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Lead isotopic systematics of massive sulphide deposits in the Urals: Applications for geodynamic setting and metal sources

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ABSTRACT

Lead isotopic compositions of 61 samples (55 galena, one cerussite [$PbCO_3$] and five whole ore samples) from 16 Volcanic Hosted Massive Sulphide (VHMS) deposits in the Urals Orogeny show an isotopic range between 17.437 and 18.111 for $^{206}Pb/^{204}Pb$; 15.484 and 15.630 for $^{207}Pb/^{204}Pb$ and 37.201 and 38.027 for $^{208}Pb/^{204}Pb$. Lead isotopic data from VHMS deposits display a systematic increase in ratios across the Urals paleo-island arc zone, with the fore-arc having the least radiogenic lead compositions and the back-arc having the most radiogenic lead. The back arc lead model ages according to Stacey–Kramers model are close to the biostratigraphic ages of the ore-hosting volcano-sedimentary rocks (ca. 400 Ma). In contrast, less radiogenic lead from the fore-arc gives Neoproterozoic (~700 Ma) to Cambrian (480 Ma) lead model ages with low two-stage model μ values of 8.8 (parameter $\mu = {}^{238}U/^{204}Pb$ reflects the averaged U/Pb ratio in the lead source), progressively increasing stratigraphically upwards to 9.4 in the cross-section of the ore-hosting Baymak–Buribai Formation. The range of age-corrected uranogenic lead isotopic ratios of the volcanic and sedimentary host rocks is also quite large: $^{206}Pb/^{204}Pb = 17.25–17.96$; $^{207}Pb/^{204}Pb = 15.48–15.56$, and generally matches the ores, with the exception of felsic volcanics and plagiogranite from the Karamalytash Formation being less radiogenic compare to the basaltic part of the cross-section, which would potentially imply a different source for the generation of felsic volcanics. This may be represented by older Neoproterozoic oceanic crust, as indicated by multiple Neoproterozoic ages of mafic–ultramafic massifs across the Urals. The relics of these massifs have been attributed by some workers to belong to the earlier Neoproterozoic stage of pre-Uralian ocean development. Alternative sources of lead may be Archean continental crust fragments/sediments sourced from the adjacent East-European continent, or Proterozoic sediments accumulated near the adjacent continent and presently outcropping near the western edge of Urals (Bashkirian anticlinorium). The contribution of Archean rocks/sediments to the Urals volcanic rock formation is estimated to be less than 0.1% based on Pb–Nd mixing models.

The most radiogenic lead found in VHMS deposits and volcanics in the Main Uralian Fault suture zone, rifted-arc and back-arc settings, show similar isotopic compositions to those of the local Ordovician MORBs, derived from highly depleted mantle metasomatized during dehydrational partial melting of subducted slab and oceanic sediments. The metasomatism is expressed as high $\Delta\,^{207}Pb/^{204}Pb$ values relative to the average for depleted mantle in the Northern hemisphere, and occurred during the subduction of oceanic crust and sediments under the depleted mantle wedge. A seemingly much younger episode of lead deposition with Permian lead model ages (ca. 260–280 Ma) was recorded in the hanging wall of two massive sulphide deposits.

1. Introduction

Island arc systems are considered the major sites of crust–mantle interaction where the lithospheric materials including altered oceanic crust and sediments are returned to the deep mantle as continental lithosphere is being produced. Island arc magmatism generated above a subducted oceanic plate is derived both from the slab and from the overlying mantle wedge. High-pressure dehydration of subducted crust releases fluids that act as a flux for the melting of mantle wedge peridotites and generation of arc magmas (e.g., Hofmann, 1997). During dehydration of the slab, crustal lead migrates into the overlying mantle

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wedge leading to an enrichment in lead in arc magmas and ultimately to high lead concentrations in the continental crust and consequently in VHMS deposits (Plank and Langmuir, 1998). The lead isotopic composition of massive sulphides and host rocks of recent and ancient VHMS deposits, associated with the mid-ocean ridges and island arcs, have been studied by a number of workers (e.g. Fouquet and Marcoux, 1995; Ellam et al., 1990). The isotopic composition of lead from deposits and host rocks of the Mid-Atlantic ridge is remarkably homogeneous and corresponds to the host MORB (Mid-Ocean Ridge Basalts). In contrast, the isotopic composition of lead in massive sulphides and rocks from island arcs varies more widely as is the case for the Mesozoic Japanese island arc (Tatsumoto, 1969) and the Tertiary Macuchi island arc (Chiaradia and Fontboté, 2001). This has been explained in terms of a variable contribution of lead from the subducted oceanic crust and sediments into the ore-forming fluids. Another potential source of lead in intra-oceanic island arc constitutes the cryptic relics of continental crust which can be rifted and dragged far from original continent within the basement of arcs, as it is the case in modern intra-oceanic arc Vanuatu (Buys et al., 2014) and the Solomon island arc (Tapster et al., 2014).

Thus, the significant differences among lead isotopic ratios within volcanic rocks in subduction zones is usually interpreted as a mixture of material derived from the subducted slab and the mantle wedge. The subducted slab consists of oceanic crust (characterised by a μ [$^{238}U/^{204}Pb$] ~8) and pelagic or continental sediments with a radiogenic component expressed in high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios. The sediment contribution can sometimes dominate the lead isotopic budget for some arcs (e.g., the Luzon arc, McDermott et al., 1993). The fluid/melt derived from the slab for continental arcs can be masked by the assimilation of arc crust (Hildreth and Moorbath, 1988). Intra-oceanic arcs are therefore more appropriate sites for distinguishing the isotopic composition of slab-derived fluid, e.g. the Izu-Bonin arc (Taylor and Nesbitt, 1998). Studies of the Mariana subduction zone have shown that lead is lost at a shallower depth, and U at a deeper depth from subducted altered oceanic crust, with about 44–75% of lead and <10% of U lost from altered oceanic crust to the arc, and a further 10–23% of lead and 19–40% of U lost to the back-arc (Kelley et al., 2005). The lead isotopic composition of back-arc material could be representative of the mantle wedge with a minor input of the slab component. Thus, the main question in interpreting of island-arc system formation has been to distinguish the signatures derived from the slab (and subducted sediments) and those derived from the overlying mantle wedge.

