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6: Classification of VMS deposits: Lessons from the South Uralides

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Abstract

VMS deposits of the South Urals developed within the evolving Urals palaeo-ocean between Silurian and Late Devonian times. Arc-continent collision between Baltica and the Magnitogorsk Zone (arc) in the south-western Urals effectively terminated submarine volcanism in the Magnitogorsk Zone with which the bulk of the VMS deposits are associated. The majority of the Urals VMS deposits formed within volcanic-dominated sequences in deep seawater settings. Preservation of macro and micro vent fauna in the sulphide bodies is both testament to the seafloor setting for much of the sulphides but also the exceptional degree of preservation and lack of metamorphic overprint of the deposits and host rocks. The deposits in the Urals have previously been classified in terms of tectonic setting, host rock associations and metal ratios in line with recent tectono-stratigraphic classifications. In addition to these broad classes, it is clear that in a number of the Urals settings, an evolution of the host volcanic stratigraphy is accompanied by an associated change in the metal ratios of the VMS deposits, a situation previously discussed, for example, in the Noranda district of Canada.

Two key structural settings are implicated in the South Urals. The first is seen in a preserved marginal allochthon west of the Main Urals Fault where early arc tholeiites host Cu–Zn mineralization in deposits including Yaman Kasy, which is host to the oldest macro vent fauna assembly known to science. The second tectonic setting for the South Urals VMS is the Magnitogorsk arc where study has highlighted the presence of a preserved early forearc assemblage, arc tholeiite to calc-alkaline sequences and rifted arc bimodal tholeiite sequences. The boninitc rocks of the forearc host Cu–(Zn) and Cu–Co VMS deposits, the latter hosted in fragments within the Main Urals Fault Zone (MUFZ) which marks the line of arc-continent collision in Late Devonian times. The arc tholeiites host Cu–Zn deposits with an evolution to more calc-alkaline felsic volcanic sequences matched with a

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change to Zn–Pb–Cu polymetallic deposits, often gold-rich. Large rifts in the arc sequence are filled by thick bimodal tholeiite sequences, themselves often showing an evolution to a more calc-alkaline nature. These thick bimodal sequences are host to the largest of the Cu–Zn VMS deposits.

The exceptional degree of preservation in the Urals has permitted the identification of early seafloor clastic and hydrolytic modification (here termed halmyrolysis sensu lato) to the sulphide assemblages prior to diagenesis and this results in large-scale modification to the primary VMS body, resulting in distinctive morphological and mineralogical sub-types of sulphide body superimposed upon the tectonic association classification.

It is proposed that a better classification of seafloor VMS systems is thus achievable using a three stage classification based on (a) tectonic (hence bulk volcanic chemistry) association, (b) local volcanic chemical evolution within a single edifice and (c) seafloor reworking and halmyrolysis.

Keywords: South Urals; VMS; Classification; Halmyrolysis; Tectonic setting; Volcanic chemistry

1. Introduction

1.1. VMS deposits and associations

VMS deposits are typically stratiform bodies of sulphides precipitated from hydrothermal fluids at or immediately below the seafloor, commonly associated with volcanic rocks. The deposits can be found throughout geological history in a spectrum of tectonic settings such as oceanic ridges, thickened oceanic crust, sedimented oceanic ridges and rifted continental margins. However, more than 80% of them are found in rifted arc settings (Barrie and Hannington, 1999; Gibson et al., 2000). Deposits are generally coeval with associated volcanism in broadly extensional settings, mostly in rifted settings within arcs and back-arcs. Most arc-related deposits seem to relate to eruption of felsic volcanic rocks (Allen et al., 2002) often with a specific petrochemistry (Lesher et al., 1986; Lentz, 1998). Structural settings are distinct, with structure often controlling both volcanism and hydrothermal activity (Franklin et al., 1981). Volcanic facies range from massive flow-dominated or pyroclastic flow-dominated, deep or shallow (Gibson et al., 2000) and may include the presence of associated subvolcanic bodies. At one end of the deposit spectrum, the direct association with volcanism is at best distal and host rocks are largely siliciclastic sediments, while others show wholly volcanic associations.

Borodaevskaya et al. (1977) recognized that the Palaeozoic volcanic sequences of the South Urals were associated with subduction-related volcanism and since then a succession of publications on the volcanic associations of the VMS deposits (including Bobokhov, 1991; Zaykov, 1991; Ivanov and Prokin, 1992; Seravkin et al., 1992; Zaykov et al., 1993, 1996; Yazeva and Bochkarev, 1995; Gusev et al., 2000), have supported the dominance of models of subduction-related volcanic arc settings for the deposits. Despite the broad consensus, there is still disagreement about the more detailed tectonic setting. Specific details of the geological features of some of the Urals VMS deposits are to be found in Prokin et al. (1993, 1998), Prokin and Buslaev (1999), Gusev et al. (2000) and many more Russian source texts referred to therein. From these, it is clear that the deposits show many features in common with VMS deposits described in the literature elsewhere (Prokin and Buslaev, 1999; Herrington et al., 2002a). Deposits are largely hosted in volcanic-dominated sequences that show strong evidence for emplacement in deep water and dominated by flows and hyaloclastites (Maslennikov, 1999). Associated sediments in the Devonian sequences include deep-water cherts, some of which are low-temperature hydrothermal sediments or exhalites (Zaykov et al., 2000) and fossiliferous limestones with a general lack of clastic sediments of non-volcanic origin (Seravkin et al., 1992). There are strong structural controls to the development of both the host volcanic sequences and the VMS deposits themselves (e.g., Zaykov et al., 2001, see Box 6-1, Herrington et al., 2005—this volume) with ore deposit clusters often controlled by semi-regional features (Zaykov et al., 2001). Seravkin et al. (1992) outline the importance of regional caldera settings to the host volcanic sequences. Studied deposits show metal zonations and host rock alteration patterns comparable to other studies (Prokin and Buslaev, 1999). There is clear evidence for a true seafloor depositional setting for many of the deposits as demonstrated by the common association of vent fauna (Little et al., 1998). A broad review of these features with respect to the Urals was made in the Global Comparisons Database (Large and Blundell, 2000) to which the reader is directed, the salient points of which are summarized in Allen et al. (2002).

Many traditional classifications of VMS deposits worldwide are based on the metal ratios in the sulphide bodies and the deposit association with types of igneous rocks or geological settings (e.g., Borodaevskaya et al., 1979, 1992; Franklin et al., 1981; Ivanov, 1983; Eremin, 1983; Ovchinnikov and Lutkov, 1983; Krivtsov et al., 1987; Filatov and Shirai, 1988; Prokin et al., 1990; Large, 1992; Barrie and Hannington, 1999). The Urals are no exception, with various authors defining types including Cyprus, Kuroko, Uralian, Baimak, Dombarovka, Atlantic and Besshi, which have been largely defined by their specific igneous rock associations (Prokin and Buslaev, 1999; Gusev et al., 2000; Zaykov et al., 2000 and references therein). Of these, there is a broader consensus in Russia on the four types of Cyprus, Atlantic, Urals and Baimak (Prokin and Buslaev, 1999; Zaykov et al., 2000). In the past, ore deposit classification in the Urals has been made in the light of incomplete and conflicting tectonic models for the orogen, but recent advances in tectonic analysis as a result of the EUROPROBE programme make this analysis easier. Table 1 shows the lithotectonic classification scheme adopted in the review of Franklin et al. (in press) with an attempt to fit the VMS deposits of the Urals into the scheme. Even given the lithotectonic models, difficulties still arise in classifying complex orebodies, often developed at different levels in a common geological structure with substantial differences in mineral compositions and geochemistry.

Experience in the Urals suggests that seafloor VMS systems may suffer extensive low or ambient temperature overprint and seafloor–seawater interactions that affect the sulphide assemblage and related sediments (Maslennikov, 1999). This process is here termed halmyrolysis and describes pre-diagenetic processes involving seawater and diverse components of all types of seafloor sediments. The AGI Dictionary of Geological Terms' (Bates and Jackson, 2001) definition of halmyrolysis is "the geochemical reaction of seawater and sediments in an area of little or no sedimentation." Here we extend the usage of the term to embrace processes of hydrolysis and hydrolytic zone refining related to seafloor sulphide deposits, their associated sediments and volcano-sediments. These processes occur in largely open systems where components may escape into seawater. The processes are thus distinct from diagenesis, a process that occurs in a largely closed system where different components in the sediments re-equilibrate with the interstitial and largely static pore fluids. Halmyrolysis may lead to complete removal of components from the system and thus may be an ore-forming process itself, while diagenesis typically results in mineralogical change without bulk chemical addition and subtraction. These seafloor effects are potentially important features, particularly in longer-lived seafloor ore systems (Maslennikov et al., 2000; Allen et al., 2002). Analyses of these effects in ancient VMS systems are difficult, given, in many cases, a relatively high degree of metamorphism (greenschist facies and above), which may obscure early textural features. More importantly, most ancient VMS systems are preserved in orogenic belts and as such suffer from post-formation deformation, metamorphism and erosion. Studies of modern systems and of well-preserved fossil systems show the importance of understanding these early post-primary features (e.g.,

Table 1
Classification of VMS deposits into broad settings and metal content classes with local names used in the literature shown

Gross setting classification after Franklin et al. (in press)	Metal content classes	Types defined in literature (*types specific to Urals)
Mafic-dominated	Cu–Zn (Cu–Zn–Co)	Cyprus Atlantic*
Bimodal-mafic	Cu–Zn (Ag, Au)	Abitibi, Urals*, Dombarov*
Pelitic-mafic	Cu (Zn, Ag, Co)	Besshi
Bimodal-felsic	Cu–Pb–Zn–Ag (Au)	Kuroko, Baimak*
Siliclastic-felsic	Cu–Zn (Pb, Ag, Au)	Bathurst, Iberian Pyrite Belt

Table 2
Key features of VMS deposits of the South Urals

Name	Age	Metal types	Host rock volcanics (affinity where known)	Type	Key deposit mineralogy	Degree of seafloor modification (see Fig. 17 after Maslennikov, 1999)	Metamorphic grade	Reserves and Grades	Reference
Komsomolsk	Silurian (Llandovery)	Cu–Zn VMS	Bimodal basalt–andesite/dacite (tholeiitic)	Urals	7 Massive sulphide lenses Zoned stockwork–massive ores (90% by vol.)-layered sulphides. Lack of mineralogical zoning largely py-ma-sphal-cpy	1	SGS	25 Mt at 1.56% Cu, 0.17% Pb, 1.75% Zn, 0.12% As	Prokin and Buslaev, 1999
Blyava	Silurian (Llandovery)	Cu–Zn VMS	Bimodal basalt–andesite/dacite (tholeiitic)	Urals	similar to Komsomolsk, based on examination of dump material	2	SGS	10 Mt at 3% Cu, 5% Zn	Herrington, 2000
Yaman Kasy	Silurian (Llandovery)	Cu–Zn VMS	Bimodal basalt–andesite/dacite (tholeiitic evolving to calc-alkaline)	Urals	single sulphide lens. Zoned from stockwork footwall–massive py-cpy-sph-cpy-py to py-ba-sph with vent chimney debris and sulphidized vent fauna. Clastic ore fringe.	1	SGS	2.3 Mt at 2.56% Cu, 5.56% Zn, 3.3g/t Au, 33.5g/t Ag	Herrington et al., 1998
Zharly Asha	Mid-Devonian	Cu–Zn VMS	Basalt	Cyprus	zoned lens. Core py. Sph-cpy-py margins. Cov-sph facies	2?	SGS	Ca. 2 Mt at 32% Fe,< 1% Cu+Zn combined	Zaykov et al., 2000
Priorskoe	Mid-Devonian (Eifelian/Givetian) Milyanshinskaya Suite	Cu–Zn VMS	Bimodal basalt–rhyolite, felsic volcanism dominated hanging wall	Urals	py-mag-cpy-sph-po	not studied	CONT	38 Mt at 0.99% Cu, 3.67% Zn, 0.1 g/t Au, 16 g/t Ag	Reserves quoted on Bonita Group Website 2001 (www.bonita.-com)
50 Years October	Mid-Devonian (Eifelian/Givetian) Milyanshinskaya Suite	Cu–Zn VMS	Bimodal basalt–rhyolite, felsic volcanism dominated hanging wall	Urals	py-cpy-sph-po	not studied	CONT	46 Mt at 1.82% Cu, 0.67% Zn	Metal Mining Agency of Japan. Unpublished data 1997
Avangard	Mid-Devonian (Eifelian/Givetian) Milyanshinskaya Suite	Cu–Zn VMS	Bimodal basalt–rhyolite, felsic volcanism dominated hanging wall,	Urals	Py-mag-cub-sph	not studied	CONT	?	

