Geology and Genesis of the Giant Gorevskoe Pb-Zn-Ag Deposit, Krasnoyarsk Territory, Russia

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Abstract

The Gorevskoe Pb-Zn-Ag mine is currently the largest producer of Pb and Zn in Russia, exploiting one of the largest sediment-hosted Pb-Zn deposits worldwide. Despite its size and economic importance, the Gorevskoe deposit remains poorly understood. It is located on the western margin of the Siberian craton within the Yenisei Ridge, a Neoproterozoic orogenic belt. Mineralization consists of three tabular orebodies that are in turn composed of multiple stacked stratiform to strata-bound lenses of galena-pyrrhotite-sphalerite-rich massive sulfide ore, hosted in organic-rich marine metalimestones and calcareous slates of Stenian to Tonian age (1,020 ± 70 Ma). Extensive Fe-Mg-Mn-carbonate alteration haloes surround the ore lenses. The Pb isotope signature of the deposit is consistent with derivation of Pb, and probably all associated metals, from an evolved crustal source at the time of formation of the host rocks. The sulfur isotope compositions of pyrrhotite, sphalerite, galena, arsenopyrite, and pyrite (δ34S = 16.0–20.4‰) do not vary considerably across the deposit and are within the range reported for contemporaneous seawater, indicating complete reduction of marine sulfate as the main source of sulfur.

The available geologic and geochemical data indicate that the Gorevskoe deposit belongs to the sediment-hosted massive sulfide (SHMS) class of Zn-Pb deposits, with an affinity to Selwyn-type deposits. Hydrothermal mineralization appears to be temporally related to rifting and distal mafic volcanism in a passive margin setting. Geologic relationships suggest that the orebodies formed in a diagenetic environment. Furthermore, the predominance of primary pyrrhotite over pyrite as the major iron sulfide, the presence of abundant siderite, and the relatively homogeneous sulfur isotope signature of the ores indicate highly reducing conditions during ore formation. They also constrain the character of the metal-bearing fluid to be similarly reducing, and of moderate temperature (200°–300°C). Gorevskoe may thus be regarded as one of the world’s largest Selwyn-type SHMS deposits.

Introduction

With pre-mining reserves and resources of 106.43 million metric tons (Mt) of ore at 6.14% Pb, 1.82% Zn, and 49 g/t Ag (Makarov et al., 2014), the Gorevskoe deposit is one of the largest Pb-Zn-Ag deposits worldwide. It is located on the Angara River, 30 km upstream of its confluence with the Yenisei River. Because the greater part of the orebodies is situated underneath the riverbed, its exploitation required the Angara River to be diverted, and the 215-m-deep open pit to be protected by a large dam (Fig. 1).

Despite its size and economic importance, very little has been published on the geology and genesis of the Gorevskoe deposit in the western scientific literature. Smirnov and Gorzhitski (1977) and Seltmann et al. (2010) only provided very broad descriptions. As a result, Gorevskoe has been variously considered as either a sediment-hosted massive sulfide (SHMS) deposit (Leach et al., 2005; Lobanov and Nekos, 2017) or a Mississippi Valley-type (MVT) deposit (Leach et al., 2010). This uncertainty is also reflected in the Russian literature where epigenetic (Sherman, 1968; Okhapkin, 1981; Plyushchev et al., 2012) and syngenetic (Kornev et al., 1974; Akimtsev, 1992) models have been proposed. All these interpretations are complicated by the extensive remobilization of the massive sulfide ores during low-grade metamorphism and deformation (Ponomarev and Zabirov, 1988).

Fig. 1. Aerial view of the Gorevskoe mine in 2017, showing the outline of the open pit as well as the new protective dam around the deposit. Photo provided by Gorevsk Ore Mining and Processing Enterprise.
The Gorevskoe deposit was discovered in 1956 during a 1:200,000-scale geologic survey led by Yu. A. Glazyrin (Sherman et al., 1963). Its discovery was greatly facilitated by the contemporaneous completion of the Irkutsk Hydroelectric Power Plant near Lake Baikal. The flow of the Angara River was stopped to fill up the reservoir, significantly lowering the water level downstream. This enabled the discovery of outcrops of Pb-Zn mineralization in the riverbed (Strimzha, 2017). The deposit was subsequently explored below thin younger cover by drilling and various geophysical methods (Sherman et al., 1963). Most papers published in the Russian (Soviet) literature are based on the results of this early exploration campaign (e.g., Sherman, 1968; Distanov, 1977; Ponomarev and Akimtsev, 1981; Brovkov et al., 1985; Kuznetsov et al., 1990).

Mine development began in 1975, and by 1984 the mine had reached a production capacity of 0.2 Mt of ore per year. In 1991, construction of the first ore processing plant was completed, and from 1993 through 2008 the Gorevskoe mine produced and processed 0.4 Mt of ore annually.

Since 2008, production has gradually been increased to 2.5 Mt of ore per year (1.8 Mt of Pb-rich ore and 0.7 Mt of Pb-Zn-rich ore in 2017), making the Gorevskoe Ore Mining and Processing Enterprise the largest active Pb-Zn-Ag mine in Russia. Construction of a new protective dam was recently completed to develop the open pit to an overall depth of 435 m below surface and allow the mine to continue operations for the foreseeable future (Fig. 1).

This contribution provides the first comprehensive English-language description of the Gorevskoe deposit. Its major aim is to develop a better understanding of the geotectonic context and genesis of the deposit based on a reinterpretation of the existing literature complemented by new observations.

**Regional Geology**

The Gorevskoe deposit is located on the western margin of the Siberian craton within the Central Angara terrane of the Yenisei Ridge, a Late Proterozoic orogenic belt (Fig. 2). It is by far the largest of more than 300 known occurrences of polymetallic sulfide mineralization in the Yenisei Ridge (Ponomarev et al., 1991b), and the only one that is currently mined.

The Siberian craton consists of several Archean to Early Proterozoic terranes that amalgamated during the Late Paleoproterozoic (Rosen and Turkina, 2007; Glebovitsky et al., 2008). In the Neoproterozoic, it was probably part of the Rodinia supercontinent (Fig. 3; Li et al., 2008; Evans, 2009), which was assembled at ~1.1 Ga and subsequently broke up at ~750 to 700 Ma (Li et al., 2008). The Siberian craton is thought to have formed a northeastern to eastern promontory of Rodinia, being directly or indirectly connected to Laurentia.
with its present southern margin (Li et al., 2008; Pisarevsky et al., 2008; Ernst et al., 2016; Fig. 3).

Up to the Early Neoproterozoic, the current western margin of the Siberian craton, then mostly on its northern side (Fig. 3), was not tectonically active. However, around 950 Ma the transformation to a subduction zone occurred (Priyatkina et al., 2018; Fig. 3). Subsequent rifting between the Siberian craton and northern Laurentia during the break-up of Rodinia at ~800 to 700 Ma resulted in their separation, so that from about 720 Ma the Siberian craton evolved as an independent landmass (Pisarevsky et al., 2013; Pavlov et al., 2015). Subduction along the current western margin of Siberia in the Neoproterozoic led to the formation of an accretionary orogenic belt that is now referred to as the Yenisei Ridge (Vernikovsky et al., 2003; Vernikovskaya and Vernikovsky, 2006; Kuzmichev and Sklyarov, 2016).

The Yenisei Ridge forms part of the western margin of the Siberian craton, extending for almost 700 km along the Yenisei River in a northwest-southeast direction (Fig. 4). It is subdivided into five lithotectonic terranes: Angara-Kan, East Angara, Central Angara, Isakovka, and Predivinsk (Vernikovsky et al., 2003). The oldest domains of the Yenisei Ridge are located in the Angara-Kan terrane preserving Paleoproterozoic crust of the Siberian craton basement, and the East and Central Angara terranes marked by a passive margin sequence of Meso- to Early Neoproterozoic age, which probably formed on the Siberian continental slope (Vernikovsky et al., 2009). The Isakovka and Predivinsk terranes, on the other hand, comprise Neoproterozoic volcano-sedimentary successions related to an island arc and ophiolite complex (Vernikovsky et al., 2003, 2009).

The five terranes are separated from each other by large, steeply dipping regional thrust faults (Angara, Priyenisei, Ishimba, Tatarka and, Ankinov, Fig. 4) that primarily strike toward the northwest. These high-angle faults are commonly accompanied by higher order splay and collisional structures of smaller blocks (Egorov, 2004). The nearly E-W-striking Angara fault divides the Yenisei Ridge into the South-Yenisei and Transangaria segments. The Priyenisei and Tatarka-Ishimba fault systems that bound the Central Angara terrane to the east and west, respectively, are the largest thrust zones in the region (Vernikovsky et al., 2003, 2008, 2011).