In general, the lead isotopic data found within an island arc setting cannot be explained by a simple mixing line between depleted MORB or OIB and the continental crust (Hofmann, 1997). Notably, U/Pb and Th/U ratios can be affected by magma generation and fractionation, by hydrothermal and metamorphic processes or by weathering (release of U). For example, the inverse correlation of $^{238}U/^{204}Pb$ and $^{206}Pb/^{204}Pb$ ratios across the Japanese island arc has been explained by preferential extraction of lead relative to uranium at shallow depths (Tatsumoto, 1969).

The Urals offers the chance to study a complete cross-section across the well-preserved Palaeozoic island-arc system from a boninite-like and calc-alkaline fore-arc sequence of the Baymak–Buribai series to the mainly tholeiitic island-arc Karamalitash Formation in an arc setting, and tholeiitic to calc-alkaline rocks of the Kiembay Formation in the back-arc setting. A number of massive sulphide deposits occur within the fore-arc, arc and back-arc geotectonic settings. The first investigation of lead isotopic composition in VHMS deposits of the Urals was made by Vinogradov et al. (1960) who concluded that the majority of the Urals VHMS deposits were formed in Carboniferous time and the lead isotopic compositions of the Urals deposits is very close to that of the VHMS deposits hosted by rocks of the same age in the Priirtishskaya zone of the Altay. The oldest Lower Palaeozoic deposits Ivanovskoye and Uluk are hosted by an ophiolite sequence within the Main Urals Fault Suture Zone and have a mantle affinity. Ershov and Prokin (1992) proposed that old crustal lead with a model age of 1900 Ma had contributed to the Formation of massive sulphide systems in the Urals, suggesting that blocks of old crustal rocks could exist at depth in the mantle. The same conclusion concerning the contribution of old crustal lead to VHMS deposits formation was reached by Sundblad et al. (1996) who studied lead isotopic compositions in some Urals-type (Uchaly, Molodezhnoye, Safyanovskoye deposits) and the Bakr-Tau deposit of Baymak type which show an average $^{206}Pb/^{204}Pb$ ~17.7 and μ ~9.6–9.7. These authors proposed crustal contamination by Riphean platform sediments, similar to the rocks of the Bashkirskiy anticlinorium, which would have contributed to the source of the volcanic rocks in Magnitogorsk zone. Brown and Spadea (1999) further developed this idea of a continental contribution, which is supposed to be a part of the East European craton, referring in particular to the Maksutovo Complex that has been dragged into the subduction zone. For this reason, the tectonic development of the Urals can be compared to that of the Papua New Guinea, Timor and Taiwan volcanic arcs where volcanism stopped shortly after the entry of continental crust into the subduction zone.

The most recent paper describing the lead isotopic composition of massive sulphide deposits in Urals was published by Chernyshev et al. (2008) who studied galenas from 13 massive sulphide deposits situated in the Middle and Southern Urals. They concluded that the ancient continental crust of the eastern island-arc margin and marine sediments of the Devonian volcano–sedimentary sequences played a crucial role in the contamination of primary mantle melts with crustal material. The trend of increasing second stage μ(2) values in the ore-hosted lead from Silurian and Early Devonian (9.48–9.54) to the Middle Devonian (9.66–9.83) was attributed to an increase in the differentiation degree of magmas and the maturity of the crust.

In this paper, the application of lead isotopic compositions as a means of testing the role of subducted oceanic lithosphere versus continental crust in the source of lead in 16 VHMS deposits of the Urals arc is investigated.

2. Tectonic setting

2.1. Urals

The Urals is a well-mineralised orogenic belt, approximately 2000 km long, and was formed during Late Devonian–Early Carboniferous time as a result of the collision between the proto-Uralian island arc and the East European (also called Laurussia) and Kazakhstan continents (Borodaevskaia et al., 1977; Zonenshain et al., 1984; Puchkov, 1997; Koroteev et al., 1997; Brown et al., 2001; Seravkin et al., 1994; Zaykov et al., 1996; Herrington et al., 2005). The structure of the Urals, and in particular that of the Southern Urals, is well-preserved. The following subdivisions can be made (Fig. 1):

(1) Main Uralian Fault (MUF) suture zone with relics of ophiolite in a tectonic melange containing blocks with ages ranging from Ordovician up to Late Devonian.
(2) Magnitogorsk island arc zone, consisting of Devonian volcanic and sedimentary rocks. An intermediate “inter-arc” basin, filled by Late Devonian–Lower Carboniferous volcanic and sedimentary rocks, divides the Magnitogorsk structure into the West and East-Magnitogorsk zones;
(3) Sakmara allochthon, consisting of several tectonic sheets, composed of bathyal sediments of the continental margin (Puchkov, 2000), overlain by Ordovician (Ryazantsev, 2010) and Devonian island arc complexes and ophiolites hosting VMS deposits.

The ages of the volcanic and sedimentary rocks in the Urals are mainly based on detailed biostratigraphic studies (Maslov and Artushkova, 2010) and range from Ordovician to Carboniferous (Puchkov, 1997). The formation of the massive sulphide deposits in the Urals began in Early Silurian times with the formation of the Yaman-Kasy deposit