Letnye	Mid-Devonian	Cu–Zn VMS	Pillowed basalt and hyaloclastite, andesites in hanging wall	Cyprus	single sulphide lens cpy-py, sphal-cpy-py and mag rich ores. Zoned lens from footwall mag to mag-cpy-py to cpy-py to sphal-cpy-py in hanging wall	4	GS	6 Mt at 2.8% Cu, 1.2% Zn, 0.17% Co, 0.6 g/t Au, 13.7 g/t Ag	Zaykov et al., 2000
Ishkinino	Silurian (Llandovery?)	Cu–Zn VMS	Serpentinites, boninitic to tholeiitic basalts	Cyprus	3 facies py-po, cpy-py-po and cob-aspy-cpy-py-po (plus sulpo-arsenides)	?	SGS	~1 Mt at 6.4% Cu, 0.2% Zn, 1.4 g/t Au, 5.1 g/t Ag, 0.2% As, 1 g/t Pt, 0.2% Co, 0.3% Ni	Nimis et al., in press
Gai	EarlyDevonian, (Emsiaan—patulus zone)	Cu–Zn VMS	Bimodal basalt–rhyolite host rocks. Sulphide developed in largely andesite–dacite–rhyolite over basalt footwall. Ore horizons covered by volcano-sedimentary units and andesite–basalt	Urals	zoned lenses. North and south zones Cu–Zn-rich, middle zone largely py. All lenses show py core to cpy mid to cpy-sph flanks. Main North zone lens has basal py, middle cpy and upper sph-cpy-py zonality. Upper lens North zone zoned from inner to outer py to sph-cpy to bn-cpy-py to bn (+tenn, gold, maws, germ etc. no tellurides)	2	SGS	380 Mt at 1.57% Cu, 0.06% Pb, 0.74% Zn Pyrite lens: 0.9 g/t Au, 6.3 g/t Ag Bornite lens: 11.95% Cu, 4.94% Zn, 0.29% Pb	Prokin and Buslaev, 1999
Dergamish	Silurian (Llandovery?)	Cu–Zn VMS	Serpentinites and gabbros; tholeiitic to boninitic basalt	Cyprus	3 facies: cpy-ma-po; cpy-sph-py; py-po	?	SGS	unknown at 1.2% Cu, 0.5 to 4.0 g/t Au, 11 g/t Ag, 0.01% Co	Zaykov et al., 2000
Buribai	Early Devonian (Emsian—serotinus zone)	Cu–Zn	Boninitic to tholeiitic basalts (tholeiitic); andesites post-ore.	Cyprus	not studied	not studied	SGS	3 Mt at 1.9% Cu, 0.1% Pb, 1.2% Zn	Estimated

(continued on next page)

Table 2 (*continued*)

Name	Age	Metal types	Host rock volcanics (affinity where known)	Type	Key deposit mineralogy	Degree of seafloor modification (see Fig. 17 after Maslennikov, 1999)	Metamorphic grade	Reserves and Grades	Reference
Makan-Okyabrsk (3 orebodies)	Early Devonian (Emsian—patulus zone)	Cu–Zn	Bimodal basalt–andesite/dacite (tholeiitic to calc-alkaline)	Urals	Multiple lenses; Cpy-py-sph, Fringe ores enriched in gal, gold	3	SGS	1.4 Mt at 6.0% Cu, 1.78% Zn 9.4 Mt at 4.17% Cu, 2% Zn 1.7 Mt at 3.38% Cu, 2.5% Zn	Seravkin et al., 2003a
Podolsk (East Podolsk)	Early Devonian (Emsian—patulus zone)	Cu–Zn VMS Cu–Zn	Bimodal basalt–andesite/dacite (tholeiitic); basalt footwall, andesite/dacite host to ore. Andesite–dacite dominated upper sequence host to East Podolsk (calc-alkaline)	Urals Baimak	Single large sulphide lens with satellite East Podolsk deposit. Masive Cu–Zn, Cu and Pyrite ores, Disseminated Cu zone.	3	SGS	80.8 Mt at 1.73% Cu, 0.13% Pb, 1.75% Zn, 0.15% As	Prokin and Buslaev, 1999; Tatarko, 2003
Yubilenoe	Early Devonian (Emsian)	Cu–Zn VMS	Bimodal basalt–dacite (tholeiitic)	Urals	not studied	1	SGS	106 Mt at 1.5% Cu, 1% Zn	Herrington, 2000
Balta Tau	EarlyDevonian (Emsian—patulus zone)	Cu–Z–Pb–Ba VMS	Andesites and dacites (calc alkaline)	Baimak	nmall sulphide lens with footwall disseminated zone. Massive py-sph, py-cpy ores with minor gal, tenn, tet, aspy. Upper barite lens with ba, tenn, tet, cpy, gal, sph, electrum	3	SGS	3.5 Mt at 3% Cu, 5.1% Zn, 4.5 g/t Au	Unpublished figures
Bakr Tau	EarlyDevonian (Emsian—patulus zone)	Cu–Zn–Pb–Ba VMS	Footwall basalts. Andesites and dacites host (calc alkaline)	Baimak	3 orebodies, 2 massive lenses, one disseminated body in qtz-porphyry. Sulphide lens zoned basal py, main mass sph-cpy-py with irregular bn zone (minor gal, tenn, asp, gold, etc.) Sph-gal-ba veins.	3	SGS	1.3 Mt at 2.63% Cu, 0.67% Pb, 4.66% Zn, 1.5 g/t Au	Prokin and Buslaev, 1999

Sibai	Mid-Devonian (Eifelian—australis/ kokelianus zone)	Cu–Zn VMS	Bimodal basalt–andesite/dacite (tholeiitic). Felsic dominated hanging wall sequence.	Urals	largest deposit of 3 formed of a stack of 3 connected lenses. Zoned deposit from py core to cpy-py main zone to cpy-sphal-py (contains vent fauna) outer zone. Base of complex lens cpy-po and cpy-mag-sid-py zone. Clastic sulphides lateral to ore lenses with vent fauna debris	1	SGS	110 Mt at 1.6% Cu, 0.04% Pb, 0.4% Zn, 0.6 g/t Au, 16 g/t Ag	Herrington, 2000
Alexandrinka	Mid-Devonian (Eifelian—australis/ kokelianus zone)	Cu–Zn–Pb–Ba VMS	Andesites and dacites (calc alkaline)	Baimak	polymetallic cpy-sph-ba-py breccia sulphide lens with primary vent chimney debris. Bn rich flank passing to ba ore.	3	SGS	10 Mt at 4.4% Cu, (Pb not quoted), 5.5% Zn, 2.2 g/T Au	Herrington, 2000
Molodezhnoe	Mid-Devonian (Eifelian—australis/kokelianus zone)	Cu–Zn	Bimodal basalt–dacite more felsic hanging wall (tholeiitic)	Urals	2 lenses at same horizon; First zoned from footwall py-cpy stockwork to massive py-cpy to cpy-py-sphal top. Clastic sulphide layers (vent fauna debris) cover lens and constitute the second ore lens. Bn-Au,-Ag sulphosalt and maws, strom, etc. in layered sulphides.	2	SGS	16 Mt at 2.56% Cu, 0.52% Zn	Gusev et al., 2000; unpublished data
Uzelga	Mid-Devonian (Eifelian—australis/kokelianus zone)	Cu–Zn VMS	Bimodal basalt–dacite (Tholeiitic). Felsic dominated upper part of sequence host to more polymetallic massive sulphide lenses	Urals (upper lenses Baimak)	8 economic and 48 sub-economic sulphide lenses in sequence. Lower ore lenses sid-cpy-py-po at core, cpy-py and sph-cpy-py margins. Middle lenses cpy-sphal-py and py-sph. Upper lenses cpy-py-sulphosalt, cpy-sph-py and py-sph ores. As-rich sulphosalt with Au–Ag enrichment	2	SGS	Copper: 27 Mt at 2.13% Cu, 0.1% Pb, 0.23% Zn, 0.8 g/t Au, 12.6 g/t Ag Zinc: 42 Mt at 0.91% Cu, 4.55% Zn (deposit average: 1.4% Cu, 2.5% Zn, 1.8 g/t Au, 35 g/t Ag)	Gusev et al., 2000; Herrington, 2000

(continued on next page)

Table 2 (*continued*)

Name	Age	Metal types	Host rock volcanics (affinity where known)	Type	Key deposit mineralogy	Degree of seafloor modification (see Fig. 17 after Maslennikov, 1999)	Metamorphic grade	Reserves and Grades	Reference
Uchaly	Mid-Devonian (Eifelian—australis/kokelianus zone)	Cu–Zn VMS	Bimodal basalt–dacite/rhyolite (tholeiitic) Prominent altered footwall dacite dome hosting disseminated/ stockwork ore	Urals	single large ore lens; zoned laterally from dacitic dome apex. Py core to cpy-py flank. Overlain by largely clastic ore: cpy-py base passing to sph-cpy-py to sph-py layers. Upper layers fine alternating py, py-cpy, py-sph and hem-qtz layers	2	SGS	113 Mt at 1.08% Cu, 3.73% Zn, 1.26 g/t Au, 18 g/t Ag (gossan 13 Mt at ~10 g/t Au)	Herrington, 2000 and refs. therein
Mauk	Mid-Devonian	Cu–Zn VMS	Metasediment and basalt (tholeiitic) host units	Besshi	reworked sulphide layers	4	AMP	3 Mt at 1.55% Cu, 1.7% Zn	Maslennikov et al., 2000; Herrington, 2000

Key: Py—Pyrite; Cpy—Chalocpyrite; Gal—Galena; Sph—Sphalerite; Tenn—Tennantite; Bn—Bornite; Hem—Hematite; Qtz—Quartz; Sid—Siderite; Po—Pyrrhotite; Ba—Barite; Tet—Tetrahedrite; Aspy—Arsenopyrite; Ma—Marcasite; Mag—Magnetite; Maws—Mawsonite; Germ—Germanite; Strom—Stromeyerite. SGS—Sub-greenschist facies, gs—Greenschist facies, AMP—Ampibolite facies, CONT—Contact metamorphosed.

Herzig et al., 1991), particularly in understanding the precise relationship between the sulphide bodies and the seafloor. Recognition of seafloor clastic reworking and early diagenetic change to the sulphide assemblages is clearly critical to any discussions concerning the relative importance of exhalative versus replacive processes (Allen et al., 2002). This paper aims to analyse the evolution of the volcanic stratigraphy of the Magnitogorsk arc which is host to VMS deposits at many stratigraphic levels (Table 2), a phenomenon atypical of many VMS camps where a single stratigraphic horizon is often highlighted (Allen et al., 2002).

1.2. The broad tectonic setting of the South Urals

The Uralide orogen is at the western margin of the Altaid orogenic collage, lying between the East European Craton (EEC) and Palaeozoic orogens of the Kazakh uplands. Numerous tectonic and metallogenic studies broadly subdivide the orogen into a western and eastern slope where the western slope represents a deformed Palaeozoic continental passive margin, whereas diverse plate tectonic models have been proposed for its eastern slope, invoking a collage of Palaeozoic magmatic arcs, micro-continents and sutured oceanic basins (Puchkov, 1997).

In the South Urals, an allochthonous package of Ordovician to Silurian ophiolite and immature magmatic arc rocks, the Sakmara zone, with a probable affinity to the "eastern slope," forms eroded thrust sheets on top of the deformed passive margin sequences of the "western slope" and contains major Cr and small VMS deposits (Koroteev et al., 1997). In the North Urals, the western margin of the "eastern slope" is marked by the Tagil zone of Silurian to Devonian arc rocks that contains major Fe–Ti, Cr, PGE and VMS deposits (Gusev et al., 2000). In the South Urals, the magmatic arc rocks of the Magnitogorsk Zone are equivalent to the Tagil zone and they host major VMS and iron-oxide deposits (Koroteev et al., 1997).

Airborne magnetic maps show that the Tagil and Magnitogorsk arcs, along with other components of the eastern slope of the Uralides, may project beyond the exposed Urals around into the Altaid orogenic collage (Yakubchuk et al., 2001). The Tagil–Magnitogorsk–Petrokamensk–Alapaevsk magmatic arc can probably be traced from the South Urals to the Polar Urals, swinging to the south-east towards RudnyAltai and eastern Kazakhstan, where VMS deposits of Middle Devonian age are found (Yakubchuk et al., 2001).

The traditional subdivisions of the Uralides, based largely on age and palaeogeography, are, from west to east, the Pre-Uralian Zone, the West Uralian Zone, the Central Uralian Zone, the Tagil–Magnitogorsk Zone (TMZ), the East Uralian Zone (EUZ) and the Trans-Uralian Zone (TUZ) (Puchkov, 1997). The Pre-Uralian, West and Central Uralian Zones correspond to the former margin of Baltica (EEC) covered by Late Palaeozoic foredeep and later sedimentary cover, while the Main Urals Fault Zone (MUFZ) marks the boundary between these and the exotic terranes to the east. The MUFZ is an east-dipping fault system with widely developed serpentinitic mélange, up to 10 km wide, which can be traced continuously along the Uralide orogen for 2000 km. Seismic profiles show that the zone dips east at different angles and is usually visible for at least 15 km down dip, probably into the lower crust (Juhlin et al., 1996; Brown et al., 1998; etc.). The MUFZ is largely a mélange of up to many kilometre-long blocks of Ordovician to Lower Carboniferous plutonic, volcanic and sedimentary rocks, with a matrix of serpentinites, derived from harzburgites, dunites and minor lherzolites (Seravkin et al., 2001). The mafic and ultramafic complexes within the MUFZ have been proposed by a number of authors to represent relics of Ordovician and probably Lower Devonian oceanic material (Savlieva et al., 1997, 2002; Puchkov, 2000; Zaykov et al., 2000). The MUFZ is considered to be one of the main suture zones of the Uralides, marking the zone of collision between units belonging to the EEC (continent) in the west and the outboard terranes (arc) to the east. The other major suture zone of comparable importance, dividing the Uralides from Kazakhstanides, is supposed to be concealed under the Meso-Cenozoic sediments of the Turgai basin in the east of the Urals (Puchkov, 2000). The region immediately to the west of the MUFZ is the footwall sequence and comprises reworked Archean to Vendian rocks, Palaeozoic shelf and slope sediments of the EEC and a Permian molasse (Brown et al., 1996). This complex has become partly overthrust by high-pressure low-temperature glaucophane-eclogite rocks, and obducted oceanic and ocean arc-related rocks, emplacement of which is related to the collision of Baltica with complexes to the east.

Eastwards across the MUFZ, the TMZ comprises Ordovician to Devonian oceanic and intra-oceanic island arc volcanic rocks with related sediments (Seravkin et al., 1992). In the south, these are represented by the Devonian Magnitogorsk arc system, which is host to the bulk of the South Urals VMS deposits discussed in this paper (Gusev et al., 2000). East of these arc rocks, the serpentinitic mélange-filled east Magnitogorsk Fault zone forms the boundary between the arc sequence and the East Uralian Zone (EUZ). The EUZ comprises deformed and metamorphosed arc rocks with blocks of Palaeozoic and Precambrian rocks which may be continental crustal fragments (Puchkov, 1997, 2000). Late Carboniferous and Permian granitoids have intruded the EUZ, giving rise to the distinctive granite axis down the spine of the Uralides (Fershtater et al., 1997). The Trans-Uralian Zone (TUZ) is a belt of Devono-Carboniferous volcanic and plutonic rocks, underlain by ophiolites and continental fragments and overlain by thick redbed sediments with evaporites. The contact between the TUZ and the EUZ is poorly exposed but has a strong geophysical expression and sporadic exposures of serpentinitic melange (Brown et al., 2002), and high-pressure rocks are also reported in the TUZ. The easterly parts of the TUZ are covered by Mesozoic and Cenozoic sediments but are assumed to be underlain by the Kazakh continent.

Since the Uralides are a largely intact orogen preserved within the tectonic plate of Eurasia (Brown et al., 2002), much of the South Urals has suffered only low-grade metamorphism and the VMS deposits of the Urals are notable for the general lack of metamorphic overprint (Prokin and Buslaev, 1999). Deposits show a high degree of preservation of primary texture and many of the deposits show ample evidence of a seafloor origin, demonstrated by the records of vent chimney debris and fossil vent fauna (Prokin et al., 1985; Little et al., 1997, 1998; Herrington et al., 1998).

Further work completed under the umbrella of the GEODE initiative and more specifically the MinUrals INCO 2—Copernicus project funded under the EU 5th Framework initiative has reviewed existing models and generated further new data on the VMS deposits (see http://minurals.brgm.fr/texte/Documents/FinalReport_Publish.pdf).

This paper aims to analyse the evolution of the volcanic stratigraphy of the Magnitogorsk arc, which is host to VMS deposits at many stratigraphic levels, a phenomenon atypical for many VMS camps where a single stratigraphic horizon is often highlighted (Allen et al., 2002). In the Urals, a better definition of the seafloor architecture of the VMS systems is possible and an evaluation of early diagenetic features, pertinent to the geochemical signature of the various VMS deposits is made. This information provides a unique insight into detailed features of a major VMS camp, to date missing from the English-speaking literature.