**Local Geology**

The Gorevskoe deposit is located near the southern margin of the Central Angara terrane close to the junction between the Angara and Priyenisei regional faults (Figs. 4, A1).

**Lithostratigraphy**

The host rocks of the Gorevskoe deposit are part of a thick Meso- to Early Neoproterozoic metasedimentary succession, comprising four major units, all of which occur in the immediate surroundings of the deposit: the Sukhopit, Tungusik, Kirgiteisk, and Shirokinsk Groups (Makarov et al., 2014; Figs. 5B, 6). The entire succession consists predominantly of deformed and metamorphosed marine siliciclastic and carbonate-rich rocks, with minor intercalated volcaniclastic rocks (Fig. 5B). The metamorphic grade of the rocks hosting the Gorevskoe deposit ranges from zeolite to lower greenschist facies (App. A, Fig. A2). Thin sediments of mid-Paleozoic to Cenozoic age overlie the Meso- to Neoproterozoic rocks (Fig. 5A).

Near the deposit, the Sukhopit Group (Postelnikov, 1980) consists of a ~1.7-km-thick succession of mostly gray to greenish-gray phyllites and slates with minor interbeds of yellowish-gray carbonate-rich rocks and basaltic metavolcanics. The dark-gray to black carbon-bearing, locally calcareous slates of the Tungusik Group unconformably overlie the Sukhopit Group with a maximum thickness of ~0.7 km. Thus, the combined thickness of these two groups in the Gorevskoe area is much lower than elsewhere in the Central Angara terrane (8–10 km; Zuev et al., 2009).

The Kirgiteisk Group, which unconformably overlies the Tungusik Group consists of mixed siliciclastic and carbonate-rich metasediments. Basal multicolored (bluish, brown, red, green) quartzitic, locally carbon-bearing slates of the Udo-rongs Formation pass into pinkish-gray to brown conglomeratic metallimestones with associated lenses of metasandstones and then into minor black to light-gray carbon-bearing slate and massive metallimestones of the Lower Stepanovsk Formation. Increasingly finer grained, mostly siliciclastic rocks in the Middle and Upper Stepanovsk Formation occur above this carbonate-rich unit. Although dark-gray slates and greenish-gray metasiltstones dominate the Middle Stepanovsk Formation, the Upper Stepanovsk Formation is dominated by greenish- to brownish-gray lithologies. Overall, the metasediments of the Kirgiteisk Group attain a thickness of ~2 km in the deposit area.
The Shirokinsk Group, which hosts the Gorevskoe deposit and many other polymetallic sulfide occurrences in the region, is separated from the Kirgiteisk Group by another unconformity. It is subdivided into the older, carbonate-dominated Gorevsk Formation (1,020 ± 70 Ma, Pb-Pb; Kuznetsov et al., 2019) and the younger, predominantly siliciclastic Sukhokhrebtinsk Formation (Fig. 5B). Regional mapping at the 1:200,000 and 1:100,000 scales (Tselykovsky, 2002; Makarov et al., 2014) shows that the Gorevsk Formation with a total thickness of >2 km can in turn be subdivided into three units.

The Lower Gorevsk Formation, which unconformably overlies the Kirgiteisk Group, is characterized by a basal metaglomerate containing abundant fragments of metamorphosed siliciclastic rocks derived from the older metasedimentary basement of the Central Angara and the East Angara terranes.
This is overlain by gray to black carbonaceous metarandalstones and calcareous slates.

The Middle Gorevsk Formation consists of abundant light- to dark-gray metarandalstones, dolomitic metaledolimestones, and calcareous slates, many of which are carbon-bearing (Zuev et al., 2009). The dark-gray laminated metaledolimestones and calcareous slates of this unit host sulfide mineralization at Gor- evskoe and Rudakovskoe (Figs. 5–8).

The Upper Gorevsk Formation comprises crossbedded and laminated dolomitic metatandstone and metasedolostone, intercalated with thin basaltic tuft horizons. The laminated dolomitic metaledolimestones host the Kartichnoe massive sulfide occurrence (Figs. 5–8).

The Sukhokhrebtinsk Formation conformably overlies the Gorevsk Formation. It is the youngest member of the Meso- to Neoproterozoic succession in the region and is markedly different in lithologic composition from the ore-bearing Gorevsk Formation. Carbonate rocks are virtually absent. Dark-gray to black carbonaceous slate, variably colored metasedanstone, metasiltstone, and mafic metavolcanic and metavolcanoliclastic rocks define the Lower Sukhokhrebtinsk Formation. The Up- per Sukhokhrebtinsk Formation has a similar composition but lacks metavolcanic and metavolcanoliclastic components.

Igneous rocks
In addition to the metavolcanic and metavolcanoliclastic rocks occurring in the Upper Gorevsk and Lower Sukhokhrebtinsk Formations (Fig. 5B), swarms of dolerite dikes and sills are present throughout the Proterozoic lithologies hosting the Gorevskoe deposit (Figs. 6–8; Kuznetsov et al., 1990). They generally form steeply dipping lens-like bodies up to hun- dreds of meters in lateral extent and 0.1 to 20 m in width, with a predominantly northwest strike. Butan (1997) report- ed the major element composition of the least altered dol- erites near Gorevskoe to be mostly basaltic (tholeiitic, with minor picrobasalts and trachytes, App. A, Fig. A3). It is likely that most of these dikes and sills are related to the Stepanovsk Igneous Complex occurring about 20 km to the north of the deposit (Ponomarev et al., 1984; Tselykovsky, 2002; Zuev et al., 2009).

Based on geologic observations in the open pit and from drill cores, Strimzha (2017) suggested that there are dikes of pre-, syn- and postmineralization age. However, this observation must be considered with caution due to the strong de- formational overprint of the deposit. Sherman (1971) cited a K-Ar age of ~915 Ma for some of the least altered dolerite sills near the deposit. This age falls outside the age range of the Gorevsk Formation (1,020 ± 70 Ma; Kuznetsov et al., 2019) and therefore suggests that the dolerites could be substan- 

ditionally younger than the mafic volcanic and volcanoliclastic rocks present in the Upper Gorevsk and Lower Sukhokhrebtinsk Formations. However, Sherman (1971) does not report any uncertainties for the ~915 Ma age, and the available evidence on the relative age of the dolerites and host rocks therefore remains equivocal.

Structural setting
The Gorevskoe deposit is located in the northeast limb of the NW-striking (305°–310°) Gorevsk syncline, which forms part of the major regional fold system (Fig. 7). The axial plane of this structure dips steeply toward the southwest (75°–85°). Minor folds overprint the Gorevsk syncline (Makarov et al., 2014). Local structures in the deposit are further char- acterized by a complex mosaic array of smaller fault blocks created by the intersection of the two major regional fault sys- tems (Fig. 7): (A) the NW-trending thrust and normal faults, and (B) the N- to NE-trending mixed thrust and transform faults that offset faults of group A (Makarov et al., 2014, Fig. A1).

Two major normal faults bound the mineralization toward the southwest and northeast (Fig. 8). The spacing between these two structures varies from 150 m in the northwest part of the deposit to 350 m in the southeast part. Although the total downthrow in the hanging wall of the southwest fault is >500 m (Fig. 8), the total amount of vertical movement on the northeast fault is not well constrained.

Located between two major normal faults, the deposit is strongly deformed. The intensity of this deformation increas- es toward the northwest as the spacing between the bounding faults decreases. Breciation, cataclasis, mylonitization, and deformation-induced foliation and boudins at different scales are commonly observed. Secondary faulting and folding are also widely developed. The secondary faults are mostly bed- parallel, dipping steeply toward the southwest (70°–80°) and are characterized by estimated along-dip displacements of 20 to 50 m (Makarov et al., 2014).

One of the largest group B faults displaces the Main and Western orebodies on its east side from the Northwestern ore- body on its west side (Fig. 8). The NE-striking mixed thrust and transform faults of group B are generally steeply dipping (70°–80°) and show along-strike displacements of 50 to 120 m and downdip displacements of 50 to 70 m (Makarov et al., 2014). They are accompanied by up to 70-m-wide zones of de- formation and low-amplitude en echelon fault arrays (Makarov et al., 2014). Cataclasis-dominated fault cores, 4 to 15 m wide, are common and generally consist of millimeter- to centimeter- size angular fragments of shale, quartz, carbonates, and sul- fides. Even though these breccia bodies have previously been described as hydrothermal-explosive breccias by Strimzha (2017), they postdate the formation of massive sulfide ore.

