Ore Geology Reviews 85 (2017) 30–63

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Metamorphism of volcanogenic massive sulphide deposits in the Urals. Ore geology

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ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 22 October 2016
Accepted 28 October 2016
Available online 29 October 2016

Keywords:
Urals
VMS deposits
Metamorphism
Deformation
Sulphide remobilisation

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 (±Pb ± Ag) mineralisation. Koktau, Tarnyer and Vesenneye 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 pseudomonoclinal 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, ±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, ±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.

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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http://dx.doi.org/10.1016/j.oregeorev.2016.10.032
0169-1368/

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; Gifkins 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, Dombarovsky and Ivanovka types. Deposits of the *Urals type*, in turn, are subdivided into two subtypes with Cu ≫ Zn and Zn ≫ 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[a]

[a] LMCE - low-melting-point chalcophile elements (Frost et al., 2002).