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Polaris as a guide to northern exploration: Ore textures, paragenesis and the origin of the carbonate-hosted Polaris Zn–Pb Mine, Nunavut, Canada

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ABSTRACT

The Polaris Zn–Pb Mine in Nunavut, Canada was one of the largest single Mississippi Valley-type ore deposits in the world. Over 20 Mt of sphalerite (ZnS) and galena (PbS) was hosted in brecciated carbonate rocks of the Upper Ordovician Thumb Mountain Formation. Three paragenetic stages are recognized: 1) early dolomite and marcasite; 2) main stage sulphide and dolomite; and 3) late calcite, marcasite and barite. Ore mineral textures range from discrete crystals to massive crystal aggregates and formed as replacements of the dolomite host rock or as fracture- and open space-filling mineralization. Zinc concentration is highest in the core of the deposit where botryoidal aggregates predominate, whereas iron is concentrated in the upper part. Observations of temperature and in situ sulphur isotope fractionation support a genetic model for the Polaris deposit in which thermochemical sulphate reduction occurred within the deposit, with locally generated hydrocarbons acting as a reducing agent. Information from the Polaris Mine indicates that hydrothermal alteration including dolomite, marcasite and barite; complex paragenesis with numerous ore textures; T_h values > 100 °C associated with organic-rich strata; and a geochemical signature that includes in situ sulphur fractionation are effective predictors for determining which showings are prospective in the vast central Arctic Pb–Zn district.

1. Introduction

The central Canadian Arctic carbonate-hosted Zn–Pb district spans an area that is roughly 450 km north–south by 130 km east–west in Nunavut, Canada (Fig. 1; Dewing et al., 2007; Kerr, 1977). About 80 Zn–Pb showings occur within the area (Fig. 2). The largest was the Polaris Zn–Pb Mine, a Mississippi Valley-type ore deposit hosted in dolomitized, brecciated rocks of the Upper Ordovician Thumb Mountain Formation. In 1971 the Polaris orebody was drilled based on a gravity anomaly, and over the next few years extensive drilling defined the extent of the deposit. The Polaris Mine was in operation from 1982 to 2002, when it shut down due to depletion of reserves. Polaris was among the largest single MVT deposits in the world in terms of tonnage of metals. Life of mine production was 20.1 Mt of ore at 13.4% Zn and 3.6% Pb. Sulphide ore minerals within the deposit were sphalerite (and/or wurtzite; ZnS) and galena (PbS). Dolomite, calcite and marcasite were the dominant gangue minerals. Sulphide minerals and carbonate minerals occur as both replacement-style mineralization and void-filling mineralization.

This study provides a description of the ore and gangue mineral textures at Polaris and the distribution of sulphide minerals within the deposit. A paragenetic sequence is presented. The existing theories on the genetic origin of the deposit are discussed and new data is interpreted to indicate a single fluid model. Lastly, we discuss how Polaris can be used as a regional exploration guide in the vast central Arctic Pb–Zn District.

2. Polaris Mine

2.1. Stratigraphy and geologic setting

The Upper Ordovician Thumb Mountain Formation is a 340 m thick package of shallow-water carbonates (Fig. 3). The Thumb Mountain Formation is divided into two informal members, the lower Thumb Mountain (LTM) and the upper Thumb Mountain (UTM). The LTM consists mainly of dolomudstone with some wackestone and grainstone, whereas the UTM is more porous, composed mainly of wackestones with only minor mudstone and shale. The UTM is overlain by deeper water shale deposited during the Upper Ordovician to Silurian. For a detailed description of the stratigraphy, refer to Dewing, et al. (2007).

The Polaris Mine is located on the northeast flank of a large NW–SE oriented anticline that formed during the Late Silurian to the Middle Devonian Boothia Uplift (Thorsteinsson and Uyeno, 1980). Beds dip

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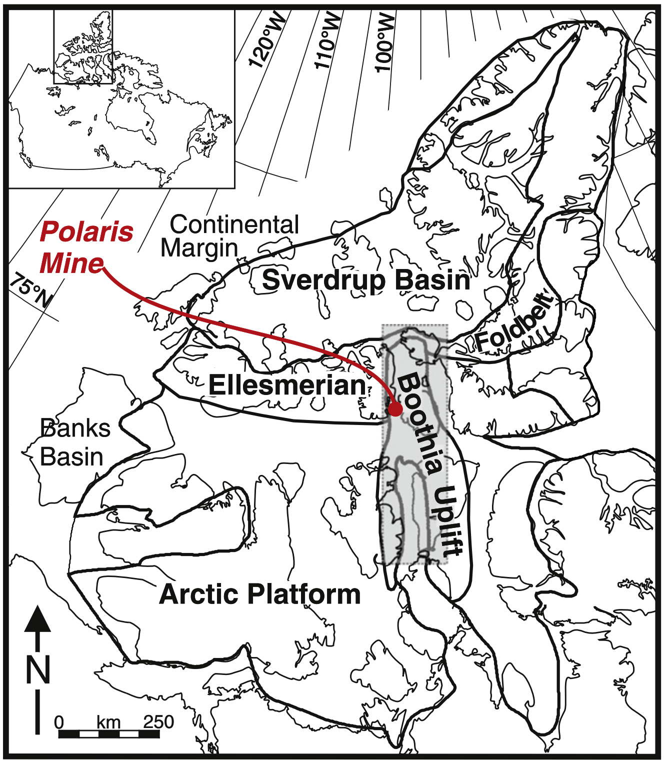

Fig. 1. Location of the study area, Canadian Arctic. The Arctic Platform consists of un-deformed lower Palaeozoic strata; the Boothia Uplift contains lower Palaeozoic strata deformed in the Late Silurian–Early Devonian; the Ellesmerian Foldbelt contains lower Palaeozoic strata deformed in the Late Devonian. Sverdrup Basin contains Carboniferous to Cretaceous strata. The Polar Continental Margin contains Cretaceous to Tertiary strata on the current margin of the Arctic ocean.