Mineralization
The polymetallic sulfide mineralization at Gorevskoe occurs as three tabular strata-bound bodies in a 10- to 300-m-wide and more than 2,200-m-long zone that strikes to the north- northwest and dips steeply to the southwest (70°–85°). Be- yond the limits of the Gorevskoe deposit, minor occurrences of polymetallic sulfide mineralization exist at Kartichnoe and Rudakovskoe (Figs. 6, 7; Makarov et al., 2014).

The three ore lenses are referred to as the Main (or Central), Western, and Northwestern orebodies (Sherman et al., 1963; Fig. 8) and consist of stacked subparallel lenses of well- 

crushed material separated by weakly mineralized host rocks. The contacts between well- and poorly mineralized material are sharp to gradational and the grade distribution of Pb and Zn within individual ore lenses is irregular to patchy (Fig. 9).

The mining operation distinguishes between two major ore types: Pb- and Pb-Zn-rich ores. The distinction is made be- cause these types are treated separately during beneficiation.
Fig. 5. Lithostratigraphy of the area surrounding the Gorevskoe deposit. A. Phanerozoic sedimentary rocks. B. Proterozoic metasedimentary rocks. Modified after Makarov et al. (2014). Stage and period boundaries in the Proterozoic rocks were changed compared to Makarov et al. (2014) to be consistent with the most recent published age for the Gorevsk Formation (Kuznetsov et al., 2019). Note, however, that the exact positions of these boundaries are still not well constrained, as indicated by the broken lines.
### Stratigraphic Unit, Thickness (m)

| Stage       | Period     | Stratigraphic Unit, thickness (m) | Lithologies                                                                 |
|-------------|------------|-----------------------------------|-----------------------------------------------------------------------------|
| Neoproterozoic | Late Riphean | Tonian                            |                                                                             |
|             |            | Sulchoktrebinsk 700-800           | Upper unit. Slate, often carbon-bearing, interbedded with quartzitic metasandstone and metasiltstone. |
|             |            | Shirokinsk 660                    | Lower unit. Carbon-bearing slate (av. 1.7 wt.% C), metasandstone, metasiltstone, porphyritic metabasalt, volcaniclastic-rich slate. |
|             |            | Gorevsk 590+                      | Upper unit. Dolomitic metamostone, cross- and parallel-bedded metadolostone, basaltic metatuff. Massive sulfides of Karlichnok. |
|             |            | 1020±70 Ma                       | Middle unit. Rhythmically bedded metamortomite and dolomitic metamostone interbedded with calcareous slate; interlayers of carbon-bearing metaglomite (up to 2.8 wt.% C) and micaceous metamortomite. Massive sulfides of Gorevskoe deposit and Rudakovskoe occurrence. |
|             |            | Stenian                           |                                                                             |
|             | Middle Riphean | Stepanovsk 400+                 | Upper unit. Chloritoid-bearing slate, interlayers of metasiltstone.          |
|             |            | Kirgiteisk 500                    | Middle unit. Slate, metasandstone, lenses of metamostone.                    |
|             |            | 550+                              | Lower unit. Massive and conglomerate-like metamostone; carbon-bearing and variegated chloritoid-bearing slate, lenses of metasandstone and metasiltstone. |
|             |            | Udarovsk 500+                     | Variegated, quartzitic and carbon-bearing slate.                              |
|             |            | Tungusk 550-700                   | Carbon-bearing slate, calcareous slate, chloritoid-bearing slate, metamortomite. |
|             | Ectasian (?)| Gorbilok 950                      | Biotite- and chloride-bearing phylilit, often with garnet and magnetite; interbeds of epidote- and chlorite-bearing slate. |
|             | Early Riphean | Calymnan 750                     | Upper unit. Biotite phylilit, often with garnet and carbonate; layers of metasiltstone, metamostone, metadolostone and basaltic metatuff. |

**Legend:**
- Clay, silt
- Claystone, siltstone, mudstone / metasandstone, metamudstone
- Sand
- Sandstone / metasandstone
- Gravel, conglomerate
- Diamicton
- Shale / slate
- Metamortomite
- Porphyritic metabasalt
- Rhythmic-bedded metamortomite
- Basaltic metatuff
- Dolostone / metadolostone
- Volcaniclastic metamudstone
- Phylilit
- Cross-bedded metadolostone
- Lignite
- Conglomerate-like metasiltstone
- Massive sulfides

Fig. 5. (Cont.)
Fig. 6. Geologic surface map and cross section of the Gorevskoe ore cluster. The ore cluster is defined as an envelope around all showings of strata-bound Pb-Zn mineralization in the vicinity of the Gorevskoe deposit. Modified after Makarov et al. (2014).
Their mean compositions are listed in Table 1. The Pb-rich ores make up about 64% of current reserves, while the Pb-Zn-rich ores constitute the balance.

The Main orebody is 60 to 90 m wide (Fig. 8) and extends to a depth of 1,200 m below surface. Below this depth, the orebody splits into a series of thin, stacked ore lenses with an overall thickness of 24.5 m that wedge out at depth. The Main orebody consists of Pb-rich (77%) and Pb-Zn-rich (23%) massive to semimassive sulfide ores and contains ~73% of the total ore reserves of the deposit (Makarov et al., 2014).

The Western orebody is located 30 to 100 m to the southwest of the Main orebody and is separated from it by units of hydrothermally altered host rocks (Fig. 8). It has a sheet-like appearance with a thickness of 1 to 43 m (avg ~18 m) and a strike length of 950 m at surface. It parallels the western outlines of the Main orebody with which it merges at depth (Fig. 8). Although it only hosts about 9% of the total ore reserves, it contains relatively less Pb-rich (36%) and more Pb-Zn-rich ore (64%) than the Main orebody (Makarov et al., 2014).

The Northwestern orebody is located underneath the Angara River. At surface, the orebody appears as a group of

Table 1. Resources of Gorevskoe Deposit as of January 1, 2014 (Makarov et al., 2014)

| Orebody Type | Mt  | Pb (%) | Zn (%) | Ag (µg/g) | Cd (µg/g) |
|--------------|-----|--------|--------|-----------|-----------|
| Pb-rich ores | 57.21 | 6.66 | 0.28 | 52 | 47 |
| Pb-Zn-rich ores | 32.29 | 5.29 | 4.67 | 42 | 114 |
| Total | 89.51 | 6.16 | 1.90 | 49 | 86 |
| Total (pre-mining) | 106.43 | 6.14 | 1.82 | n.a. | n.a. |

Notes: n.a. = not available
Fig. 8. Geologic map and cross section of the Gorevskoe deposit. Modified after Sherman et al. (1963) and Makarov et al. (2014). Note that the footwall and hanging wall of the deposit are defined in both stratigraphic and structural terms (i.e., footwall is stratigraphically lower).

Siderite, quartz-siderite and quartz alteration
Surface / covered by r. Angara
Dolomite and ankerite-dolomite alteration
Carbonaceous limestones
Gossanous material
Upper Unit. Undifferentiated carbonate rocks
Clayey and micaceous limestones
Dolostone
Kazachinsk Formation. Clays, argillites, marlstones and siltstones
Gorevsk Formation

Fault
Cataclastic zone
Dolerite dike
Pb sulfide mineralization
Pb-Zn sulfide mineralization
Outline of open pit
River Angara, covering geological units (note color changes)
NNW-striking lenses over 850 m long and up to 200 m wide (Fig. 8). It contains both Pb-rich (29%) and Pb-Zn-rich ore (71%) and constitutes ~18% of the total reserves of the deposit (Makarov et al., 2014).

**Host rocks**

Unaltered host rocks to the mineralization consist of laminated metalimestones and calcareous slates of the Middle Goryevsk Formation (Figs. 10B, C, 11A, B). The fine laminations in these rocks mostly reflect variations in grain size, mineralogy, and concentration of organic matter.

The unaltered metalimestones are calcite-dominated (80–90 vol %), with lesser amounts of quartz (<10 vol %), sericite, and other micas (biotite, muscovite) (8–12 vol %), as well as accessory siderite, tourmaline, organic matter, and chlorite (Strimzha, 2017). The calcareous slates, on the other hand, contain less calcite (<60 vol %), and more quartz (up to 15 vol %) and micas (up to 25 vol %), with a similar assemblage of accessory minerals (Strimzha, 2017). Locally, dolomite and/or ankerite occur in significant quantities (up to 15 vol %).

Minor pyrrhotite (<1–4 vol %) is present throughout the entire succession, normally in the form of small cleavage-parallell patches (Fig. 11A, B). In addition, pyrrhotite occurs in quartz veins that crosscut bedding and cleavage planes (Figs. 10F, 11D).

