Au-Ag-tellurides in the assemblages of separate drop-like inclusions is considered by Ciobanu et al.

(2006) as an indicator of crystallisation from relatively low-temperature melt; occurrences of such mineral assemblages and possible melting for Tarnyer deposit is discussed by Belogub et al. (2011);

- (3) Galena and chalcopryrite together with the titanium oxide form spheroidal inclusions with a lattice internal structure within thick mafic dyke of the Alexandrinskoe deposit. Such structures are likely to be a result of decomposition of the solid solution from partially melted ore xenoliths (Vikentyev et al., 2016). Similar textures as well as subgraphic, symplectitic, eutectic, mosaic, lattice fabrics, with participation of galena, tennantite, chalcopryrite, bornite, sphalerite, pyrite in different relationships, occur in ore xenoliths and ore bodies locally contact-metamorphosed near thick dykes, e.g. Gai (Starostin, 1964), Uchaly (Vikentyev et al., 2016), Sibai (Vorobyov, 1995) or large granitoid massifs, e.g. Koktau, Kaban (Filimonova, 1949; Vikentyev et al., 2016).

Recently, the hypothesis of migration of sulphide material in relatively low-temperature polymetallic melts, containing Bi, Au, As, Sb, Pb and Te, became popular (Ciobanu et al., 2006; Tomkins et al., 2007; Belogub et al., 2011; Novoselov et al., 2013; Tomkins, 2013; Vikentyeva and Bortnikov, 2015). Participation of sulphide melt in VMS transformation in the shear zones has long been considered by researchers of Rudny Altai for the migration of sulphide matter over a distance of tens of metres (Starostin et al., 1989).

The late Alpine-type veins and veinlets (Zavaritsky, 1936, 1941) are also classified as metamorphogenic mineralisation. They are usually composed of low-Fe sphalerite, chalcopryrite and tennantite-tetrahedrite (Zavaritsky, 1941; Shadlun, 1950; Prokin and Buslaev, 1999). Such veins occur in many VMS deposits of the Middle Urals, such as the Karabash group and the above-described Kuznechikha or small Sukhoviyazovo deposit, where the veins consist predominantly of galena, with subordinate sphalerite and chalcopryrite (Rakcheev, 1962). The gangue minerals are mostly quartz, carbonate or baryte, but they may be absent in high strain areas. The polymetallic veins are generally accompanied by numerous gold-bearing quartz-carbonate veins and veinlets containing tourmaline, phlogopite, baryte, anhydrite, gypsum, base metal sulphides, and rare axinite. The veins can be often traced far beyond the VMS-bearing zones as, for example, monomineral low-Fe sphalerite veins were reported in the hanging wall of the Shaitanskoe deposit that was interpreted to have formed due to the zinc remobilisation from primary ore (Smirnov, 1988).

A prograde stage of each tectonometamorphic cycle begins with folding and formation of the faults, when ductile flow and deformation of massive sulphide ores dominate. During the metamorphic peak and during the beginning of the subsequent retrograde stage, remobilisation of ductile sulphides (chalcopryrite, tennantite, sphalerite  $\pm$  galena, minor electrum and tellurides) is accompanied by fluidal and diffusive transfer of components towards low strain areas, such as the outer parts of a shear zone, an uppermost termination of steeply-dipping ore lenses, pressure shadow zones, hinge zones of minor folds and small extension fractures in the quartz-rich ore boudins. Under peak metamorphic conditions, with increasing temperature and decreasing deformation rates, partial melting and metal diffusion, including diffusion through the intergranular fluid-saturated space, occur and is followed by hydrothermal transport of metals by concentrated chloride solutions during the retrograde stage (Vikent'ev, 1995b). The cycle was terminated by a stage of brittle deformation with formation of late fractures and Alpine-type veins.