2. The role of tectonic setting and volcanic chemistry

2.1. Broader tectonic setting

Work to date has determined that the VMS deposits in the South Urals are largely restricted to four distinct tectonic zones within the orogen: Sakmara Zone (allochthon), Main Urals Fault Zone (MUFZ), Magnitogorsk–Tagil Zone and West Mugodzhar–Dombarov Zone (Gusev et al., 2000). Each of these settings is quite distinctive within the evolution of the Uralide orogen with a consequent range of deposit styles indicated (Fig. 1).

The broadly island arc setting for the bulk of VMS deposits, specifically those in the Magnitogorsk–Tagil Zone, is well known (e.g., Prokin and Buslaev, 1999; Gusev et al., 2000). Revised tectonic models for the South Urals developed during the EUROPROBE programme (e.g., Brown et al., 1996; Puchkov, 1997; Chemenda et al., 1997; Brown et al., 1998; Brown and Spadea, 1999; Hetzel, 1999; Brown et al., 2002) have provided a better framework for analysis and recent authors have attempted a better definition of the VMS deposits with respect to stratigraphy and arc architecture (Herrington et al., 2002a; Seravkin et al., 2003a; Buschmann et al., in press).

One aspect of the earlier interpretations of the Urals deposits has been that ages of mineralization for the various deposits have not been compiled in detail. It is apparent that the Urals VMS deposits are, unusually, developed at a number of stratigraphic levels within the orogen, even within a single arc system (cf. Allen et al., 2002). Excellent compilations

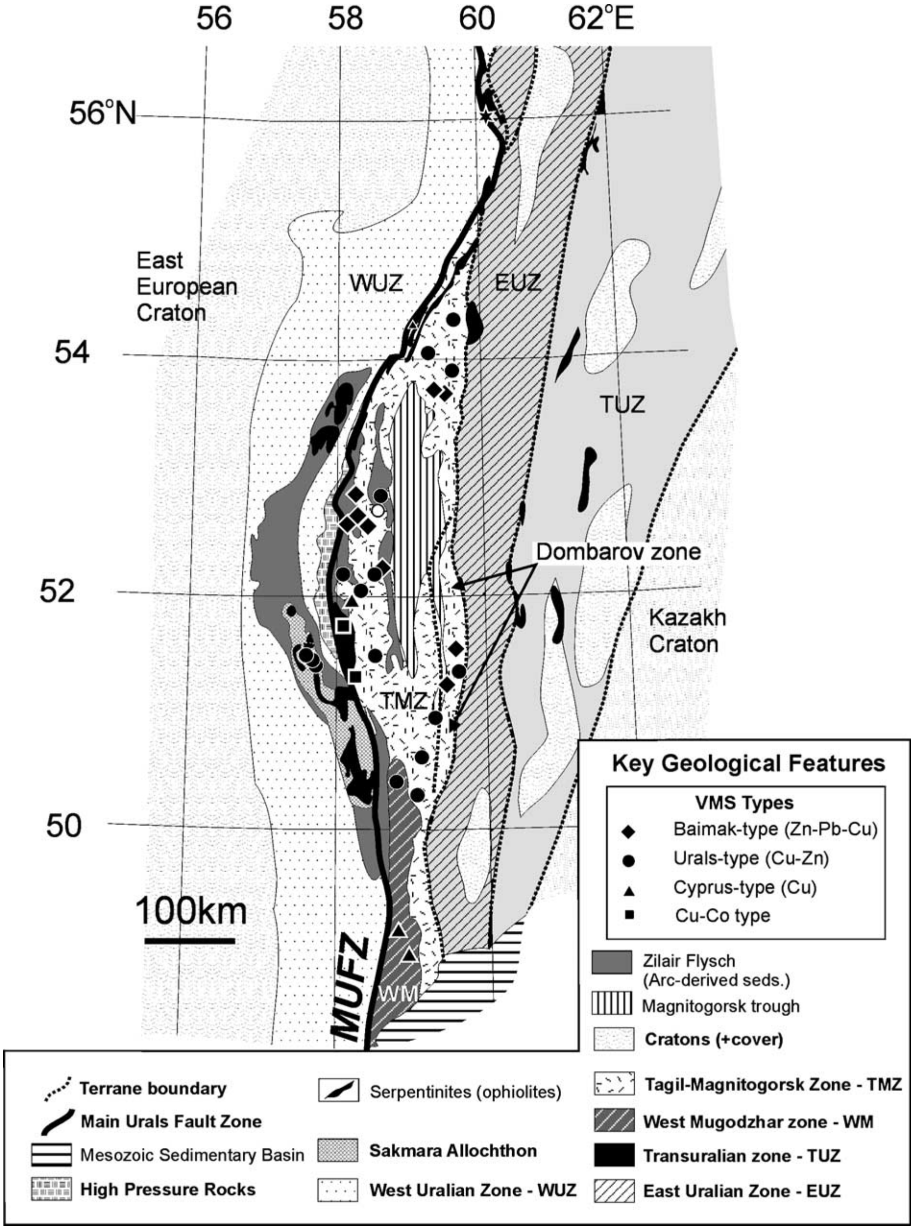


Fig. 1. Simplified terrane map of the South Urals showing main regions of arc volcanic sequences (after Zaykov et al., 1996, 2000; Prokin and Buslaev, 1999; Gusev et al., 2000; Brown et al., 2002; Herrington et al., 2002a; Seravkin et al., 2003b).

of biostratigraphic data for the regional sequences are available in the Russian literature (Maslov et al., 1987, 1993; Artyushkova and Maslov, 1998) and this has been recently synthesized and articulated into a compilation with the VMS host volcanic sequences by Buschmann et al. (in press), allowing a much better analysis of age, facies and petrochemical associations of the different deposits to be made (Fig. 2).

Within this framework, VMS deposits in the South Urals have been traditionally classified into three main types: Cyprus-type, Urals-type and Baimak-type (Pro-

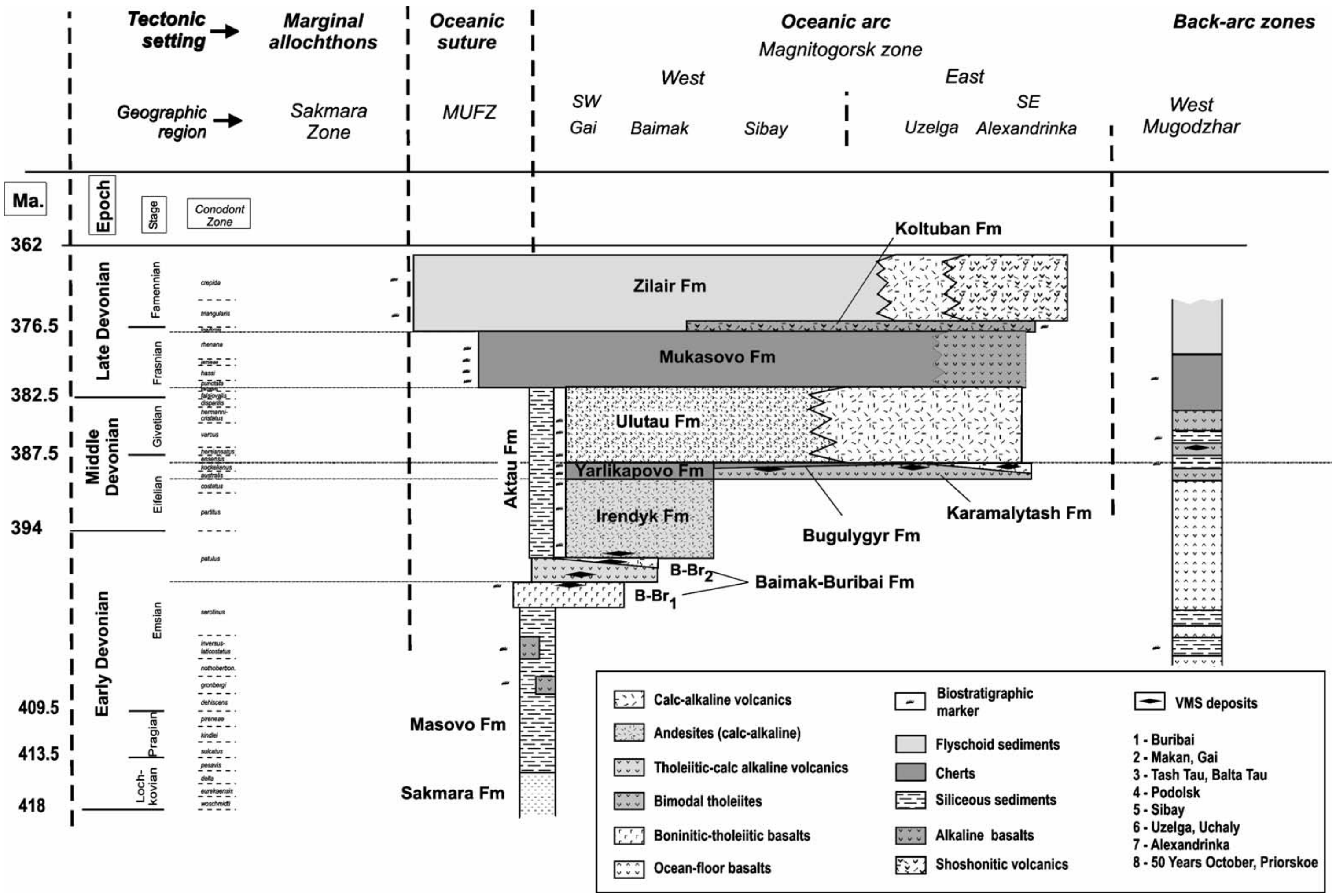


Fig. 2. Stratigraphic correlations across the volcanic arc sequences of the Magnitogorsk and contiguous zones (after Maslov et al., 1987, 1993; Zaykov et al., 1996, 2000; Herrington et al., 2002a; Buschmann et al., in press).

kin and Buslaev, 1999). Other authors have also identified further Besshi-type (Zaykov et al., 2000) and Atlantic-type deposits (Zaykov, 1991; Zaykov et al., 2000) and it is apparent that there is not a clear consensus amongst the Russian authors as to which deposits fit into which category. Nevertheless, this classification can be more or less compared with western terminologies as shown in Table 1 (after Barrie and Hannington, 1999; Herrington et al., 2002a) and is made on a combination of metal association and host rock type, the latter broadly relating to tectonic setting (Prokin and Buslaev, 1999).

Some of the four tectonic zones discussed above are characterized by single VMS types defined above. For example, the VMS deposits of the Sakmara Zone are all classified as Cu–Zn Urals-type deposits (Zaykov et al., 1995; Prokin and Buslaev, 1999; Herrington et al., 1998). The rather unusual VMS deposits of the MUFZ are classified on their own as Cu–Co Atlantic type (Zaykov et al., 2000). These distinct associations may support the concept of deposit type linked to specific petrogenic suites (hence tectonic setting) as has been generally proposed by previous authors for ancient deposits worldwide (Franklin et al., 1981, in press).

Although the richly mineralized Magnitogorsk Zone is interpreted (at least in the western part) in terms of a simple single evolving arc system (e.g., Herrington et al., 2002a), it hosts Cyprus-type, Urals-type and Baimak-type deposits within it (Fig. 1). This suggests that each of the deposit types is not restricted to a single tectonic setting and a more sophisticated scheme appears to be needed. In some of the larger, more complex orebody systems, both Urals-type and Baimak-type VMS deposits are noted in the same volcanic edifice. Nevertheless, Herrington et al. (2002a) had previously suggested that deposit type could be linked to tectonic setting across the western part of the Magnitogorsk Zone in its broadest sense, with the Cu deposits in the forearc, Baimak-type in the true arc and Urals-type deposits in rifted arc settings as supported by lead isotope data.

In this paper, we review the current analysis summarized above and examine each of the four tectonic settings hosting VMS deposits. A more in-depth analysis of petrochemical data from the Magnitogorsk Zone is presented here using data from published sources (e.g., Seravkin et al., 1992; Spadea et al., 1998, 2002; Gusev et al., 2000; Herrington et al., 2002a), comparing individual VMS deposit types with respect to the nature of the host volcanic suites.

2.2. The Main Urals Fault Zone (MUFZ)

The first preserved ocean volcanism in the Uralides is observed in subalkaline basalts and cherts, fragments of which are found in the MUFZ, the earliest of which are ascribed to initial epicontinental rifting (Savelieva and Nesbitt, 1996). The geochemical signature of these relics is interpreted as either n-MORB or subalkaline basalt (Puchkov, 1997). The MUFZ also contains a diversity of rocks and comprises a melange of serpentinites derived from mantle harzburgites, less common dunites and minor lherzolites, crust-mantle transition of ophiolite slabs with blocks of ca. 460 Ma Ordovician to ca. 370 Ma Middle Devonian volcanic rocks and sediments (Seravkin et al., 2001). The volcanic rocks include depleted oceanic basalts from a MOR setting of Ordovician age (Savlieva et al., 1997; Gaggero et al., 1997; Spadea et al., 2002), which probably record the presence of true oceanic crust in the MUFZ (e.g., Zaykov et al., 2000; Savlieva et al., 1997, 2002).

The history of the MUFZ is rather complex since the presence of Ordovician volcanic rocks suggests that the zone contains part of the record of the initial rift volcanism and opening of an oceanic basin in similar fashion to the Sakmara allochthon (see below), but also records intra-oceanic subduction and arc-continent collision in the Middle Devonian (Puchkov, 2000). The MUFZ now forms a major suture between the accretionary wedge on the East European craton to the west and the forearc basement of the Magnitogorsk arc zone lying to the east.

The MUFZ also contains mafic–ultramafic complexes that are hosts to small VMS deposits and in at least one case these rocks are extensions of interpreted ophiolite (Nimis et al., in press), similar to other ophiolitic fragments described within the MUFZ. Reconstruction of the host stratigraphy to the deposits is problematic due to poor outcrop and general tectonic complications. The rocks hosting mineralization are variously altered ultramafics and mafic to intermediate volcanic rocks. Nevertheless, the geochemical signature of the basalt and andesite lithotypes varies from arc-tholeiite to boninite in composition

(Simonov et al., 2002; Jonas, 2003; Nimis et al., in press) and the supra-subduction zone imprint of the ultramafics precludes a MOR setting for the deposits previously proposed by Wipfler et al. (1999). Similar small Cu–Co-bearing VMS deposits are known associated with basalt-komatiite flows in the Timmins district of the Archaean Abitibi belt (Jonasson, personal communication).

The presence of mass flows containing abundant ultramafic clasts (Seravkin et al., 2001, 2003c; Jonas, 2003) and hydrated mafic and ultramafic breccias and detrital chromite in the host sequences point to the exposure of ultramafic crust on the seafloor at the time of deposit formation (Nimis et al., 2003). The features of these deposits are shown in Fig. 3.