**Alteration lithologies**

Extensive sideritization, dolomitization, and silicification of the metalimestones and calcareous slates of the Middle Goryevsk Formation are associated with the massive sulfide ore lenses (Fig. 8). The alteration is systematically zoned away from the sulfide lenses, with the thickness of individual zones varying from 2 to 80 m. In most locations, this alteration has obliterated all primary sedimentary textures (Makarov et al., 2014).

Quartz-siderite and quartz-only assemblages dominate in direct contact with the sulfide ores. This is followed outward by siderite-only assemblages that account for 75 to 50% of the altered rock volume. With increasing distance from the sulfide lenses, first ankerite and then dolomite predominate as alteration products. The altered rocks generally have sharp contacts with the unaltered limestones (Fig. 10B, C). Quartz-carbonate veins and lenses, oriented parallel to foliation are abundant in the ankerite- and dolomite-rich alteration zones (Fig. 10D). All altered lithologies are characterized by fine-grained granoblastic textures of carbonates and contain a similar assemblage of accessory minerals (biotite, sericite, chlorite, tourmaline) to the unaltered limestones (Sherman et al., 1963).

Low-grade sulfide mineralization is abundant, especially in the siderite-only and siderite-quartz alteration zones of the hanging wall. It occurs mainly as fine disseminations, stringers, veinlets or irregular clusters of galena, sphalerite, and pyrrhotite (Fig. 11C–F). Quartz-carbonate-sulfide veins locally crosscut the alteration lithologies. These are generally between 1 and 100 cm wide and postdate the major deformation and metamorphism (Figs. 10F, 11A, D). In the alteration halo, galena, sphalerite, and pyrrhotite are generally associated with milky quartz and sparry calcite (Figs. 12, 13).

**Mineralization styles**

Semimassive to massive sulfide ores dominate. They are generally fine-grained and show strong evidence of extensive remobilization and deformation. In most locations, chaotic folding and brecciation have resulted in the complete destruction of primary textures. However, in some hand specimens compositional banding with a probable pre-metamorphic origin is still recognizable (Sherman et al., 1963).

Based on the degree and style of deformation, three major textural ore-types are distinguished: brecciated, folded, and banded ores (Sherman et al., 1963). However, any specific specimen usually shows features of several of these types, and to some degree the exact classification depends on the scale of observation. In particular, brecciation textures generally occur at the scale of larger blocks and do not appear at the scale of individual hand specimens. Even though the brecciated and folded ores are present across the deposit, their occurrence is rarely linked to any obvious large-scale geological structures.

Brecciated ores are widespread and occur in all orebodies. They are characterized by subangular to rounded (Fig. 12A, B) undeformed fragments of shale, silicified limestone, and quartz-carbonate rocks (with a predominance of quartz over carbonates) hosted in a uniformly fine-grained quartz-carbonate-sulfide matrix (5–50 vol %). Boundaries between the clasts and matrix are generally sharp, with some evidence for partial replacement or abrasion of clasts.

In cases where isolated clasts of quartz or quartz-rich host-rock occur in a sulfide-only matrix, they are generally well rounded, showing strong signs of abrasion (Fig. 12C, D). This feature is referred to as “ball-texture” by Russian authors (Kovalev, 1984; Kuznetsova, 2007). It indicates large degrees of plastic deformation in the sulfide matrix. This is also indicated by the contours of alternating layers of sulfides (e.g.,...
Fig. 10. Open-pit exposures of host rocks, alteration, and ores at the Gorevskoe deposit. A. Overview of the open pit in 2015. B. Foliated hanging-wall limestones of the Middle Gorevsk Formation, Main orebody. C. Contact of foliated footwall limestones to equally foliated altered rocks of the Main orebody. D. Quartz-carbonate veins aligned to foliation in dolomite-ankerite altered limestone. E. Irregular lens of oxidized material within the Main orebody. F. Quartz-siderite-pyrite vein cutting across Pb-Zn ore.
Fig. 11. Unaltered (A-B) and altered (C-F) host rocks of the Gorevsk Formation, showing variable degrees of mineralization. A. Fine-grained foliated limestone with disseminated aggregates of pyrite cut by very thin calcite and pyrrhotite veinlets. B. Slaty limestone with signs of plastic deformation, pyrrhotite mineralization, and coarse calcite crystals. C. Finely disseminated pyrrhotite and sphalerite in altered host rock. D, E. Thin and discontinuous veinlets of pyrrhotite in altered host rocks, note quartz-chlorite (green) vein. F. Irregular lenses and streaks of pyrrhotite and galena within altered and deformed host rocks. See Table 3 for mineral abbreviations. Chl = chlorite.
Fig. 12. Mineralization styles I, A, B. Brecciated Pb ore, footwall. Clasts of fine-grained limestones with pyrite mineralization are cemented by galena-pyrrhotite-quartz assemblage. C, D. “Ball-textured” quartz clasts in highly deformed massive sulfide ores. E, F. Folded ores: dense networks of galena-pyrrhotite veinlets within complexly deformed and brecciated host rock consisting of limestone (light-gray), shale (dark-gray), and megaquartz (white), note boudinage of quartz in (E). All samples taken from Main orebody. Mineral abbreviations as in Figure 11 and Table 3, Lst = limestone.
pyrrhotite and galena) that produce flow bands and record the injection of sulfide-rich matrix into clasts of the more competent host-rocks (Fig. 12C, upper left).

The folded ores are characterized by a predominance of plastic deformation in the host-rocks. While the limestones and quartz-rich lithologies mostly behaved in a relatively brittle manner during deformation, preferentially forming brecciated textures and boudins, the calcareous shales deformed more plastically (Fig. 12E, F). In these ores, sulfides mostly occur as networks of veinlets within the host rock, or as matrix between larger host-rock fragments (Fig. 12E, F).

The banded ores are characterized by coarse, mostly bedding- or foliation-parallel layers (<0.1–5 cm) of fine- to medium-grained sulfides in the host rock (Fig. 13A, B). Boudinage of the host rock layers has generally resulted in small-scale fragmentation, giving them a granular appearance. The total sulfide content of the banded ores usually varies between 50 and 70%.

Overall, the textural variability of the Gorevskoe ores is best explained by the interplay of differences in the rheology of the major ore constituents, variations in their relative proportions, and overall strain rates during deformation. Plasticity decreases in the order sulfides > shales >> limestones > quartz, resulting in the generally plastic behavior of the sulfides in all ore types, while the behavior of the other components depended on the relative proportions of different rock types. For instance, shales behaved plastically in shale-quartz-dominated lithologies (folded ores) but behaved in a brittle manner in the sulfide-dominated ores (banded and brecciated ores). Depending on their composition, ores that have been affected by greater strain rates would generally be expected to show greater degrees of foliation and smaller grain sizes (Spry, 1969).

Ore mineralogy and metal zonation

The sulfidic ores are characterized by a relatively uniform mineral assemblage that does not vary substantially with mineralization style and spatial position in the deposit (Makarov et al., 2014). The mineralogy is summarized in Table 2 and illustrated by selected micrographs in Figure 14. The total sulfide content mostly varies between 20 and 25 vol % (semimassive ores) and 50 to 70 vol % (massive ores). Galena, sphalerite, and pyrrhotite are the dominant sulfides, with a generally greater abundance of galena than sphalerite (3:1–5:1). Pyrite

Fig. 13. Mineralization styles II. A, B. Fine-grained and highly deformed banded Pb-Zn ore comprising mainly of sphalerite, galena, and pyrrhotite. C. Coarse quartz clasts within highly deformed sulfide matrix. All samples taken from Main orebody. Mineral abbreviations as in Figures 11, 12, and Table 3.
Fig. 14. Optical micrographs of host rocks (A, B), alteration (C), and ores (D-I). A. Massive limestone, composed of fine-grained calcite, hanging wall of the deposit (transmitted light, crossed polars). B. “Laminated” metamudstone of the host rocks between the Main and Western orebodies, preserving original signs of lamination overprinted by foliation (transmitted light, crossed polars). C. Calcite within the limestone with muscovite vein and organic matter (dark-gray), between Main and Western orebodies (transmitted light, crossed polars). D. Sulfide-bearing quartz-carbonate vein, Main orebody (transmitted light, crossed polars). E. Sulfide vein in quartz-carbonate-altered host rock, Western orebody (reflected light). F. Replacement of quartz-carbonate assemblage by sulfides, Main orebody (reflected light). G. Massive sulfide ore composed of pyrrhotite and galena with minor quartz and sphalerite, Main orebody (reflected light). I. Replacement of the quartz assemblages by sulfides, Western orebody (reflected light). Mineral abbreviations as in Figures 11, 12, and Table 3, Msq = muscovite.
is generally absent, or only present in minor amounts, being most abundant in the peripheral parts of the Main and Western orebodies, as well as in the Northwestern orebody. Several other minor and accessory sulfide minerals such as tennantite, boulangerite, and pyrrhotite are also present (cf. Table 2). While these minerals are not important in volumetric terms, they are major hosts for various trace elements (e.g., Ag).