18° to the east (Fig. 4) and were weakly re-folded during the Late Devonian Ellesmerian Orogeny into a series of folds with NE–SW trending fold axes (Jober et al., 2007). Mineralization occurred preferentially along the NE–SW fold axes, implying that mineralization postdated the main phase of the Ellesmerian Orogeny (Jober et al., 2007).

2.2. Geometry of the Polaris deposit

The mined orebody was 300 m wide by 800 m long by 20 to 150 m high, with the long axis oriented parallel to the strike (Figs. 4 and 5). The orebody consisted of a tabular upper portion, called the 'Panhandle Zone', and a lower part called the 'Keel Zone' composed of a vertical vein stockwork. A broad, asymmetrical dolomite alteration halo (with traces of Zn–Pb mineralization) surrounds the orebody and is about 1200 m long by 800 m wide (Fig. 6). On the east side of the orebody, dolomitization and sulphide mineralization decrease rapidly to zero, usually within 15 m of the ore boundary. On the western side, the dolomite halo extends 550 m up dip where it is exposed at the surface on Polaris Peninsula.

2.3. Age of mineralization

Several dating techniques have been used to determine the age of mineralization of the Polaris deposit. Paleomagnetics (Symons and Sangster, 1992), Rb–Sr dating of sphalerite (Christensen et al., 1995) and Re–Os dating of bitumen (Selby et al., 2005) each indicated a Late Devonian to Early Carboniferous age for the mineralizing event.

2.4. Geochemical background information

2.4.1. Temperature

Fluid inclusions in replacement and void-filling dolomite and sphalerite crystals from Polaris have homogenization temperatures from 67 to 141 °C (Savard et al., 2000). After correcting for pressure difference, T_h is estimated to be about 105 °C (Jowett, 1975; Randell and Anderson, 1996; Savard et al., 2000). In support of this estimated temperature, vitrinite-equivalent reflectance values for the base of the UTM around the Polaris orebody equate to a temperature just above 100 °C (Barker and Pawlewicz, 1994; Héroux et al., 1999; Randell, 1994). Vitrinite-equivalent reflectance for the base of the Cape Phillips Formation immediately above the orebody reaches indicates that peak temperature may have reached 135 °C.

The spatial distribution of T_h around the main orebody suggests a model in which high-T (≥105 °C) fluids travelled up a fracture zone in the lower part of the main orebody and then spread obliquely upward between the upper Thumb Mountain and lower Thumb Mountain Formations (Sami et al., 1995).

2.4.2. Organic matter and hydrocarbons

Estimated temperature values for the Polaris deposit place it at the low end of the oil generation window (Héroux et al., 1999; Savard et al., 2000). Randell (1994) and Stasiuk (1992) describe petrographic evidence for localized transformation of algal material into bitumen and other hydrocarbons, and Savard et al. (2000) reported hydrocarbons in fluid inclusions in replacement and void-filling dolomite and sphalerite from Polaris.

An organic-rich marker bed (termed the VR marker) occurs about 10 m above the base of the UTM. It contains abundant oil-prone (Type I) kerogen. Bulk pyrolysis experiments using Rock-Eval (see Obermajer et al., 2007 for data and methodology) indicate an increase in free hydrocarbons (S1 peak) in the VR marker within the orebody as compared to away from the deposit (Table 1). The interpretation is that hot (>105 °C) ore fluids matured organic matter in the Thumb Mountain Formation to produce hydrocarbons within the Polaris orebody. Biodegradation of organic compounds discussed by Disnar and Héroux (1995) and Selby et al. (2005) may have occurred after the main phase of ore deposition.

2.4.3. Stable isotopes

Sulphur isotope ratios for sphalerite and galena from the Polaris deposit give an average $\delta^{34}S$ of 8‰ (Randell, 1994; Appendix A). Anhydrite in the Middle to Upper Ordovician Bay Fiord Formation and older Baumann Fiord Formation, the likely source of sulphate for Polaris, has $\delta^{34}S$ averaging 27‰ (Davies and Krouse, 1975; Mossop, 1979; Randell, 1994). This reflects a fractionation from the parent material (anhydrite) to the daughter product (sphalerite) of approximately −19‰.

Laser ablation done on a sample of botryoidal sphalerite from Polaris indicates that the sulphur within the sphalerite has inhomogeneous $\delta^{34}S$ values (Fig. 14). At the core of the botryoid $\delta^{34}S$ is 7.9‰ and increases in a linear fashion up to 12.0‰ at the outer edge of the botryoid (laser ablation done in the Dept. of Physics, University of Calgary, by Jaroslaw Nowak using a YAG Nd laser coupled to a mass spectrometer, unpublished data, Fig. 14). This indicates a change in the amount of fractionation of sulphur as mineralization progressed.

Strontium ratios ($^{87}Sr/^{86}Sr$) from replacement and void-filling dolomites within the Polaris deposit indicate no basement or basal clastic involvement in sourcing the dolomitizing and mineralizing fluids (Dewing et al., 2007).

3. Mineral system

Our work is based on thin sections, drill core and hand samples from the Polaris Mine stored at the Geological Survey of Canada —