2.3. Sakmara Zone (allochthon)

The Sakmara Zone is an allochthon structurally overlying the Upper Devonian Zilair Formation which is itself parautochthonous upon Devonian shelf sediments overlying the European continental margin to the west of the MUFZ. There is a crude stratigraphic stacking to the thrust sheets of the allochthon from deepwater sediments to an olistostrome unit, to the flysch unit (Zilair Formation). Above the Zilair flysch lies serpentinite melange, pillow lavas, cherts, epiclastic tuffs and oceanic and island arc volcanic rocks, in turn overlain by the uppermost "sheet" consisting of the ophiolitic ultramafic complexes of Kempirsai and Khabarny (Savelieva and Saveliev, 1991). The root zone of the thrust sheets corresponds to the MUFZ, which it abuts in the east (Puchkov, 2002).

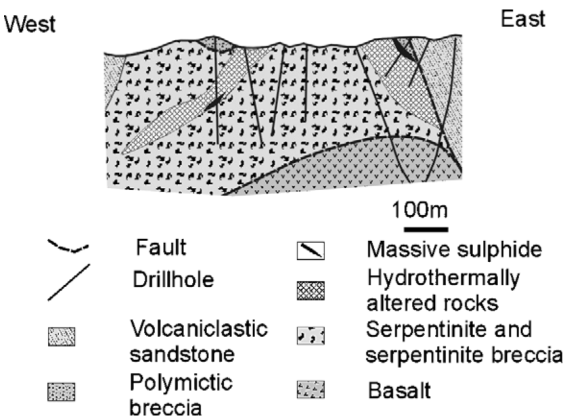


Fig. 3. Cross-section of the "Atlantic-type" (Cu–Co) Ishkinino deposit (after Zaykov et al., 2000; Nimis et al., 2003).

Savlieva et al. (2002) summarized the three broad associations in the units within the allochthon: (a) molasse sandstone and conglomerate of likely Cambrian to Ordovician age representing the onset of the Urals palaeo-ocean rifting; (b) basic pillow lavas and cherts dated as Middle Ordovician in age (Korinevsky, 1991), which lie above the gabbros and sheeted dykes of the Kempirsai ultramafic complex that are part of the spreading ocean (Savelieva and Saveliev, 1991) and (c) Silurian to Devonian volcano-sedimentary rocks, including boninites, tholeiites and a calc-alkaline series of likely arc association (Seravkin and Rodicheva, 1990). Closer correlations within the Sakmara Zone are acknowledged to be difficult due to the dismembered nature of the succession (Puchkov, 2002), although a compilation of comparative stratigraphy has recently been assembled (Fig. 4).

The third association of volcanism includes the Blyava Formation in the Mednogorsk region, which is host to four small to medium sized VMS deposits, Blyava, Komsomolsk, Yaman Kasy and Razumovsk. The host Blyava Formation has been proposed by some to be Ordovician in age, based on conodont identification (Prokin and Buslaev, 1999). However, hanging wall shales of the Blyava deposit, which are interbedded with volcanic rocks related to mineralization, yield monograptids, confirming an early Llandoverian age for the VMS ores (Korinevsky, 1991; Buschmann et al., 2001). A single K–Ar date of 412 Ma from Yaman Kasy yields a minimum age but confirms that the deposits are older than Early Devonian (Little et al., 1997).

Mineralization in the Blyava group is developed at two distinct stratigraphic levels within the package, each representing a cycle from basaltic flows to dacites and rhyolites directly associated with mineralization. Geochemistry from the host Blyava group volcanic suite confirms they are largely low TiO_2 bimodal tholeiitic at the base passing to transitional calc-alkaline rhyolites at the ore horizon (Seravkin et al., 1992; Prokin and Buslaev, 1999; Buschmann et al., 2001; Herrington et al., 2002a). Prokin and Buslaev (1999) propose that these are arc volcanic sequences, age and facies equivalents to volcanic rocks in the Tagil zone to the north. However, a marginal sea setting is proposed by other authors (Zaykov et al., 1995), largely

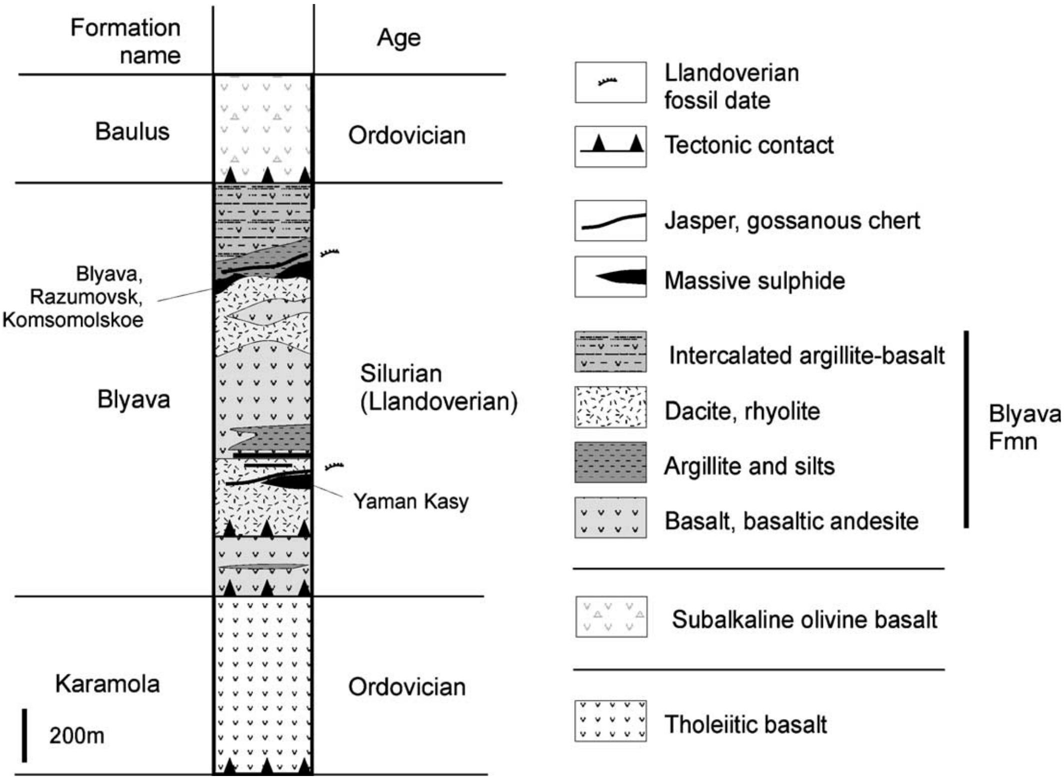


Fig. 4. Stratigraphic correlations of units between the Sakmara allochthon and the MUFZ (compiled by Buschmann et al., 2001; Jonas, 2003 after Maslov et al., 1993).

on the basis of associated sediments that may have a continental source. A supra-subduction setting for the Blyava group is suspected (Herrington et al., 2002a), supported by evidence for a supra-subduction overprint to the ultramafic sequences in the southern part of the Sakmara allochthon at Kempirsai.

The VMS deposits are all classed as Urals-type (Prokin and Buslaev, 1999). All appear to have formed on the seafloor as classic exhalative mounds with stockwork feeder zones (Zaykov et al., 1995; Herrington et al., 1998; Prokin and Buslaev, 1999). The host volcanic rocks to the deposits are bimodal tholeiitic with evidence of an evolution to more calc-alkaline lavas after mineralization (Buschmann et al., 2001).

2.4. Tectonic evolution of the Magnitogorsk–Tagil Zone

The geographically separate Magnitogorsk and Tagil zones are collectively referred to as the Magnitogorsk–Tagil Zone as they occupy the same relative structural position with respect to the MUFZ suture zone (Brown et al., 2002). The Magnitogorsk–Tagil Zone hosts the bulk of the economically significant VMS deposits in the South Urals with the most productive region being found in the more southerly Magnitogorsk Zone. The Tagil zone is far less well understood and hence will not be discussed here although the broad geological features are seen to be similar to the Magnitogorsk Zone (Gusev et al., 2000), albeit of different age due to the apparent diachronous nature of the volcanic arc development along the Uralides (Puchkov, 2000). To the south, the Magnitogorsk Zone correlates with the West Mugodzhar–Dobarov Zone, which, due to documented differences, is discussed below.

The MUFZ marks the arc-continent suture, related to Devonian subduction along the margin of the Magnitogorsk arc. Immediately east of the MUFZ, Upper Emsian (~400 Ma) boninites are the earliest record in the Magnitogorsk Zone of the onset of eastward (current geographical orientation) intra-oceanic subduction and formation of the extensive Magnitogorsk volcanic arc (Spadea et al., 2002). There is a clear eastward temporal and spatial progression of arc-volcanic complexes from the boninites and a series of volcanic complexes for the arc system which are, from west to east, the Baimak–Buribai, Irendyk Formation and Karamalytash Formation, culminating in the more widespread development of the latest volcano-sedimentary Ulutau Complex (Fig. 2). Above this dominantly volcanic sequence lie three significant, largely sedimentary sequences of the Ulutau, Mukas, Koltubanian and Zilair, which are important markers of the evolution of the arc. In the central part of the region, the Ulutau Formation comprises up to 1800 m of epiclastic volcanic sediments, largely turbidites, with locally reworked blocks of fossiliferous limestone. It is restricted to the central and east, which implies that part of the volcanic package (Irendyk Formation) may have exerted a physical barrier to sedimentation (Brown et al., 2001). The Ulutau Formation contains some eruptive rocks with rare uneconomic stockwork sulphide zones but otherwise the unit is devoid of VMS deposits, apart from some chert horizons that are locally manganiferous. The unit may be time-equivalent to parts of the condensed Aktau Formation, the stratigraphic equivalent of which is developed to the west of the Irendyk volcanic "ridge" (Fig. 2).

Overlying the Ulutau Formation is the Mukasovo Formation. This regionally extensive unit, largely fine siliclastic or chert facies with minor basaltic intercalations, is developed over much of the west of the Magnitogorsk Zone, the MUFZ, parts of the Sakmara allochthon and probably even down to the West Mugodzhar zone. East of the Irendyk ridge, the Mukasovo is conformable upon the Ulutau Formation, whereas in the MUFZ and Sakmara zones, it marks the structural unconformity to the accretionary mélange, confirming the dynamic nature of this margin. At the western margin of the Magnitogorsk Zone, the Mukasovo Formation is gradational from the Aktau Formation or else is unconformable upon the Baimak–Buribai and Irendyk complexes. The unit marks the onset of regional sedimentation into the forearc from the east.

The final "arc"-related sequence is the Zilair Formation comprising a lower 100-m-thick olistostrome-bearing unit that has blocks of limestone, basalt, rhyolite, chert and sandstone. In the west, this level of the Zilair Formation correlates with a volcanic series known as the Koltubabian Formation. The Zilair Formation becomes largely greywacke turbidites (flysch) with increasing carbonate up sequence. In the east, the Zilair Formation interfingers with calc-alkaline and even shoshonitic lavas and associated subvolcanic facies that are a possible source for some detrital components (Puchkov, 1997). The unit is interpreted as having developed in the forearc during active arc-continent collision (Brown et al., 2001; Willner et al., 2002) with mixed sedimentary and volcanic detritus being deposited in flysch troughs (Puchkov, 2002) during uplift of the arc and accretionary complex. The unit shows a diachronous development across the forearc, typical for such a setting where oblique collision is implicated (Puchkov, 2002). The Zilair Formation effectively marks the end of subduction along the MUFZ with cessation of arc-related volcanic activity.

Some authors then propose a switching of the arc volcanism further east (e.g., Surin, 1991) although many complexities associated with such a switch (Prokin and Poltavets, 1996) still remain poorly explained. In the Magnitogorsk Zone, magmatic activity above the Zilair Formation is essentially post-collision type, related to sedimentation, extension and magmatic activity. This largely A-type magmatism is associated with the formation of large magnetite skarn bodies (Herrington et al., 2002b).

The waning of arc-related volcanism in the west coincides with the entrance of the East European continental margin (rocks west of the MUFZ) to the subduction zone. The timing of arc-continent collision with respect to arc volcanism and mineralization may be very important. Subduction of forearc rocks is estimated to have commenced at ca. 386 Ma, with continental crust probably entering the subduction zone at ca. 380 Ma (Brown et al., 1998) before being exhumed as a high-pressure complex west of the MUFZ between 375 and 315 Ma (Leech and Stockli, 2000). The most intense period of VMS formation occurred between 398 and 390 Ma (Maslov et al., 1993), probably within the error of the timing estimates for the forearc subduction mentioned above.

Arc-continent collision in the SE Urals also resulted in the attachment of a shallow crustal accretionary complex comprising the MUFZ rocks, allochthonous slices rooted in the MUFZ, relics of oceanic crust and early arc sequences (like the Sakmara Zone), onto the margin of the East European Plate. Other complexes such as the Kraka nappe may be similarly thrust onto the margin of the East European margin.

2.5. Tectono-stratigraphic setting of VMS deposits in the Magnitogorsk Zone

The spatial distribution of the Magnitogorsk arc sequences is shown on the simplified map in Fig. 5. Accompanying this is a simplified cross-section (Fig. 6) taken from the MUFZ eastwards along the line A–B of the VMS deposits shown. The section is described from west to east below:

2.5.1. Baimak–Buribai Formation

Close to the MUFZ in the region around Buribai, the lowermost exposures of the Lower Devonian Baimak–Buribai Formation are found (e.g., Spadea et al., 1998). The basal part of this unit is a sequence of massive and pillowed flows, which pass from a thick, pillowed basalt into upper basalt-andesite lavas and hyaloclastites. These sequences have been ascribed to "basaltic shield" volcanoes (Seravkin et al., 1992; Gusev et al., 2000), forming a long chain of basaltic centres through the region, measuring tens of kilometres in strike extent. In the region of Buribai, thin rhyodacite intrusives accompany the development of the massive sulphide deposit of Buribai (Cyprus-type Cu deposit) described by Prokin and Buslaev (1999) and shown on Fig. 7.

Above this is an upper sequence locally known as the Tanalyk Formation (Spadea et al., 2002). This comprises up to 1200 m of basaltic–andesitic-acid lavas, lava breccias and hyaloclastites intruded by rhyodacite dykes and sills. The top of this unit hosts the major VMS camp of Makan and Oktyabrskoye (Urals-type Cu–Zn deposits) and it may also be the level of the main Podolsk (Urals-type Cu–Zn) massive sulphide body (Figs. 8 and 9). This sequence of volcanic rocks locally fills large linear volcanic depressions, specifically in the main sulphide camps (Fig. 6) (Gusev et al., 2000).