The main gangue minerals are carbonates (10–50 vol %) and quartz (20–60 vol %). Chlorite, sericite, and biotite commonly occur as minor constituents, while tourmaline, rutile, and to a lesser degree ilmenite and garnet occur as accessories.

Sulfur isotope studies of mineral concentrates from various SHMS deposits (42 g/t; cf. data in Singer et al., 2009). Silver is mostly hosted by galena and a suite of silver minerals (Table 3), including sternbergite, argentite, and pyrargyrite (cf. Table 2).

Table 2. Mineral Composition of Sulfide Ores of Gorevskoe Deposit (after Makarov et al., 2014, and own observations)

| Minerals       | Ore                          | Gangue                        |
|----------------|------------------------------|--------------------------------|
| Main           | Galena, pyrrhotite, sphalerite | Quartz, siderite, ankerite,    |
|                |                              | calcite, dolomite, chlorite,   |
|                |                              | sericite, biotite, magnetite   |
| Minor          | Pyrite, chalcopyrite, arsenopyrite, tennantite, boulangerite, jamesonite, bouronite, marcasite |                                |
| Accessory      | Sternbergite, argentite, native silver, proustite, pyrargyrite, dyscrasite, native gold | Tourmaline, rutile, ilmenite, garnet |

Geochemistry of Ores and Host Rocks

The following subsections give a brief overview of available data on the chemical and isotopic composition of the ores, as reported in the Russian literature and company reports (Sherman et al., 1963; Grinenko et al., 1984; Kuznetsov et al., 1990; Ponomarev et al., 1991a; Makarov et al., 2014).

Chemical composition

In conjunction with variations in the absolute and relative abundances of the different ore and gangue minerals, the sulfide ores at Gorevskoe show considerable variability in their elemental composition. This is illustrated by the data presented in Table 3, which are derived from the studies of Sherman et al. (1963) and Makarov et al. (2014). Note, however, that the means and ranges of values cited in this table refer to sample sets collected for research purposes. Therefore, reported values for Cd and Ag differ slightly from those cited in Table 1, which are based on the current block model of the entire deposit. Table 3 also includes information on the major host mineral(s) of each element where this is known.

The overall composition of the deposit is unusually Pb-rich and Cu-poor compared to typical SHMS and Mississippi Valley-type (MVT) Pb-Zn deposits (Figs. 15B, C). With a value of 3.4, the Pb-Zn ratio of the Gorevskoe ores is higher than 90% of all known SHMS deposits. In fact, the Pb-Zn-Cu composition of the ores is most similar to the sandstone-hosted Pb subgroup of MVT deposits, which typically have a Pb:Zn ratio > 1 (Fig. 15D).

At 49 g/t, the mean Ag content of the Gorevskoe ores is moderate, being somewhat higher than the median value for SHMS deposits (42 g/t; cf. data in Singer et al., 2009). Silver is mostly hosted by galena and a suite of silver minerals (Table 3), including sternbergite, argentite, and pyrargyrite (cf. Table 2).

The concentrations of other valuable (Ga, Ge, In) and deleterious (As, Bi, Cd, Sb, Se, Te, Tl) trace elements in the ores also fall within the general ranges expected for Pb-Zn ores (cf. Feiser, 1966; Schwarz-Schampera and Herzig, 2002; Cook et al., 2009; Frenzel et al., 2016). Unfortunately, a more detailed comparison is not possible at present since databases with representative ore compositions similar to those provided in Singer et al. (2009) for Pb, Zn, Cu, and Ag do not exist for these elements. Nevertheless, an interesting feature of the ores at Gorevskoe is the reported importance of quartz as a host of Ge, accounting for 85% of the total Ge content (Table 3). This is unusual, since sphalerite is generally considered to be the most important host for this element in Pb-Zn ores (e.g., Bernstein, 1985; Frenzel et al., 2014).

Sulfur isotopes

Sulfur isotope studies of mineral concentrates from various ore types have yielded remarkably uniform δ34S values be-
between +16.0 and +22.1 ‰ in the semimassive and massive ores (Grinenko et al., 1984; Table 4), with an overall median value of +19 ‰, which falls within the range of Late Mesoproterozoic to Early Neoproterozoic seawater sulfate (δ$^{34}$S = 10 – 24 ‰; Chu et al., 2007; Guo et al., 2015; Fakhraee et al., 2019). Within reported analytical uncertainties, the observed sulfur isotope values appear to be mostly independent of mineral, mineral association, and ore type (Grinenko et al., 1984). However, a trend towards isotopically heavier values is observed in the peripheral parts of the orebodies (Grinenko et al., 1984). Sulfides in the syn- to postmetamorphic veins have systematically lighter sulfur isotopes than their counterparts in the semimassive to massive ores, yielding mean δ$^{34}$S values between +11.9 and +16.6 ‰ (Table 4). Sulfur isotope analyses were also obtained from unmineralized host-rocks of the Gorevsk Formation, as well as isolated samples of crosscutting dolerite dikes. These gave δ$^{34}$S values of +13.0 (±4.2) ‰ and +2.7 (±1.0) ‰, respectively (Grinenko et al., 1984).

**Carbon and oxygen isotopes**

Table 5 summarizes the results of carbon and oxygen isotopic analyses of carbonate minerals in unaltered and altered host rocks within and around the Gorevskoe orebodies. The mean δ$^{13}$C values of most lithologies fall within the range of -2 to +1 ‰, typical of Proterozoic marine carbonate rocks (Schidlowski et al., 1975; Chu et al., 2007). Only siderite from the siderite-quartz altered rocks has a significantly lighter isotopic signature with a mean δ$^{13}$C value of −7.1 (±1.4) ‰.

Oxygen isotope values show two groupings. While the unaltered limestone proximal and distal to the sulfide ores, as well as siderite from the siderite-quartz zone show lighter mean δ$^{18}$O values of around +16 to +17 ‰, dolomite and ankerite from the more distal alteration zones show values of around +20 ‰. These differences are statistically significant. However, all measured δ$^{18}$O values are still within the range expected for Proterozoic marine carbonates (Schidlowski et al., 1975).

Fig. 15. Cu-Pb-Zn systematics of Gorevskoe (blue triangle) compared to four types of base metal sulfide deposits. A. Volcanic-hosted massive sulfide (VHMS) deposits. B. Sediment-hosted massive sulfide (SHMS) deposits. C. Mississippi Valley-type (MVT) deposits. D. Sandstone-hosted Pb (SHPb) deposits. Blue dots represent individual deposits. Data from Mosier et al. (2009) and Singer et al. (2009). Missing Cu values were imputed for each deposit type based on reported Pb, Zn, and Ag values, using the R-package “ Amelia” (Honaker et al., 2018) with log-ratio transformed data (alr, Zn as base, cf. van den Boogaart and Tolosana-Delgado, 2013).
**Lead isotopes**

There are no major differences between the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios of the ores and host rocks reported by Grinenko et al. (1984) and Kuznetsov et al. (1990) (Table 6). Only the $^{208}\text{Pb}/^{204}\text{Pb}$ ratio is somewhat lower in the ores. In general, the Pb isotope composition of the ore is relatively homogeneous and significant lateral or vertical changes in lead isotopes are not observed within the deposit (Kuznetsov et al., 1990). Based on a comparison with different models for the evolution of lead isotopes in the continental crust, the measured signatures permit a derivation of the lead from a crustal source at the time of formation of the host rocks at 1,020 ± 70 Ma (cf. Appendix A).

**Discussion**

**Tectonic setting and depositional environment of the host rocks to ore**

Given their age, the Meso- to Early Neoproterozoic sedimentary rocks around the Gorevskoe deposit were probably laid down along the passive northern margin of the Siberian Craton, up to and perhaps overlapping with, its transformation into a subduction zone at ~950 Ma (Likhanov et al., 2014; Priyatkina et al., 2018; Kuznetsov et al., 2019). Based on a comparison with modern and Proterozoic sedimentary environments (Reading, 1996; Grotzinger and James, 2000), we further interpret the Kirgiteisk and Shirokinsk Groups, including the immediate host rocks of the mineralization, to record deposition in a carbonate ramp environment (Wright and Burchette, 1996).