#### 6.5. Correlation of tectonic events and ages of metamorphism in the VMS zones of the Urals

The U-Pb ages for zircons dating the Palaeozoic metamorphic events in the Tagil and Magnitogorsk zones (Puchkov, 1997; Petrov et al., 2008

etc.) and for arc-related and syncollisional diorites and granites (Fershtater et al., 1997, 2007; Grabezhev, 2014) fall into several clusters. The first significant metamorphic event for different parts of the Tagil zone corresponds to 418–388 Ma. In the Emsian times, a significant gap in sedimentation is recorded in the Tagil zone (Shub, 1983; Mikhailov, 1987). This is reflected in the Rb-Sr ages of  $395 \pm 12$  and  $397 \pm 8$  Ma for epidote-amphibolite metamorphism in the Khobeyiz metamorphic complex of the Tagil zone (Yudovich et al., 1995). Dating of metamorphism of Kempirsai ophiolites in the South Urals also yielded  $397 \pm 20$  Ma (Edwards and Wasserburg, 1985). The retrograde metamorphic evolution of the Khabarninsky mafic-ultramafic complex in the Sakmara allochthon of the Tagil zone progressed from granulite ( $t = 850\text{--}750$  °C,  $P = 7\text{--}5$  kbar) to amphibolite and, finally, to epidote-amphibolite facies ( $t = 650\text{--}450$  °C,  $P = 3\text{--}4$  kbar) (Pushkarev et al., 2009). The age of amphibolite metamorphism (398–390 Ma) is distinctly younger than that of the granulite metamorphism (423–410 Ma). This *pre-Eifelian event* (Petrov and Svyazhina, 2006) for the Urals closely corresponds to the Acadian epoch of tectonic deformation and metamorphism at 419–400 Ma, which corresponds to metamorphic ages in the Scandinavian and Scottish Caledonides (Milnes et al., 1997; Mendum, 2012) (Table 11).

The first deformational event in the Magnitogorsk zone can be attributed to the period between 378 and 360 Ma (*Late Devonian event*, Puchkov, 1996). It was the most substantial “all-Uralian” episode of high-pressure eclogite-glaucophane metamorphism recorded in the  $^{40}\text{Ar}/^{39}\text{Ar}$ , U-Pb and Sm-Nd isotopic age data from the MUF zone (~370 Ma; Yazeva and Bochkarev, 1996; Ivanov, 1998; Petrov et al., 2008; Puchkov, 2010, and 380–372; Beane and Connelly, 2000). Probably, the VMS deposits in the MUF experienced dynamic metamorphism during this period (Mauk, Derdamysh, Ishkinino, Yuluk deposits). It is confirmed by Re-Os age of  $366 \pm 2$  Ma for Dergamysh deposit (Gannoun et al., 2003). Deformation and metamorphism of other deposits, probably, were less significant, although sericite from the quartz-sericite schist of the Gai deposit was K-Ar dated at  $376 \pm 13$  Ma (Buslaev and Kaleganov, 1992). Re-Os dating of sulphides (Tessalina et al., 2017) revealed similar  $362 \pm 9$  Ma ages for unmetamorphosed Late Ordovician Yaman-Kasy deposit located in the Sakmara allochthon, as well as for weakly and moderately metamorphosed Kul-Yurt-Tau ( $363 \pm 1$  Ma) and Alexandrinskoe deposits ( $355 \pm 15$  Ma). These Re-Os ages of ore mineralisation are ca. 80 m.y. younger than the hosting stratigraphic units of Late Ordovician to Early Silurian age (ca. 440 Ma) and 40 to 30 m.y. younger than hosting Early and Middle Devonian (ca. 400 and 390 Ma) stratigraphic units, respectively. The first generation of arc-related granites intruded the MUF zone and the Magnitogorsk zone between 365 and 362 Ma (Fershtater et al., 1997; Gorozhanin, 1998). HT/HP gneiss complexes formed between 372 and 367 Ma (Petrov et al., 2008 and references therein) that generally corresponds to the relatively short interval from the mid-Frasnian to the mid-Famennian.

The processes of the Early Carboniferous accretion correspond to the Tournaisian – mid-Visean (Yazeva and Bochkarev, 1996). Based on the K-Ar isotope data on sericite from deformed massive sulphide ore at the San-Donato (350–335 Ma), Levikha (340 Ma), and Gai ( $347 \pm 10$  Ma) deposits (Buslaev and Kaleganov, 1992; Prokin and Buslaev,

1999), as well as on the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for sericites from the early Eifelian Barsuchiy Log deposit ( $344.7 \pm 2.0$  Ma and  $344.8 \pm 2.9$  Ma) and for late Eifelian Babaryk deposit ( $340 \pm 7$  Ma) (Tessalina et al., 2017), this interval can be constrained between 348 and 335 Ma, corresponding to the late Tournaisian – mid-Visean (*Tournaisian-Visean event*, Puchkov, 2000).