Spadea et al. (2002) defined four major petrochemical groups in the Baimak–Buribai Formation. The

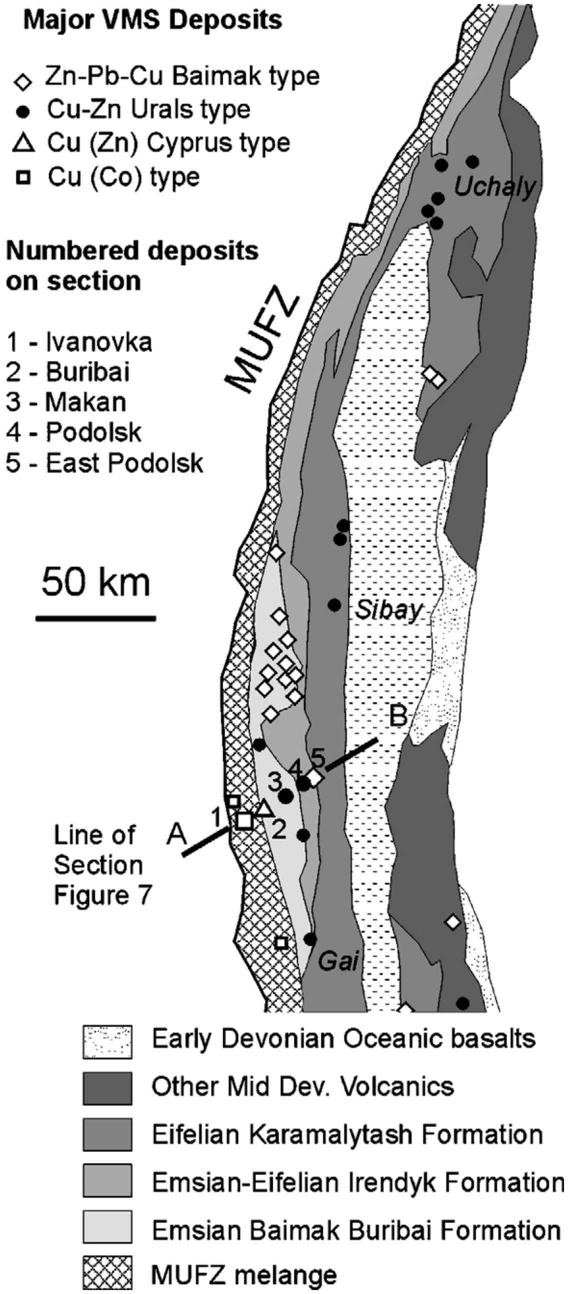


Fig. 5. Simplified map showing the main volcanic formations of the Magnitogorsk Zone (after Seravkin et al., 2003a). Line of section for Fig. 6 is indicated as 'A–B.'

first group, boninites, form petrographically distinct, glassy aphyric and sparsely olivine and pyroxene phyric rocks, chromite-bearing, with no plagioclase. They show low TiO_2, a primitive signature, strongly

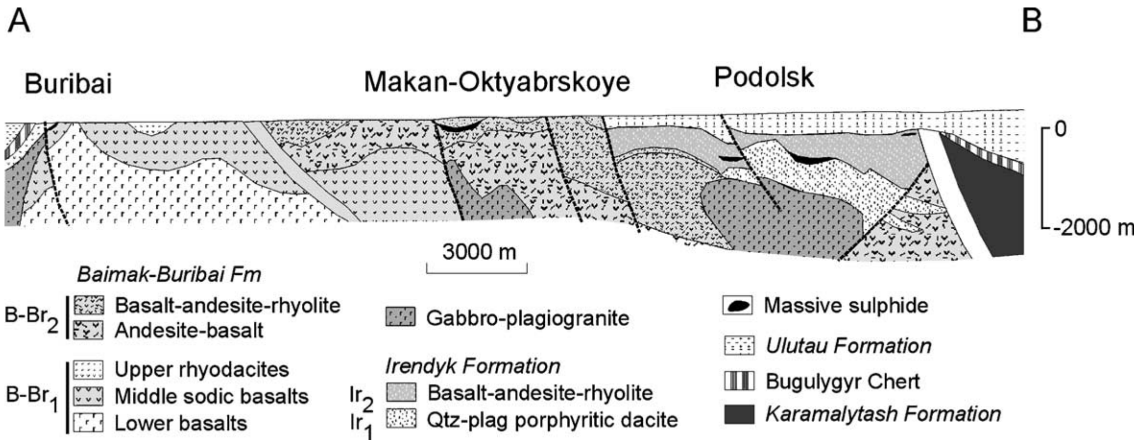


Fig. 6. Simplified cross-section through the Magnitogorsk arc volcanic rocks from Buribai eastwards (after Seravkin et al., 2003a). See location on Fig. 5.

depleted in HFSE with respect to n-MORB. They have characteristic flat REE patterns, similar to high-Ca boninites from Izu-Bonin and Tonga (Spadea et al., 1998; Spadea and Scarrow, 2000). The second group of high-Mg basalts are both aphyric and porphyritic where they contain plagioclase laths. Flat to negative REE patterns are typical (Herrington et al., 2002a; Spadea et al., 2002). The third group comprises pyroxene or pyroxene–plagioclase phyric rocks that show flat or slightly LREE enriched patterns of IAT affinity. The fourth group comprises calc-alkaline basalts to andesites, which are mainly porphyritic with pyroxene, plagioclase and olivine phenocrysts in variable amounts with marked LREE enriched patterns (Herrington et al., 2002a; Spadea et al., 2002). Fig. 10 shows a graphic log through the Baimak–Buribai Formation along the section shown in Fig. 6 (after Seravkin et al., 2003a), with corresponding compiled chondrite-normalized REE plots. An evolution from primitive to more evolved volcanic rocks is seen with an increase in the abundance of acid extrusives upwards. These data are supported by Herrington et al. (2002a), who describe a general evolution up the sequence from the primitive boninitic rocks closest to the MUFZ rising to distinctly calc-alkaline rocks that are host to the polymetallic deposits in the Baimak region (Fig. 11). Within this general trend, large volcanic troughs are infilled with large volumes of bimodal tholeiitic magmatism that host the large Urals-type deposits. The VMS deposits also show a similar evo-

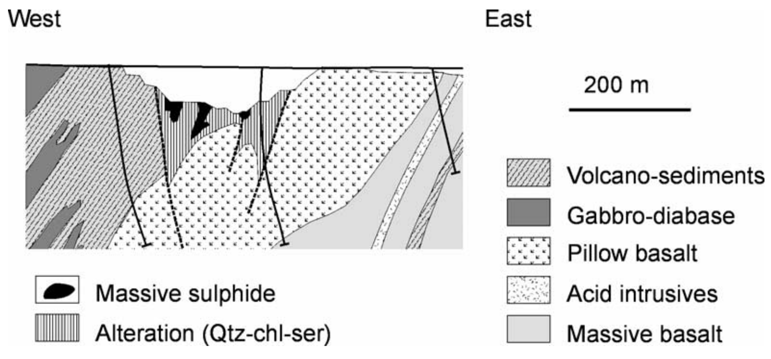


Fig. 7. Cross-section of the Cyprus-type (Cu) Buribai deposit (after Seravkin et al., 2003b) (see location on Figs. 5 and 6).

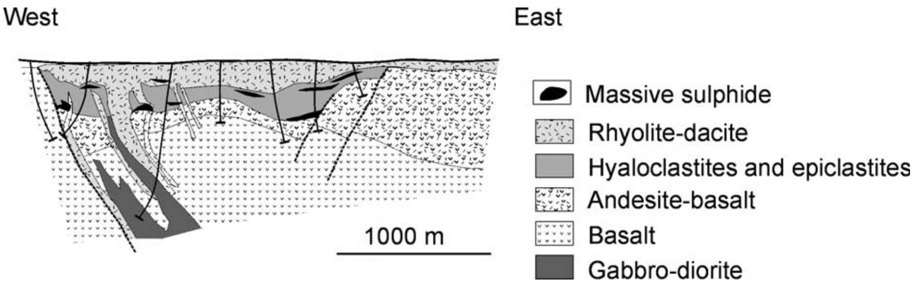


Fig. 8. Cross-section of the Makan–Oktyabrskoe Urals-type (Cu–Zn) deposits (after Seravkin et al., 2003b). See location on Figs. 5 and 6.

lution in trend. Copper-rich Cyprus-type deposits are associated with the early forearc sequence, copper–zinc Urals-type deposits with voluminous bimodal tholeiites and the polymetallic Baimak-type deposits with the calc-alkaline parts of the sequence containing generally more felsic volcanic units.

2.5.2. Irendyk Formation

In the western part of the Magnitogorsk Zone, the Baimak–Buribai Formation is locally overlain by the Turat sedimentary formation (Spadea et al., 2002), the lateral equivalent of the condensed Aktau sedimentary sequence, which is seen to the north in place of volcanism (Fig. 2). In the east, this same stratigraphic period of the Turat Formation is represented by the dominantly volcanic Irendyk Formation.

In the southern part, the Irendyk Formation comprises a lower volcano-sedimentary sequence up to 300 m thick with a middle section of volcanic breccias and lavas of andesitic to dacitic composition. The lowermost Irendyk Formation is host to the polymetallic East Podolsk massive sulphide deposit (Tatarko, 2003) and possibly the Balta Tau polymetallic body (Holland, 2004) although elsewhere the Irendyk Formation is a largely homogeneous sequence of pyroxene and plagioclase phyric basalts and basaltic andesites, generally devoid of economic VMS deposits (Herrington et al., 2002a).

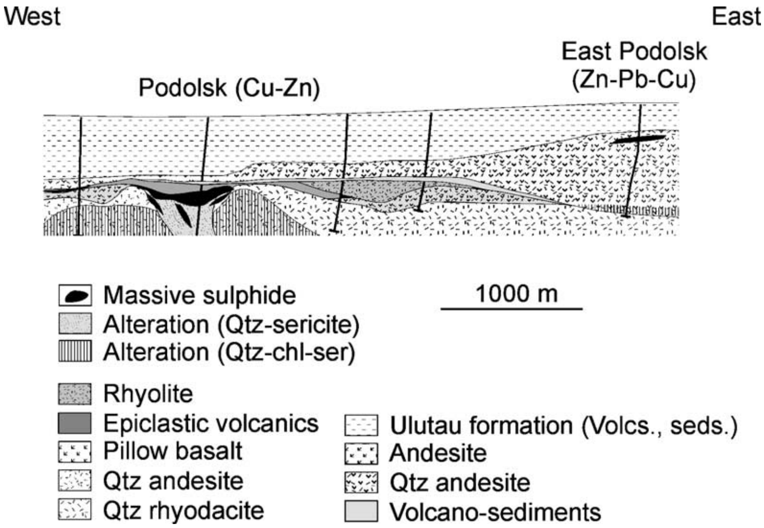


Fig. 9. Cross-section of the Podolsk Urals-type (Cu–Zn) deposit and east Podolsk Baimak-type (Zn–Pb–Cu) in the same volcanic structure (after Seravkin et al., 2003b). See location on Figs. 5 and 6.

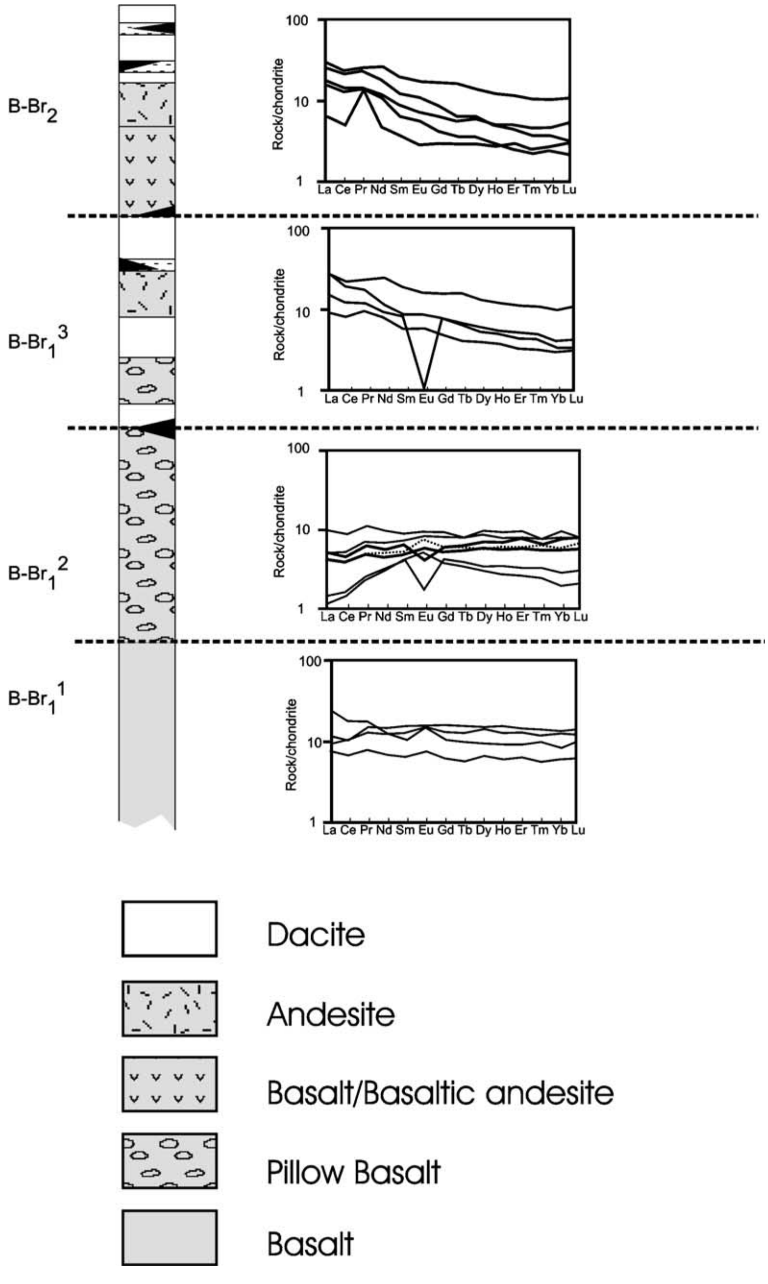


Fig. 10. Graphic log and REE patterns for mafic-intermediate lava suites of the Baimak–Buribai Formation along line of section in Fig. 6 showing key VMS horizons (data from Seravkin et al., 2003a).

The Irendyk lavas are mostly basalts and basaltic andesites, dominated by pyroxene–plagioclase phyric lavas. Spadea et al. (2002) defined three petrochemical groups, relatively primitive MORB-like tholeiites, IAT basalts and IAT tholeiitic andesites and dacites that are similar to the former group. Graphic logs of the Irendyk lava sequence in the west (Fig. 12) show the distinct changes to largely homogenous LREE-depleted and consistently flat REE patterns, similar to data from Herrington et al. (2002a).