Lithological variations within the two groups are likely due to changes in relative sea-level and sediment input. Fine-grained, commonly carbonaceous, siliciclastic rocks, marlstones and laminated limestones record the deep-water environments of the outer ramp, with terrigenous material derived either from aeolian input, or through long-shore transport (Wright and Burchette, 1996). Massive and cross-bedded limestones of the Upper Gorevsk Formation record deposition in a carbonate ramp environment (Wright and Burchette, 1996). These carbonate-dominated units (silstones, sandstones) of the Upper Stepnovsk and Sukhkobreitinsk Formations probably represent transient increases in terrigenous input to the basin. In the Sukhkobreitinsk Formation, this appears to be related to rifting as indicated by the presence of contemporaneous mafic volcanic and volcanioclastic rocks. Extension associated with incipient subduction prior to ~950 Ma is the most likely cause of this rifting event (cf. Priyatkina et al., 2018).

**Relative and absolute ages of mineralization and host rocks**

The presence of extensive Fe-Mg-Mn-carbonate alteration around the sulfide lenses strongly suggests that ore-formation
occurred in a diagenetic environment. It is inconsistent with exhalative ore-formation since this would have resulted in extensive alteration of the footwall only. Similarly, it is inconsistent with epigenetic ore-formation, since the low permeability of the fine-grained host-rocks after lithification would not have allowed widespread penetration and circulation of the ore-forming fluids and the associated alteration. We further note that a diagenetic age is consistent with the formation of most well-preserved SHMS deposits elsewhere in the world (Cooke et al., 2000; Leach et al., 2005; Magnall et al., 2016), with which Gorevskoe shares many geological similarities.

Accepting that the ores formed diagenetically, they should have approximately the same absolute age as the host rocks, i.e., 1,020 ± 70 Ma (Kuznetsov et al., 2019). This just overlaps with the previously published Pb model age of 850 ± 100 Ma (Ponomarev et al., 1991a) for the deposit. However, we note that Pb model ages generally have large uncertainties, as demonstrated by a re-evaluation of the Pb isotope data available for Gorevskoe in Appendix A using different models for the evolution of the continental crust (section A4). This showed that the uncertainty of ±100 Ma cited by Ponomarev et al. (1991a) is probably understated by at least a factor two. Therefore, we prefer the more reliable direct Pb-Pb age of 1,020 ± 70 Ma (Kuznetsov et al., 2019). This just overlaps with the previously published Pb model age of 850 ± 100 Ma (Ponomarev et al., 1991a) for the deposit. However, we note that Pb model ages generally have large uncertainties, as demonstrated by a re-evaluation of the Pb isotope data available for Gorevskoe in Appendix A using different models for the evolution of the continental crust (section A4). This showed that the uncertainty of ±100 Ma cited by Ponomarev et al. (1991a) is probably understated by at least a factor two. Therefore, we prefer the more reliable direct Pb-Pb age of 1,020 ± 70 Ma (Kuznetsov et al., 2019) for the deposit.

**Relationship to magmatic activity**

The presence of mafic volcanic and volcanoclastic rocks in the Upper Gorevsk and Lower Sukhokhrebtinsk Formations suggests that distal magmatic activity coincided with ore formation. However, while the dolerite sills and dikes in the immediate surroundings of the deposit have been described as showing evidence for pre-, syn- and post-mineralization emplacement (Strinzh, 2017), such a close association is not unequivocal.

**Table 4. Average Sulfur Isotope Composition of Various Associations of Ore Minerals (Grimenko et al., 1984)**

| Mineral Association                        | No | Mean δ34S ± 2σ (%)<sup>1</sup> |
|-------------------------------------------|----|-------------------------------|
| Pyrrhotite association                    |    |                               |
| Pyrrhotite                                | 12 | 20.2 (±3.2)                   |
| Sphalerite                                | 7  | 22.1 (±1.8)                   |
| Galena                                    | 8  | 19.5 (±1.3)                   |
| Arsenopyrite                              | 4  | 19.6 (±1.5)                   |
| Pyrite                                    | 4  | 16.5 (±3.7)                   |
| Galena-pyrrhotite-sphalerite association  |    |                               |
| Pyrrhotite                                | 5  | 19.3 (±1.9)                   |
| Sphalerite                                | 27 | 20.4 (±1.6)                   |
| Galena                                    | 15 | 19.0 (±1.2)                   |
| Arsenopyrite                              | 5  | 18.5 (±3.1)                   |
| Pyrite                                    | 7  | 16.0 (±2.0)                   |
| Pyrrhotite-galena association             |    |                               |
| Pyrrhotite                                | 12 | 16.1 (±2.0)                   |
| Sphalerite                                | 3  | 19.0 (±1.0)                   |
| Galena                                    | 28 | 16.2 (±1.7)                   |
| Sulphides of later veins                  |    |                               |
| Pyrrhotite                                | 7  | 13.3 (±1.8)                   |
| Sphalerite                                | 5  | 16.6 (±1.2)                   |
| Galena                                    | 2  | 11.9 (±2.0)                   |
| Pyrite                                    | 9  | 12.2 (±2.5)                   |

<sup>1</sup>Relative to Canyon Diablo Troilite (CDT; Beaudoin et al., 1994)

**Table 5. Average Values of Isotope Composition of Carbon and Oxygen of Carbonate (Ponomarev et al., 1991a)**

| Mineral Association                        | No | δ13C (PDB) ± 2σ | δ18O (SMOW) ± 2σ |
|-------------------------------------------|----|-----------------|-----------------|
| Goresvsk Formation limestones distal to ores | 3  | −1.8 (±0.4)     | +16.1 (±2.3)    |
| Ore-hosting limestones                     | 3  | +0.8 (±0.6)     | +16.9 (±0.6)    |
| Dolomites (peripheral to ore bodies)       | 4  | −1.3 (±1.2)     | +20.1 (±0.6)    |
| Ankerite (peripheral to ore bodies)        | 4  | −2.0 (±0.9)     | +19.5 (±0.7)    |
| Siderite in siderite-quartz alteration zone| 9  | −7.1 (±1.4)     | +15.9 (±3.1)    |

Notes: PDB = Pee Dee Belemnite (Brand et al., 2014); SMOW = Standard Mean Ocean Water (Brand et al., 2014)

Nevertheless, the available data point towards a temporal association between distal mafic magmatism and mineralization. It is interesting to note in this context that an association with magmatism is a feature of some sediment-hosted Pb-Zn deposits (Leach et al., 2005; Emsbo et al., 2016). For example, temporal associations with mafic rocks like those associated with the Gorevskoe deposit have been described for several Selwyn-type deposits (Cooke et al., 2000), including Rammelsberg (Large and Walcher, 1999) and Sullivan (Lydon, 2004). A broad temporal association with distal mafic magmatism has also been described for the Irish Midlands (Wilkinson and Hitzman, 2015). Generally, these associations are thought to reflect the extensional tectonic setting in which the deposits formed rather than a direct genetic link to magmatic activity (Leach et al., 2005; Emsbo et al., 2016). That is, crustal thinning caused both magma generation and the regionally elevated geothermal gradients necessary for fluid circulation and ore formation. This also seems to be the case at Gorevskoe. The relatively small volume of magmatic rocks present in the vicinity of the deposit makes it unlikely that they could have acted as a major heat source.

**Conditions of ore formation**

Despite the strong deformational overprint, the available mineralogical, geologic, and geochemical data allow us to derive some important constraints on the physico-chemical conditions of ore formation at Gorevskoe.

First, the alteration halo of the deposit does not contain any calc-silicates or other silicate minerals such as andradite garnet or pyroxenes typical of high-temperature (300°–500°C) carbonate replacement deposits (Meinert et al., 2005). Instead, it has a simple overall mineralogy consisting mostly of quartz and various Fe-Mg-Ca-carbonates. This is similar to many classic SHMS deposits, such as the Tom and Jason deposits (Cooke et al., 2000; Magnall et al., 2016), Rammelsberg (Large and Walcher, 1999); Lady Loretta (Large and McGoldrick, 1998), Century (Broadbent et al., 1998), and McArthur River (Large et al., 2000). It points toward a low to moderate temperature of ore formation (100°–300°C; cf. Cooke et al., 2000; Magnall et al., 2016). The chemical composition of the ores, with a predominance of Ge and Ga over In, is also typical of low- to moderate-temperature Pb-Zn ores (cf. Frenzel et al., 2016).

Second, the abundance of pyrrhotite and siderite, as well as the relative scarcity of pyrite in most of the deposit indicates
that ore formation occurred under low $f_{O_2}$ and low $f_{S_2}$ conditions (Berner, 1964; Toulmin and Barton, 1964; Cooke et al., 2000; Magnall et al., 2016). The coexistence of pyrite and pyrrhotite, as well as magnetite, in some ores allows us to constrain the maximum values for both $f_{O_2}$ and $f_{S_2}$, assuming equilibrium between these minerals during ore formation. This assumption is discussed further below. The values represent maximum estimates, because many parts of the deposit only contain pyrrhotite (and siderite) without pyrite or magnetite and must therefore have formed at lower $f_{S_2}$ and $f_{O_2}$.