The next intense and most important deformational event in the Urals known as the continent/continent “*Permian hypercollision*” (Yazeva and Bochkarev, 1998) occurred at about 300 Ma, i.e., near the Carboniferous/Permian boundary. This interval (313–288 Ma) embraces various dated events including a hiatus in sedimentation and the formation of the weathering crusts in the Urals (Shub, 1983; Mikhailov, 1987), emplacement of collisional granites in the South Urals (Fershtater et al., 2007), and formation of the Dzhabyk gneiss complex (Görz et al., 2004). Most geologists correlate this period with “rigid” collision between the East European craton and the Kazakh Palaeozoic terranes, which is a major orogenic event in the Urals (Puchkov, 2010). The K-Ar dating of metamorphic sericite yielded 310–288 Ma for some massive sulphide deposits in the shear zones (Ivanov and Prokin, 1992). During this time interval, the high-grade metamorphic transformations took place within the major shear zones, accompanied by low P/T facies contact metamorphism (Spear, 1993), due to the influence of large syncollision granite plutons in the Urals. This was probably the main tectonic deformation, high-grade metamorphic and ore remobilisation event, which included partial melting and ore redeposition. The peak metamorphism might have led to escape of metals from the VMS bodies up to the complete destruction of small ore deposits. This may explain presence of numerous small deposits and only one large deposit (Degtyarsk) in the stronger metamorphosed middle segment of the Urals relative to the southern Urals (Ivanov and Prokin, 1992).

Unfortunately, dating of metamorphic events for massive sulphide deposits in the Urals largely relied on the dating of metamorphic sericite by K-Ar method. Therefore, more precise dating of polychronous deformations and metamorphism of VMS ores needs to be done to better constrain metamorphic ages.

## 7. Conclusions

1. Most VMS deposits in the Urals were deformed and subjected to contact and/or dynamo-thermal metamorphism on the regional or local scales. The VMS deposits of the Middle Urals were polychronously deformed at 200–450 °C and to moderate pressures. Only a small number of VMS deposits in the Urals can be classified as unmetamorphosed or metamorphosed at the zeolite facies of metamorphism (Yaman-Kasy, Komsomolskoe, Kundyzy and Galkinskoe).
2. *Regional metamorphism* in the Urals broadly covers zeolite to amphibolite facies conditions. Burial metamorphism of VMS deposits mostly corresponds to the prehnite-pumpellyite and lower greenschist facies, with quartz, albite, chlorite, sericite, epidote, calcite, prehnite and pumpellyite as major metamorphic minerals in volcanic rocks. The majority of deposits, metamorphosed at the greenschist facies (and all ones of higher levels) show evidence of significant dynamo-metamorphic modifications that are expressed

**Table 11**  
Synthesis of tectonic-metamorphic events for the oceanic and arc-related VMS-bearing complexes of the Urals.

Laurussia		Urals		
Tectonic-metamorphic event	Age	Geodynamic stage <sup>a</sup>	Tectonic-metamorphic event	Approximate age <sup>b</sup> , Ma
Acadian (proto-Variscan)	Mid-Devonian	Island arc	pre-Eifelian event	418–388
Variscan orogeny	Breton	Late Devonian	Late Devonian event	378–360
	Sudetian	end of Early-Carboniferous – Mid-Carboniferous	Early Carboniferous (Tournaisian-Visean) event	348–335
	Saalian	Late-Carboniferous – Early Permian	Perm hypercollision	313–288

<sup>a</sup> After Puchkov (2017).

<sup>b</sup> See text for discussion and refs.

as steeply-dipping, folded, flattened, pinch and swell geometry of the ore bodies. Some deposits were highly reworked in the epidote-amphibolite and amphibolite facies by orogenic metamorphism (such as the Karabash group, Mauk and Kuznechikha deposits).