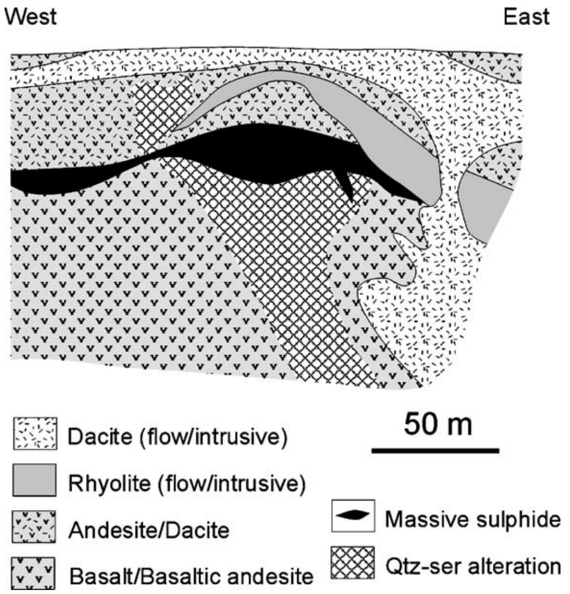


Fig. 11. Cross-section of the Baimak-type polymetallic Tash Tau deposit (after Gusev et al., 2000 with modifications).

The Irendyk Formation clearly formed a physical barrier between the west and east of the Magnitogorsk arc system (Fig. 5), which may even have been an emergent arc at the time (Herrington et al., 2002a) and therefore unlikely to host VMS deposits. The general lack of variation in volcanic chemistry and concomitant lack of significant VMS deposits (with the exception of the East Podolsk deposit and possibly Balta Tau deposits in the lowermost unit) is striking.

2.5.3. Karamalytash Formation

The Karamalytash Formation is seen to generally succeed the Irendyk Formation but the former is only developed to the east of the ridge-like development of the Irendyk volcanic rocks. Conversely, Baimak–Buribai rocks are unknown to the east of the Irendyk ridge despite drilling to more than 2 km below surface. West of the Irendyk ridge, the time period of the Karamalytash Formation is represented by the continued condensed sedimentary sequence of the Aktau and the Jarlikapovo chert sequences (Fig. 2).

The Karamalytash Formation is largely composed of basaltic rocks with thin dacitic interlayers in the lower part, passing into dacitic–rhyolitic layers with thin basalt interlayers in the upper part. Volcanic flows and hyaloclastic facies dominate with minor subvolcanic intrusives. True pyroclastic rocks are largely absent. The dacitic and rhyolitic rocks are of two broad groups. One facies, which is represented by plagioclase and pyroxene phyric rocks with abundant fine-grained groundmass magnetite, is interpreted as a differentiate from the basalts (Gusev et al., 2000). The second facies comprises abundant porphyritic, quartz plagioclase and amphibole phyric dacites–rhyolites, often with spherulitic groundmass. This second facies forms acid volcanic rocks typically associated with the massive sulphide deposits like Sibay, Uchaly and Uzelga (Prokin and Buslaev, 1999; Herrington et al., 2002a).

The top of the Karamalytash Formation is marked by the distinctive Bugulugyr chert, which is manganiferous in places (Zaykov et al., 1993; Telenkov and Maslennikov, 1995), particularly close to Sibay where at the contact with the overlying Ulutau Formation, economic manganese mineralization is being worked (Zaykov et al., 2000). The Bugulugyr chert unit correlates with the uppermost parts of the Jarlikapovo chert and Aktau condensed sequence in the west, based on conodont data (Maslov and Artyushkova, 2002). The north-east of the region is complicated by the absence of the Bugulugyr chert. Nevertheless, chert layers within basaltic sequences close to the Alexandrinka VMS deposit yield late Eifelian conodonts of similar age to that of the Bugulugyr chert (Artyushkova and Maslov, 1998) and this allows fairly complete correlation across the entire arc region (Fig. 2), including the West Mugodzhar zone.

Spadea et al. (2002) recognized both island arc tholeiitic basaltic andesites and minor calc-alkaline basalts in their limited sampling of the Karamalytash Formation. Herrington et al. (2002a) recognized the bulk of the type section of Karamalytash Formation in the Sibay area as IAT with the felsic volcanic units showing similar LREE-depleted patterns to the mafic rocks. A single late dyke in the Sibay pit shows similar features to the calc-alkaline lavas reported by Spadea et al. (2002). A graphic log from Seravkin et al. (2003a) illustrates this in Fig. 13. Herrington et al. (2002a) also noted the distinctly calc-alkaline nature of the volcanic rocks in the south-east region, hosting the Baimak-type Alexandrinka deposit which indicates an evolution to more calc-alkaline lavas in the upper parts of the Karamalytash Formation.

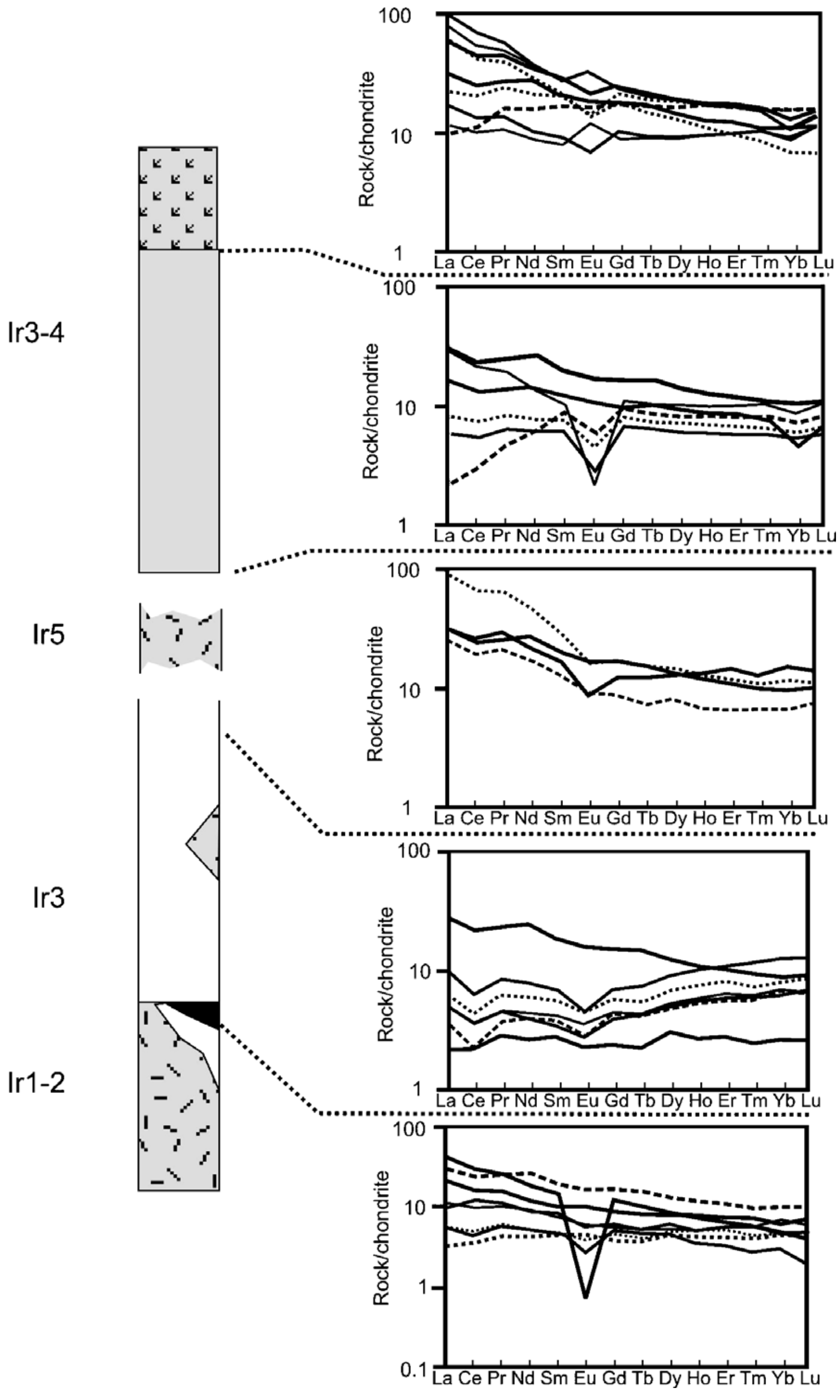


Fig. 12. Graphic log and REE patterns for mafic-intermediate lava suites of the Irendyk Formation along line of section in Fig. 6 showing key VMS horizons (data from Seravkin et al., 2003a). Key for graphic log as for Fig. 10.

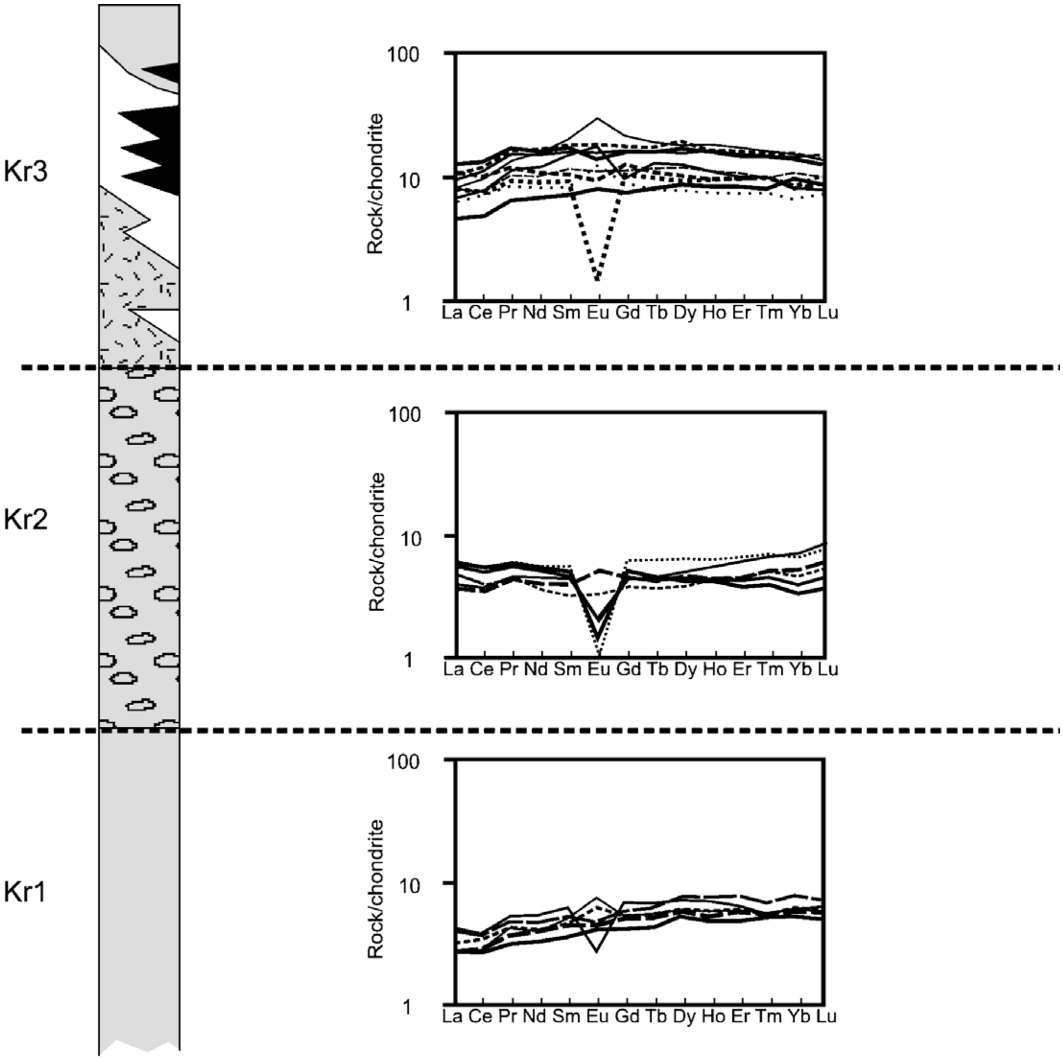


Fig. 13. Graphic log and REE patterns for mafic-intermediate lava suites of the Karamalytash Formation along line of section in Fig. 6 showing key VMS horizons (data from Seravkin et al., 2003a). Key for graphic log as for Fig. 10.

The thick bimodal tholeiitic sequences of the Karamalytash Formation are host to the giant Urals-type VMS deposits of Sibay, Uzelga and Uchaly. The calc-alkaline facies of the Karamalytash equivalent hosts the polymetallic Baimak-type Alexandrinka deposit (Herrington et al., 2002a).

In the literature, the geochemistry of felsic volcanic suites has been used to discriminate productive versus non-productive systems in Archaean VMS camps (Lesher et al., 1986). Lentz (1998) extended these studies to Proterozoic and Phanerozoic systems and more recently Hart et al. (2004) evaluated data globally from deposits through geological time. These studies indicate that rhyolites with low Zr/Y and La/Tb and relatively flat REE patterns are shown to be more productive for massive sulphide deposits than other suites. These studies are largely empirical, although Lentz (1998) shows that this type of geochemistry is consistent with magmas that have had minimal fractional crystallization of hornblende and low crustal residence times, indicative of rapid magma ascent in extending crust. Hart et al. (2004) suggest that the more productive systems are linked to thinned crust where magma chambers intrude up into fractured crust, increasing convective seawater fluid flow.

Rhyolites from the Baimak–Buribai and Karamalytash Formations that host the bulk of the VMS deposits in the South Urals are all characterized by low normalized La/Yb ratios (Gusev et al., 2000; Herrington et al., 2002a; Spadea et al., 2002). Fig. 14 shows a plot of Zr/Y for the Urals volcanic rocks plotted together with the broad fields empirically defined by Lesher et al. (1986). The dataset shows a clear discrimination between the Baimak–Buribai calc-alkaline rhyodacites (associated with small polymetallic VMS) and Karamalytash tholeiitic rhyolites (associated with giant Urals-type VMS). The Karamalytash rhyolites from Sibay plot close to the FIIIa field of Lesher et al. (1986), considered to have a much higher mineralization potential (Hart et al., 2004).

2.6. West Mugodzhar–Dombarov Zone

The West Mugodzhar–Dombarov Zone (Dombarovka–Mugodzhary Zone in Zaykov et al., 2000) formed as a back-arc basin situated behind the Magnitogorsk island-arc system (Fig. 1), on strike from the Magnitogorsk trough, and faulted in the east against the Mugdzar ”microcontinent” (Puchkov, 1997, 2000). Current exposures of this back-arc basin measure 20 to 50 km with a 400 km north–south extent. The zone is bounded by faults along strike, each block showing differences in sedimentary magmatic history (Zaykov et al., 1996). The Western Mugodzhary fault forms a shear zone, 1 to 2 km in width, which restricts the zone. Granitoid plutons of Carboniferous age extend along the contact between volcanic rocks and metamorphic rocks of the Eastern Mugodzhary zone.