Using the equations of Kishima (1989) for the pyrite-pyrrhotite-magnetite buffer which fixes both $f_{S_2}$ and $f_{O_2}$, and assuming a temperature of 250°C and pressure of 250 bars, the maximum log $f_{O_2}$ value we derive for ore formation is –38.1, while the maximum log $f_{S_2}$ value is –13.4. We chose these P-T conditions to be able to compare the estimated $f_{O_2}$ value with the phase diagrams of Cooke et al. (2000) and Magnall et al. (2016) that are commonly used in the description of SHMS systems (Fig. 16). These diagrams show the stability regions of different Fe minerals in equilibrium with a typical 250°C basinal brine, as well as solubility contours for Pb, Zn, and Ba.

As Figure 16 shows, pyrrhotite(-siderite)-dominant assemblages are only stable at $f_{O_2} < -37$ in this model system. This is in good agreement with the maximum $f_{O_2}$ value estimated from the pyrite-pyrrhotite-magnetite buffer above and identifies the conditions at Gorevskoe as highly reducing in the sense of Cooke et al. (2000), i.e., very far into the field where reduced sulfur species predominate in the fluid.

Ore formation under low $f_{O_2}$ conditions is also supported by the relatively homogeneous sulfur isotope composition of the ores across the deposit (Table 4). As Ohmoto (1972) showed, appreciable sulfur isotope fractionation between fluid and sulfide minerals, which could cause strong spatial fractionalation, is only expected to occur above log $f_{O_2}$ values of –38 to –35 at 250°C, depending on pH.

Finally, we note that the pyrrhotite stability field contracts with decreasing temperature and falls outside of the Pb-Zn transport window below ~200°C (cf. Cooke et al., 2000, figs. 3, 4). This provides a lower limit on the formation temperature of the deposit.

These inferences rely on the interpretation of pyrrhotite and associated Fe minerals as primary minerals. While pyrrhotite is often a product of metamorphic processes in massive sulfide deposits (Craig and Vokes, 1993), the low metamorphic grade and comparative lack of preserved pyrite-rich
ores at Gorevskoe make such a scenario unlikely. Extensive pyrite-pyrrhotite conversion is only observed in deposits that experienced much higher metamorphic grades than Gorevskoe (amphibolite and granulite facies; Craig and Vokes, 1993). Pyrite in massive sulfide deposits metamorphosed to upper zeolite or lower greenschist facies, like Gorevskoe, does not usually convert to pyrrhotite (e.g., Neves Corvo, Relvas et al., 2006; Frenzel et al., 2019; Rammelsberg, Large and Walcher, 1999; Century, Broadbent et al., 1998). Therefore, the abundance of pyrrhotite at Gorevskoe very likely reflects a primary feature of the mineralization.

The same is probably true for the quartz-magnetite-pyrite horizons reported from the Northwestern orebody, even though their exact mode of formation is not well constrained (Makarov et al., 2014). So far, they have only been reported from drill core. For disseminated pyrite and magnetite, a primary origin is unclear. However, we note that the assumption of equilibrium between pyrite, pyrrhotite, and magnetite for the ore assemblage constrains the maximum fO2 value. If pyrite and magnetite do not reflect primary features of the mineralization but are instead due to secondary overprints, then the fO2 value must necessarily be lower than this maximum.

Note in this context that abundant primary pyrrhotite also occurs in several other massive sulfide deposits (e.g., Nicholas-Denys (VHMS/SHMS) in the Bathurst mining camp, Canada (Deakin et al., 2015), and Draa Safaar (VHMS) in Morocco (Marcoux et al., 2008; Moreno et al., 2008)). These examples appear to have formed under similar conditions as Gorevskoe (moderate temperature, low fO2, and sulfur-deficient conditions).

**Character of the metal-bearing fluid**

Figure 16 indicates that the ore fluids were reduced brines in the field labeled “Selwyn-type ore fluids” (cf. Cooke et al., 2000). Fluids from the field “oxidized brines,” while able to carry enough Pb and Zn, would not be able to reach the indicated ore-forming environment without precipitating their metal load.

Accepting these arguments, the ore fluid associated with Gorevskoe appears to resemble a Selwyn-type ore-fluid as proposed by Cooke et al. (2000). An alternative, a McArthur River-type fluid would be oxidizing and should have formed at a lower temperature (~150°C; Cooke et al., 2000) than the available evidence permits. We also note that the nature of the underlying basin fill is in agreement with a Selwyn-type setting rather than a McArthur River-type one (cf. App A, sec. A3). Furthermore, the fluid must have been relatively sulfur-poor, since it would not otherwise have been able to transport sufficient Pb and Zn (cf. Embsø et al., 1999; Embsø, 2000).

Despite the constraints on the reducing character and moderate temperature of the ore fluid, Gorevskoe shows two important characteristics that are not typical for formation from a Selwyn-type fluid: (1) the extensive Fe-Mg-Mn-carbonate alteration haloes surrounding the ore lenses, and (2) the apparent absence of barite and/or witherite. Both would be more typical of a McArthur River-type deposit (Cooke et al., 2000). However, they may also be explained by the specific features of the Gorevskoe deposit.

First, the Fe-Mg-Mn-carbonate halo can be explained by ore formation in a carbonate-rich host rock rather than the sidericlasic, carbonate-poor host lithologies generally associated with Selwyn-type deposits (cf. Cooke et al., 2000). As shown by Magnall et al. (2016) (cf. Fig. 16B), even a slight increase in the availability of carbonate in the ore-forming environment can stabilize siderite under reducing conditions, a feature not reported by Cooke et al. (2000).

Second, the absence of Ba minerals can be explained by a lack of Ba in the ore-forming fluids. As Figure 16 shows, the probable pH-fO2 field for ore-forming conditions at Gorevskoe crosses the Ba solubility contours. While Ba would have been mobile in the ore-forming environment at log fO2 values below –39 to –40 (see Fig. 16), the pyrite-magnetite-quartz assemblages in the Northwestern orebody, if primary, can only have formed beyond the solubility limits of Ba. Therefore, if appreciable Ba had been present in the ore-forming fluids it should have precipitated in association with the Northwestern orebody.

Following the arguments of Emsbo (2000), the absence of Ba is atypical of a reducing SHMS ore fluid. However, we note that recent work on the Tom and Jason deposits, both classic examples of Selwyn-type mineralization (Cooke et al., 2000), has shown that the formation of Ba minerals preceded Pb-Zn mineralization, representing a distinct diagenetic event (Magnall et al., 2020). This suggests that the Pb-Zn mineralizing fluids in these deposits may also have been poor in Ba. The absence of significant Ba at Gorevskoe could then be due to a lack of diagenetic Ba fixation from seawater during the diagenesis of the host rocks, rather than the ore fluid having an atypical composition.

Thus, there is no contradiction between these apparently atypical features and the formation of the deposit by a Selwyn-type fluid. Particularly the presence of Fe-Mg-Mn-carbonate alteration appears to be inconclusive evidence for oxidized ore fluids as previously suggested (cf. Cooke et al., 2000). Instead, it can be produced from oxidizing and reducing fluids.

**Precipitation mechanism**

Cooke et al. (2000) identified several possibilities to cause metal precipitation from a Selwyn-type fluid: temperature decrease (± reduction), pH increase, and the addition of (reduced) sulfur by fluid mixing. All of these are likely to occur at a typical trap site (Cooke et al., 2000; Magnall et al., 2016). However, by far the most efficient process for the precipitation of Pb and Zn is the addition of reduced sulfur (Cooke et al., 2000; Magnall et al., 2016).

At Gorevskoe, all these processes probably operated in concert to precipitate Pb-Zn mineralization. Buffering by carbonates in the host rock could have caused an increase in fluid pH, while reaction with organic material could have caused an increase in fO2. Significant cooling of the ore fluids would also have occurred due to proximity of the site of ore formation to the sediment-water interface (cf. Magnall et al., 2016). Finally, the advection of seawater into the ore-forming system combined with thermochemical sulfur reduction, aided by the oxidation of organic matter in the host rocks, may have introduced additional sulfur (cf. Magnall et al., 2016).

**Sources of sulfur and metals**

Lead and sulfur isotope compositions provide some constraints on the sources of Pb and sulfur. In particular, the Pb
isotope composition of the deposit is compatible with derivation from an evolved crustal source at the time of formation of the host rocks (App. A), whereas sulfur isotope compositions are indistinguishable from Stenian-Tonian boundary seawater (Chu et al., 2007; Guo et al., 2015). Therefore, the most likely scenario is that Pb, as well as the other metals, were leached from the continental crust underlying the deposit, while sulfur was derived from contemporaneous seawater.