3. Lateral metamorphic zoning is recorded along the Tagil and Magnitogorsk zones. In general, the metamorphic grade of the Devonian volcano-sedimentary complexes increases from south to north in the northern part of the Magnitogorsk zone. The zeolite and prehnite-pumpellyite facies are common in the south, but from the Uchaly region northward the grade of regional metamorphism reaches the epidote-amphibolite and amphibolite facies. The highest metamorphic grade corresponds to the latitudinal Trans-Urals compression zone at its junction with the Ufa promontory. The correlation between the increase in intensity of deformation in the massive sulphide orebodies, in a northern direction, and an increase in the metamorphic grade of their host rocks is apparent. The gentle and thick ore lenses, typical of the VMS deposits of the South Urals, are not found in the Uchaly and Karabash ore districts. Instead, the steeply-dipping, more flattened ore sheets and NS-trending sulphide veins, both much smaller in size, are common in the Karabash and Kuznechikha ore fields.
4. The dynamo-metamorphic effects, coupling with thermal effect mostly ranging from prehnite-pumpellyite to greenschist facies, are unevenly displayed in major shear zones of the Middle Urals and within the local zones of the South Urals. The age of collisional processes, accompanied by formation of large granitoid massifs, corresponds to discrete episodes with a major peak at 300–295 Ma. The dynamically metamorphosed VMS deposits typically form steep pseudomonoclines that host tabular and lenticular orebodies. The tectonic movements and strain led to the formation of gneissic and schistose textures, both in host rocks, especially in hydrothermally-altered ones, and in massive sulphide ores. The orebodies possess steeply-dipping apophyses and bulges, with obtuse terminations. Generally, mineralisation in the shear zones is richer in base metals and contains smaller proportions of quartz and baryte with respect to mineralisation of the undisturbed deposits. This seems to be caused by pressure-induced dissolution of the gangue minerals and their redeposition outside the schistose zones. The highest gold content (~2–5 g/t and higher) occurs in the uppermost and peripheral parts of the large steeply-dipping VMS lenses and in the small ribbon-like or vein-like orebodies developed in the hanging and foot walls of the major ore zone.
5. The most prominent features of the effects of metamorphism on the VMS deposits are modification of the orebody morphology, transformation of the ore textures towards the dominance of linear and planar fabrics, and the selective changes of the mineral composition of ores with crystallisation of the gangue and ore mineral neoblasts. The geometry of individual ore lenses evolved in the direction of preferential growth of their length, with their thickness being reduced, resulting in formation of the flattened and ribbon-like orebodies. The bulges and apophyses appear due to mechanical protrusion and accompanying diffusion-hydrothermal redistribution of sulphides.
6. Significant modifications were found in the contact metamorphosed deposits, where the Koktau and Tarnyer deposits are the best examples of the regional contact transformation, i.e., contact metamorphism in relation to large granitoid plutons. The Letneye and Dzhusinskoe deposits are representative of more local, dyke-related, contact metamorphism. During contact metamorphism, host rocks were metamorphosed up to the hornblende-hornfels and pyroxene-hornfels facies. Massive and semi-massive sulphide ores are modified, through recrystallisation and remobilisation, into coarse- and giant-grained, porphyroblast, and pegmatoidal, “skarn-like” aggregates, although such thermal metamorphism has locally left relics of primary fabrics in these ores (Koktau deposit).
7. In some regional and local shear zones (Kaban, Krasnouralsk, Levikha and Karabash ore fields, Tarnyer, Zyuzelskoe, Kuznechikha and Tash-

Yar deposits), intense dynamo-thermal metamorphism was accompanied by contact metamorphic changes, which were caused by large plagiogranite or granodiorite plutons. The superposition of the dynamic and contact types of metamorphism resulted in folding and boudinage of the sulphide bodies, as well as in the development of the zonal geochemical pattern in the steeply-dipping remobilised orebodies, commonly with complete obliteration of the primary geochemical zoning. We argue that smaller reserves in the higher metamorphosed Silurian VMS deposits of the Tagil zone in comparison with much larger Devonian VMS deposits in the Magnitogorsk zone caused by partial dispersion of “Silurian” ore matter due to dynamo-thermal metamorphism in the shear zones and contact metamorphism in the thermal aureoles of the plagiogranite plutons.

8. The mechanism of sulphide remobilisation is interpreted to be a combination of mechanical deformation, fluid transport and, in some cases, partial melting of sulphides and metal scavenging by polymetallic Bi-bearing sulphide melt. Ductile flow of massive sulphides was dominant during the prograde stage of tectonometamorphic cycle. Metal diffusion through the intergranular fluid-saturated space and partial melting took place during peak of metamorphism and during the subsequent retrograde stage, when hydrothermal transport of metals prevailed. Migration of metals (Cu, Zn, Pb, Ag, Au) can be traced, in some cases, for up to several hundred metres, followed by their redeposition in the areas of extension and at the top selvages of the steeply-dipping ore sheets and lenses. This selective synmetamorphic remobilisation of polymetallic sulphides left large amounts of residual pyrite. The cycle was terminated by the stage of brittle deformation with formation of the late transverse faults and the Alpine-type veins with sulphide mineralisation.

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