Although less well studied than the Magnitogorsk Zone, the base of the volcanic section in the West Mugodzhar zone is represented by ca. 900 m of basaltic rocks, known as the Mugodzharskaya suite, that are exposed as parallel volcanic centres up to three kilometres wide (Zaykov et al., 2000). Eroded sections are cut by parallel dykes, feeder systems for the upper lava flows. Mafic volcanic units in the zone are shown to be oceanic basalts (Semenov, 1990), with major and trace element plots consistent with their MOR origin (Puchkov, 2000). The upper part

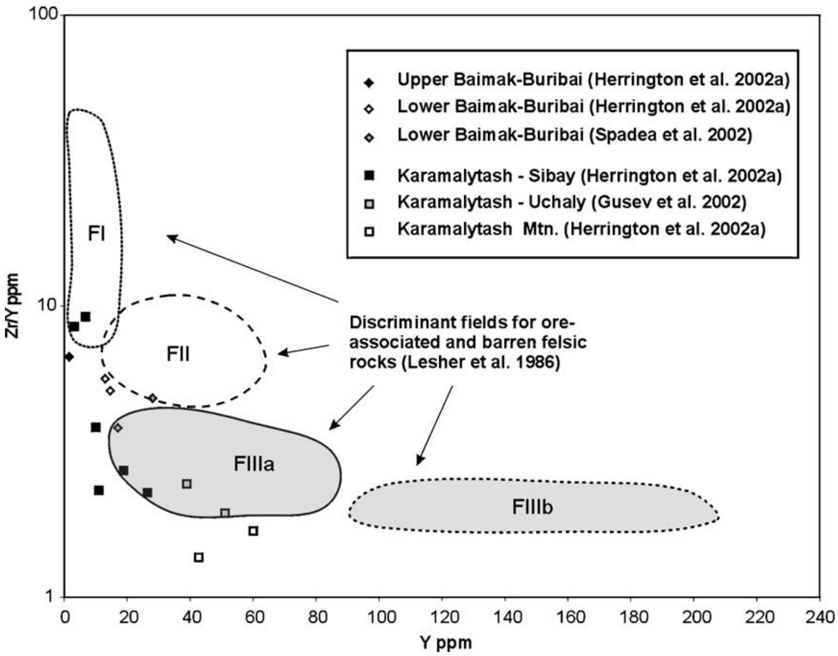


Fig. 14. Zr versus Y plot for felsic volcanic rocks of the Uralian VMS belts. Discriminant fields plotted after Lesher et al. (1986) for Canadian and other belts.

of the section is composed of jasper. The sequence is considered to be typical oceanic crust from a spreading ocean (Zaykov et al., 2000).

The upper part of the mafic sequence is a 150- to 450-m-thick basalt-jasper dominated sequence of the Kirkuduk suite. Ferruginous metalliferous sediments are common with numerous basaltic flows and sills emplaced into non-lithified mud. Picritic sills are also found (Zaykov et al., 2000). These sequences host the small Zharly Asha Cu VMS deposit. Above these lie the largely bimodal basalt–rhyolite Milyashinskaya suite that is host to significant Urals-type VMS deposits such as Priorskoye and 50 Years of October (see Fig. 2). These volcanic rocks have been shown to be transitional between back-arc tholeiitic and island arc calc-alkaline rocks in major element and trace element compositions (Seravkin and Rodicheva, 1990) and appear to mark the evolution from MORB-like magmas related to seafloor spreading and island arc tholeiite calc-alkaline suites of more mature arc affinity. Again this evolution is matched by the change from Cyprus-type Cu to Urals-type Cu–Zn deposits. The rhyolite–basalt complexes of the eastern region of the West Mugodzhar–Dombarov Zone lie at similar stratigraphic and structural positions as the eastern part of the Magnitogorsk Zone, which lies further to the north (Fig. 2). The top of the mafic dominated section of volcanic rocks is capped by the Shuldak chert, which is correlated with the Bugulugyr chert of the Magnitogorsk Zone (Zaykov et al., 2000).

2.7. Summary

In general terms, primary classification of the South Urals VMS deposits can be accommodated within the scheme embraced by Franklin et al. (in press), building on previous studies. In the case of the Urals, deposit classification can be clearly linked to footwall volcanic associations and thus to broad tectonic settings as had been previously proposed (Herrington et al., 2002a). It is proposed that the "Atlantic-type" deposits located in the MUFZ may be included as "Cyprus-type" since the host rocks have been shown to be similar seafloor hydrothermal systems in a forearc setting (Nimis et al., 2003, in press) with the Cu–Co mineralogy simply reflecting the chemistry of the largely ultramafic footwall source rocks.

In more detail, within the Magnitogorsk arc, there is clear evidence of a diversity of deposit types within a single volcanic edifice (e.g., Podolsk, Uzelga). A similar pattern is reported from the Rouyn–Noranda camp in the Abitibi belt of Canada (Gibson and Watkinson, 1990). Here, the largely mafic volcanic units of the 7- to 9-km-thick Noranda shield volcano span an age of only 3.5 million years, hosting both Cu-rich and Zn-rich VMS deposits. This is directly comparable to the Urals case where, for example, at Podolsk a ca. 3-km-thick volcanic sequence hosting the stratigraphically lower Cu–Zn and higher polymetallic VMS deposits probably spans a similar period of geological time in volcanic rocks of largely similar composition (Fig. 2). Gibson and Watkinson (1990) suggest for Noranda that waning temperatures in the hydrothermal systems may be responsible for the Zn-rich nature of the VMS higher in the sequence. At Podolsk, a similar model may be proposed, although the clear concomitant increase in felsic volcanism in the footwall to the polymetallic VMS (with much higher initial Pb and Zn content in fresh rocks) may point to a more polymetallic metal budget in the hydrothermal system in any case.

3. The role of early seafloor alteration processes including halmyrolysis

3.1. Seafloor hydrothermal activity

The previous section shows that the tectonic setting and hence volcanic suites have the primary influence on the initial metal budgets of VMS systems. Nevertheless, work on modern VMS systems has established that massive sulphide compositions can be modified by high-temperature metasomatism, low-temperature hydrothermal oxidation, submarine weathering, and degradation by mass wasting to oxides before they become part of the stratigraphic record. Subsequently, deposits can be further modified by subaerial oxidation processes.

There is abundant literature on models for establishing the primary zonation of metals in seafloor VMS systems and the processes of "zone refining" (e.g., Lydon, 1988; Large, 1992). Other authors invoke the role of evolving hydrothermal fluids (Krasnov et al., 1995) and later metamorphic processes

(Hannington et al., 1999b) for the upgrade and redistribution of copper in VMS systems. The abundance and variation of gold in VMS systems in particular has been the subject of much debate (Hannington et al., 1999a) with evidence of gold enriched in low-temperature fluids possibly overprinting the high-temperature systems (Prichard and Maliotis, 1998). The debate has largely centred on the relative importance of contrasting hydrothermal regimes and the effect of cold seawater interacting with them; the effect of the circulation heated or cooled ambient through sulphide mounds. However, the nature of their degraded and transported products has been largely neglected (Allen et al., 2002). Nevertheless, economically important gold-rich ochres, which are the product of weathering of massive sulphides in the presence of ambient seawater, are described from the VMS deposits of Cyprus where they may contain in excess of 20 ppm gold (Herzig et al., 1991). Terrestrial weathering of mined sulphide ores has been well described in the environmental literature where the variable reactivity of differing sulphide assemblages in the presence of diverse host rocks is recognized (Seal et al., 2002). Below we suggest that primary deposited sulphide ores left on the seafloor may, in a direct analogy of terrestrial supergene weathering, produce a variable, yet distinct secondary mineralogy controlled by the pH and E_h variation of ore-forming solutions and their mixing with seawater (Maslennikov et al., 2000).

Zoning in individual black smoker chimneys illustrates the process on a small scale. Pyrrhotite, isocubanite, and chalcopyrite are minerals stable under reducing conditions and precipitate in the chimney conduits where interaction with ingressing seawater is inhibited (Tivey and McDuff, 1990). Anhydrite, pyrite, marcasite, bornite, covellite, low-Fe sphalerite, barite, magnetite, and hematite are stable under oxidizing conditions and are deposited in the porous outer wall, where the fluid is quenched and mixed with seawater. As the chimney wall grows and effectively becomes sealed, these minerals become replaced by a prograde growth of chalcopyrite. Indications of seawater–fluid interaction have been documented in black smoker chimneys at the Yaman Kasy and Alexandrinka deposits (Herrington et al., 1998; Maslennikov, 1999; Maslennikov et al., in press) and more recently on the modern seafloor (e.g., Rouxel et al., 2004).

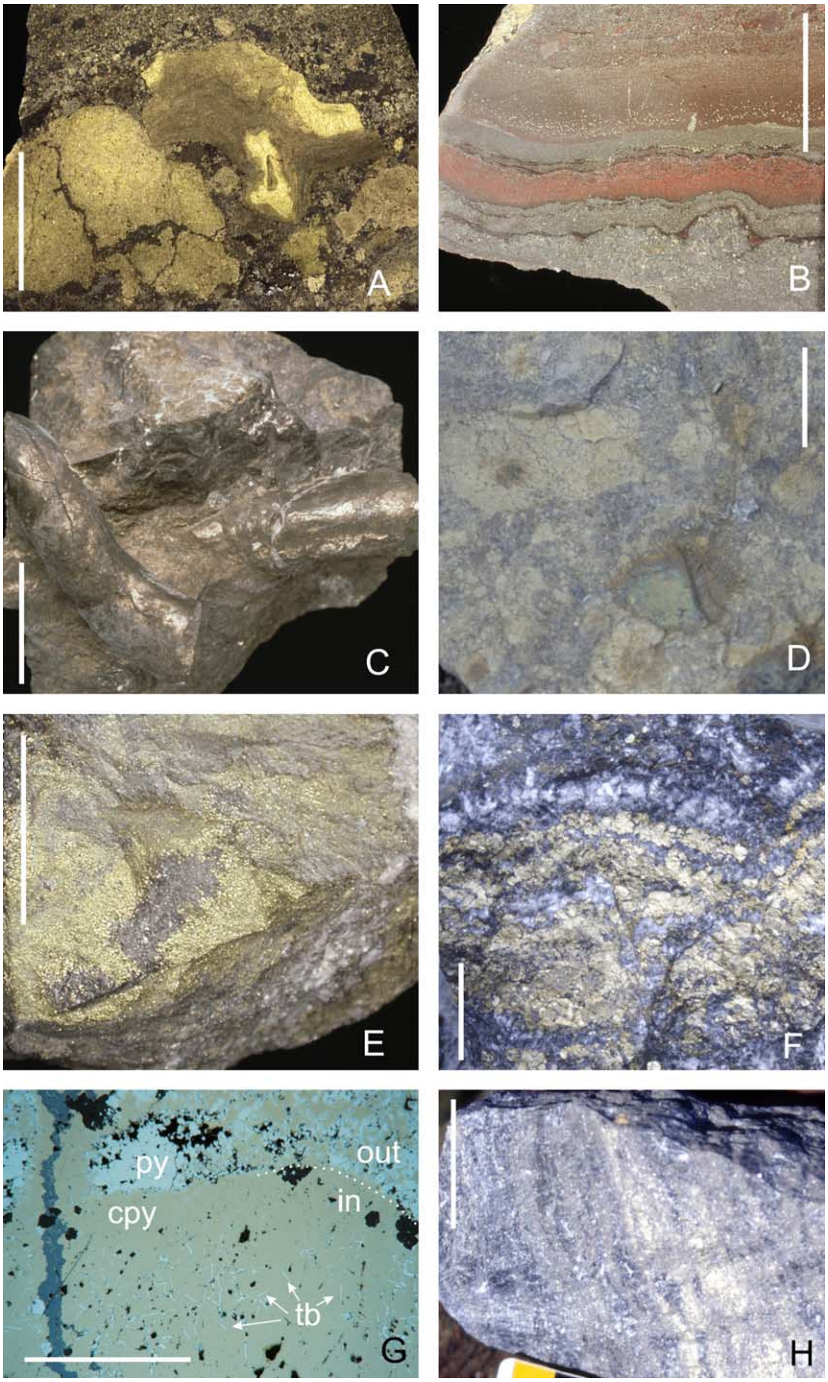
The pH and redox properties of hydrothermal fluids depend not only on the initial temperature and amount of mixing with seawater but also on the reactivity and buffering properties of rocks in the footwall. Limestone, serpentinite, basalt, and carbonaceous shales inhibit any increase in pH or E_h conditions of the hydrothermal fluids. Rhyolite, dacite, and siliceous footwall rocks are weak or inert acid buffers while silica-rich rocks (e.g., quartzites and sericite–quartz altered rocks) may actually contribute to an increase in acidity of the fluids (Zharikov, 1982).

The most obvious manifestation of sulphide precipitation on the seafloor is the formation of black smoker chimneys, documented in active vent sites and described above. The history of chimney growth serves as a useful model for seafloor VMS systems as they undergo a history of mineralization, heating, cooling, sealing by low-temperature overprint and then seawater halmyrolysis. The unequivocal similarity in zoning chimneys in the Urals (Herrington et al., 1998; Maslennikov, 1999) and modern sulphide chimneys clearly indicates common processes of mineralization regardless of black smoker age (Herrington et al., 1998). Following common models of sulphide chimney growth and consequent diagenesis, the growth can be modelled as follows.

A primary anhydrite, amorphous silica shell often forms from the hydrothermal plume, growing in two opposite directions at the interface with cold seawater (Haymon, 1983; Paradis et al., 1988). In some cases, the silica or anhydrite shell is absent with a skeletal

Fig. 15. Photographs of selected ore textures. (A) Coarse clastic sulphide ore showing graded chimney debris passing to finer sulphide sand above: talus breccia ore (Yaman Kasy). (B) Fine interlayered clastic ore with rhythmic sulphide/oxide rich bands: distal mound debris (Yaman Kasy). (C) Casts of vent fauna preserved in pyrite-chalcopyrite ore: vent-proximal biomorphic ore (Yaman Kasy). (D) Coarse sulphide breccia ore (Uchaly). (E) High-grade chalcopyrite-sphalerite ore with obvious well-preserved hydrothermal conduit texture (Tash Tau). (F) Pyrite-barite-rich ore (Alexandrinka). (G) Photomicrograph of polished sample of vent chimney conduit from Yaman Kasy. Image shows contact between inner chalcopyrite (cpy) rich core zone and pyrite (py) rich outer wall. Abundant laths of tellurobismuthite (tb) seen arrowed within primary chalcopyrite. (H) Bornite–tennantite-(barite)-rich banded ore: supergene upgrade ore (Alexandrinka). Scale bar in each case is 3 cm except panel (G) where it is 0.2 mm.

framework of sulphides being the first formed (Paradis et al., 1988). This shell or framework may show initial bladed and dendritic sulphate/sulphide growth. The conduit thus formed by the shell then grows by thickening, comprising collomorphic and dendritic sulphides with amorphous silica. The thickened shell



results in thermal insulation with an increase in temperature of the venting fluids (Paradis et al., 1988). The conduit then fills with chalcopyrite, isocubanite, less abundant pyrrhotite, and then with marcasite, sphalerite (wurtzite), barite, and quartz. The outer surface becomes covered by a dendrite-like botryoidal or laminar colloform pyrite: sulphide-oxidizing and sulphate-reducing bacteria actively participate in this process (Herrington et al., 1998). Macrofauna such as sulphide tolerant worms (alvinellids) may take part in the biomineralization process, as is suggested for the modern counterparts of sulphide chimneys (Juniper et al., 1992).