However, the deposit is unusually Pb-rich and Cu-poor when compared to typical SHMS deposits, with which Gorevskoe shares many other geologic characteristics (Table 7). The global median Pb/Zn ratio for SHMS deposits is 0.44 (Fig. 15B), only slightly higher than the crustal average of 0.20 to 0.25 (Rudnick and Gao, 2003). This compares with a value of 3.4 for Gorevskoe.

The unusual Pb enrichment at Gorevskoe could reflect either a source signature or fractionation of Pb from Zn during leaching, transport, and/or precipitation of the metals by the ore-forming fluids. Since the hydrothermal fluid system that formed the deposit likely leached a very large volume of crustal rocks (cf. Leach et al., 2005), the mean composition of the source region of the metals would not be expected to be considerably different from average continental crust (cf. Stacey and Kramers, 1975; Leach et al., 2005). Therefore, it is likely that fractionation played a significant role in generating the high Pb/Zn ratio. This fractionation most likely occurred during leaching and/or precipitation of the metals.

Yardley (2005) showed that elevated Pb/Zn ratios relative to the crustal average may occur in low- to moderate-temperature crustal fluids. Leaching experiments have also shown that Pb can be more easily mobilized than Zn from most sedimentary rocks (Long and Angino, 1982; Lydon, 2015). However, the observed enrichments in these cases are only slight and cannot account for the high Pb/Zn ratio seen at Gorevskoe. Therefore, it is likely that the Pb/Zn ratio of the ore fluids was increased further by preferential precipitation of galena during ore formation. Figure 16 shows that galena is less soluble than sphalerite and should therefore precipitate first when the fluid enters the ore-forming environment (as indicated by the positions of the solubility contours for Pb and Zn). Evidence for this is preserved by the metal zonation of the Gorevskoe deposit, with Pb/Zn ratios decreasing stratigraphically upward. If indeed precipitation of the metal load from the ore-forming fluid was incomplete, the lower solubility and preferential precipitation of galena should have resulted in the formation of a Pb-enriched deposit.

Similar fractionation processes are thought to have operated in the formation of sandstone-hosted Pb deposits, which

Table 7. Classification of Gorevskoe according to criteria in Cooke et al. (2000) and Leach et al. (2005)

| Feature | MVT | SHMS | Gorevskoe | Indicated type1 |
|---------|-----|------|-----------|----------------|
| Relationship to host rocks | Epigenetic | Syn- to diagenetic | Syn- to diagenetic | Diagenetic2 | SHMS/MVT |
| Association to igneous rocks | None | Distal felsic volcanic association | Mafic to alkaline volcanic association for several deposits | Distal association with mafic magmatism | SHMS-S |
| Host rocks | Dolostones, limestones, rarely sandstones | Carbonaceous dolomitic silstones/shales | Carbonaceous siliciclastic silstones/shales, generally vs. little carbonate | Carbonaceous lime- stones, shales | SHMS-M/MVT |
| Mineralogy | Sph, gn, py, marc, (ba) | Sph, gn, py, po, ba, (marc) | Sph, gn, py, po, ba, (marc) | Po, gn, sph, (py) | SHMS-M |
| Ore fluid | Basinal brine (ox./red.) | Oxidized basinal brine | Reduced basinal brine | Reduced brine | SHMS-M/MVT |
| Tectonic setting | Epigenetic foreland, rift basins | Epicontinental marine platform-intracontinental rift | Epicontinental marine basin-rifted continental margin | Epicontinental marine basin – rifted continental margin | SHMS-S |
| Deposit morphology | Locally discordant, stratataound, sometimes stratiform | Generally stratiform | Generally stratiform | Stratiform2 | SHMS (MVT) |
| Alteration | Dol | Sid > ank > dol halo | No strong alteration halo, some sid in vent complex | Sid > ank > dol halo | SHMS-M |
| Ore controls | Structural, lithological | Structural, lithological | Structural, lithological | Unknown2 | SHMS/MVT |
| Ore textures | Brecciated, coarse to fine-grained, sometimes banded | Brecciated to laminated, fine-grained, banded | Brecciated to laminated, fine-grained, banded | Brecciated to banded, fine- to coarse-grained2 | SHMS (MVT) |
| Metal zonation | Variable, distal or proximal Pb | Pb > Zn + Fe > Ba | Pb > Zn + Fe > Ba | Pb > Zn + Fe | SHMS/MVT |
| Age of host rocks | Generally Phanerozoic | Paleoproterozoic to recent | Paleoproterozoic to recent | Mesoproterozoic | SHMS (MVT) |
| \(\delta^{34}S\) (%1) | Median: +8.5 | Median: +14 | Paleoproterozoic to recent | Mesoproterozoic | SHMS (MVT) |
| Range: -18 to +30 | Range: -4 to +18 | | Range: -4 to +18 | |

Overall classification: SHMS-S

1Meaning of entries: SHMS/MVT = equal probability for either type; SHMS (MVT) = greater probability for SHMS than MVT, but not unambiguous; SHMS = unambiguous indication for SHMS; SHMS-M = indication for McArthur-type SHMS; SHMS-S = indication for Selwyn-type SHMS; where only SHMS is listed, this means the subtype indication is not unambiguous

2Feature affected by metamorphism and deformation; may have been altered significantly in the process

3Statistics of median values for individual deposits as summarized in Leach et al. (2005)

Notes: Mineral abbreviations are identical to those used in Table 3 and Figure 1
show similarly high Pb/Zn ratios as Gorevskoe (Fig. 15D; Björlykke and Sangster, 1981; Björlykke and Thorpe, 1982). We also note that most Broken Hill-type deposits show Pb/Zn ratios > 1 (Spiry et al., 2009). However, the origins of this class of deposits remain enigmatic since all known examples have been affected by high-grade metamorphic overprints (Large, 2003; Emsbo et al., 2016).

**Classification**

Drawing on the empirical classification scheme introduced by Leach et al. (2005) for sediment-hosted Pb-Zn deposits, Table 7 summarizes the major features of Gorevskoe and indicates whether they favor its classification as MVT, SHMS, or both. With reference to the work of Cooke et al. (2000), the SHMS category is further subdivided into McArthur River and Selwyn-type deposits.

Within the SHMS class, Gorevskoe shows ambiguous characteristics that point to both subtypes. While its association with mafic magmatism and the setting in a rifted continental margin would be more typical of a Selwyn-type deposit, the carbonate-rich nature of the host rocks, apparent absence of barite, and extensive Fe-Mg-Mn-carbonate alteration halo point toward an affinity with McArthur River-type deposits.

However, we note that the key distinguishing characteristic between Selwyn- and McArthur River-type deposits according to Cooke et al. (2000) is the nature of the ore fluids. There is strong evidence for Gorevskoe having formed from reduced, sulfur-poor ore fluids with close affinities to the Selwyn-type fluids defined by Cooke et al. (2000). Thus, Gorevskoe should be included with the Selwyn-type deposits, rather than those of McArthur River-type.

**Summary and Conclusions**

This contribution provides the first English-language account of the geologic, geochemical, and mineralogical data available on the giant Gorevskoe Pb-Zn deposit. Overall, the available evidence suggests that Gorevskoe is an SHMS deposit with affinities to Selwyn-type mineralization that formed during the rifting of a passive margin sequence. Its subseafloor, diagenetic formation probably occurred at low to moderate temperatures in a highly reducing, sulfur-deficient environment that was accompanied by extensive Fe-Mg-Mn-carbonate alteration of the host limestones. The metals were likely derived from a crustal source, while sulfur appears to have been derived from contemporaneous seawater. Sulfide precipitation from the reduced ore fluid was probably caused by a combination of cooling, pH increase, reduction, and possibly addition of sulfur from advected seawater.

Several important features of the deposit are somewhat atypical of classic Selwyn-type SHMS deposits. These are (1) the extensive Fe-Mg-Mn-carbonate alteration halo surrounding the ore lenses, (2) the abundance of primary pyrrhotite, and (3) the absence of barite. However, these features are consistent with a reducing, carbonate-rich, ore-forming environment that was produced from a reducing, Ba-poor, ore fluid with a temperature of 200° to 300°C.

Gorevskoe has a Pb/Zn ratio (3.4/1) that is higher than 90% of all other SHMS deposits. However, the origin of this feature is not well constrained. It could reflect either an enriched source or, more probably, fractionation of Pb from Zn during metal leaching, transport, and precipitation.

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