Various tellurides have been shown to have precipitated in well-preserved sulphide chimneys in the Urals within the zone of hydrothermal fluid and seawater interaction, commonly along the outer boundary of the drusy chalcopyrite zone seen to line the chimney orifice (see Fig. 15G; Maslennikov, 1999; Herrington et al., 1998; Maslennikov et al., in press). This was accompanied by the infilling of the chimney material with opal and sphalerite. As hydrothermal activity decreased, the outer rim of the sulphide chimney disintegrated or became replaced by limonite and hematite, as seen in modern black smokers (Hekinian et al., 1980). Continued oxidation in a dynamic seafloor setting resulted in chimney and mound degradation. This led to clastic ore accumulation as a rubbly sulphide mound proximal to the venting site with finer sediments dispersed in an apron around it.

Tellurides are important minor phases in many of the Urals VMS (Prokin and Buslaev, 1999). Studies on the various telluride phases in vent chimney material from Yaman Kasy show the sensitivity of the tellurium phases to oxidation state of the fluid; indeed tellurides would be expected to be unstable in oxidizing environments (Maslennikov et al., in press). Primary sylvanite, coloradoite, tellurobismuthite, volynskite, altaite, stützite-hessite, and Te-bearing cobaltite are the most abundant tellurium-bearing phases. Tellurides are replaced by sulphotellurides and native tellurium as the chimneys “age.” Sylvanite becomes replaced by a native gold; hessite by an acanthite, and native tellurium by an oxide phase. It is clear from this that tellurium geochemistry could be a useful measure of redox reactions within degrading sulphide bodies and might be even better than the use of Se, Co, Hg or sulphur stable isotope data.

3.2. Halmyrolysis of seafloor sulphide bodies

In the following analysis, the a priori assumption is made that the sulphide bodies all started as sulphide mounds exposed on the seafloor in oxygenated seawater. The classic model for seafloor VMS systems is a mound of sulphide exposed on the seafloor topped by black smokers, developed above a pipe-like stockwork (Lydon, 1988; Large, 1992). Seafloor, near-pristine mound-like massive sulphide deposits with preserved fossil vent fauna and/or evidence of seafloor vent chimney debris and near-vent sulphide talus breccias are all found in the South Urals (Little et al., 1997, 1998; Herrington et al., 1998; Tesalina et al., 1998). This model is a reasonable one for the Urals deposits given the high percentage of Urals deposits which have an unequivocal seafloor setting, hosted in deep-water rocks dominated by lava flows, flow breccias and hyaloclastites (Maslennikov, 1999; Prokin and Buslaev, 1999).

Fig. 16 shows two plots, showing on one axis the aspect ratio of the deposit (which can be considered as a proxy for the degree of mound degradation) and on the other axis either Au/Te or Ag/Te ratio. These data, together with detailed sulphide facies mapping at the various deposits, clearly support the notion that the behaviour of tellurium is a potential marker of the relative degree of seafloor alteration and reworking (Maslennikov, 1999). Taking this analysis further, VMS deposits in the Urals can be grouped into subtypes based on the degree of physical and geochemical reworking. Maslennikov et al. (2000) have made a broad four-fold subdivision based on these criteria (Fig. 17):

(1) The first sub-type of massive sulphide deposit is characterized by distinctive mound morphologies with steeply terminating margins made up of coarse clastic sulphide breccia facies (Fig. 15A). This passes to a core hydrothermal facies represented by massive chalcopyrite-pyrite, chalcopyrite-pyrrhotite, and chalcopyrite-sphalerite-pyrite ores. Finer layers of ore clasts occur at the flanks of the mounds where they form thinly bedded units (Fig. 15B). A poorly

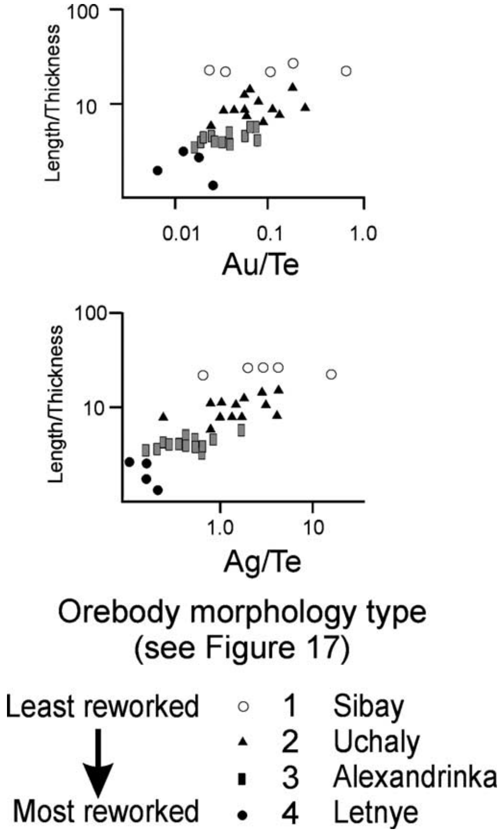


Fig. 16. Plots of Ag/Te and Au/Te ratio against aspect ratio of massive sulphide deposits of the South Urals (data from Maslennikov et al., 2000).

developed submarine supergene facies is related directly to clastic ore. Ore clasts may be replaced by chalcopyrite and, in rare cases, by bornite associated with enrichment of the upper part of the layers in gold. Sulphide sandstones are well preserved mineralogically, as pyritic ore clasts at the base of turbiditic units commonly retain primary sphalerite, framboidal and colloform pyrite. Some interlayers contain the euhedral pyrite crystals and only at the top of fine clastic ore layers are sulphides replaced by hematite. One facies of hydrothermal sulphides (Fig. 15C) shows well-preserved pyrite cast fossils in typical deposits of this type (e.g., Yaman Kasy, Sibay; Little et al., 1997, 1999). In addition to macrofauna, fine colloform pyrite and marcasite may be associated with bacterial ghosts (Little et al., 1997).

(2) The second type of deposits comprises lenticular bodies taking the form of subdued sulphide mounds. Examples of these are the Molodezhnoe, Uchaly, Uzelga and Yubilenoe deposits. The hydrothermal facies of sulphides includes chalcopyrite-pyrite, sphalerite-chalcopyrite-pyrite, and sphalerite-chalcopyrite-pyrrhotite ores. In the cores of massive sulphide lodes, hydrothermal facies dominates over clastic ore. Nevertheless, in some cases, the amount of breccia-like ore may be considerable (e.g., Uchaly; Fig. 15D). Rhythmically bedded fine clastic ore occasionally occurs on the roof of the ore lenses

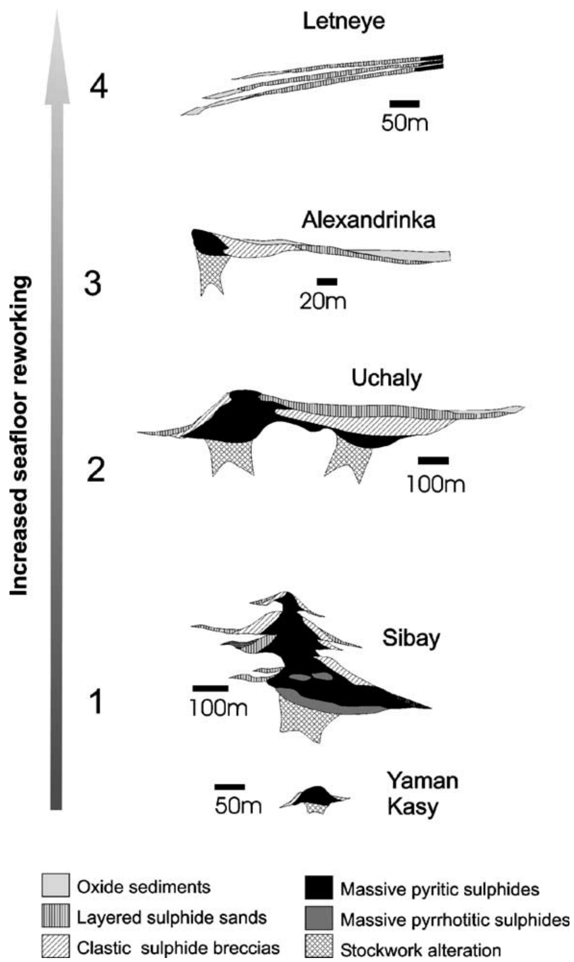


Fig. 17. Summary sections of key VMS deposits of the South Urals showing ore facies. Four orebody types are discriminated subjectively, based on the degree of sulphide mound reworking (after Maslennikov, 1999; Maslennikov et al., 2000).

and at the fringes. There is some evidence of vent fauna fragments in this zone (Molodezhnoe), indicating that this hydrothermal facies ore formed originally on the seafloor. Colloform pyrite is well preserved in the lode roofs (e.g., Blyava). Fragments of colloform pyrite are also retained in ore clasts. A well-developed, more oxidized sulphide facies is represented by a tennantite-sphalerite-bornite ore, which replaces the clastic ore in the zone of submarine supergene enrichment on the flanks of sulphide mounds (Fig. 15H). Mawsonite with native gold in fractures accompanies this tennantite-bearing facies (Zaykov and Herrington, 1998). In such conditions, Au-bearing tellurides are unstable: sylvanite, calaverite and krennerite, which are found in the first sub-type of deposits, are rare in the second and third sub-types (Maslennikov et al., 2000). Ag and Au substitute into complex sulphides such as jalpaite, stromeyerite, and mackinstryite and native gold. A barite-rich subfacies is related to the submarine leaching of clastic ore (Fig. 15F) along with development of magnetite–hematite and hematite subfacies of complete submarine oxidation (submarine gossans) (Maslennikov and Zaykov, 1991). The presence of magnetite and abundant hematite in flanking volcanic clast-rich sediments appears to correlate with abundant basaltic hyaloclasite and intercalated calcareous material at Molodezhnoe (Maslennikov et al., 2000).

(3) The third orebody sub-type forms elongate lenses of sulphide (e.g., Alexandrinka and Tash Tau). The pyrite, quartz-chalcopyrite-sphalerite-pyrite hydrothermal facies in the core of the sulphide lens often shows a breccia-like mottled texture, which indicates the fragmentation of massive sulphide chimney ore and its subsequent cementation by hydrothermal and early supergene mineral assemblages. Relict drusy chalcopyrite and sphalerite aggregates (Fig. 15E) are testament to the presence of hydrothermal conduit zones (probably feeders to vent chimneys or channelways in permeable sulphide mounds). A supergene bornite–tennantite mineralization is developed not only flanking the sulphide lenses but also overlying the central part of the lens (Tesalina et al., 1998; Maslennikov et al., 2000). In addition to breccia-like ore, fine-grained sulphide sandstones and sulphide turbidites are widely developed, commonly at the top of clastic units or as particular layers. The sulphide sandstones are silicified and contain only rare relics of colloform pyrite fragments along with framboid and pyritohedra. Sulphides with relics of macro and microfauna are locally preserved.

(4) The fourth type of sulphide body comprises thin ribbon-like sulphide sheets, mainly composed of bedded ore. Hydrothermal and coarse clastic facies are extremely rare. The signs of clastic origin of bedded ore are difficult to identify because the ore clasts are mostly replaced by pyritohedra. This has led to the banding being referred to the metasomatism or metamorphism (Yarosh, 1973). Nevertheless, the intercalation of sulphide layers with massive vitroclastic sandstone, chloritolites and cherty rocks is often observed, graded from coarser sulphide basal parts with evidence of scouring and compaction features (Maslennikov, 1999).

The need for further research in this field is clearly warranted, as it is also evident from the research of Maslennikov (1999) that the mineral composition of mixed clastic sulphide-sediment intercalations now partially reflects the nature of the intercalated sediment type. Sulphides interlayered with basaltic hyaloclastites show higher pyrrhotite contents while sulphides associated with acid hyaloclastites are pyrite or complex sulphide-rich. Magnetite-bearing metalliferous sediments are associated with basaltic hyaloclastites and carbonaceous sediments while pyrite-sericite-quartz rocks occur as interlayers in acid hyaloclastites (Maslennikov, 1999).

4. Conclusions

More detailed evaluation of the relationship between footwall lithologies and the composition of the massive sulphide bodies supports the observation of Franklin et al. (1981, in press) that this is probably the most important factor controlling orebody chemistry. In addition to this, it is recognized that both the evolution of volcanic suites within a single setting and superimposition of seafloor alteration processes have major roles to play in the style and nature of the VMS deposits formed. These processes can be summarized by three "degrees of classification," each controlled by a different process:

I. In broad terms, the composition of the footwall rocks in the South Urals, and hence major metal reservoir for the seafloor hydrothermal systems, is largely dictated by tectonic setting (Herrington et al., 2002a). Forearcs and rifted arcs contain larger volumes of mafic volcanic rocks, while more mature parts of the arc have more felsic volcanic rocks. In addition, ultramafic parts of the earliest forearc units showed significant exposure on the seafloor.

II. The composition of volcanism within individual volcanic suites in the arc evolves, and with this, there is a concomitant evolution of the chemistry of the massive sulphide bodies. In the Magnitogorsk Zone, key host volcanic suites evolve from boninitic–tholeiitic to a more calc-alkaline composition with a concomitant increase in the proportion of felsic extrusive rocks. This is matched by a concomitant evolution in the VMS deposits themselves. The tholeiites associated initially with Cu, or Cu–Co in ultramafic-rich substrates, and then with Cu–Zn deposits as the percentage of acid (rhyolite–dacite) lavas increases. The more calc-alkaline volcanic rocks of variable intermediate to felsic composition generally host more Zn-rich massive sulphides with increased contents of Ba, Pb, Au and Ag.

III. The relative degree of seafloor reworking appears to have a profound effect on orebody style and probably eventual chemistry. At the detailed scale, this can be seen in oxidized layers of clastic sulphide showing secondary sulphides and increased gold contents and it is highly likely that the process can be scaled up to the complete reworking of massive sulphide bodies on the seafloor to reworked clastic layers showing intense interaction with oxidized seawater and admixed clasts of volcanic rocks.

Given the consistency of many of the other identified parameters controlling the formation of VMS deposits, these superimposed processes discussed above for the Urals scenario can account for the complex diversity of mineralogical types identified by previous workers. This may also be the reason for the difficulty in classifying the VMS deposits into precise "types." The analysis of the effect of seafloor reworking should be extended to the study of other VMS camps where the recognized complexity of systems (e.g., Large, 1992) may be more comprehensible as a result.

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