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Hydrothermal controls on iron and lead mineralization on the farms Leeuwbosch and Cornwall, Thabazimbi District, South Africa

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ABSTRACT

The Paleoproterozoic Malmani Subgroup and Penge Formation (Transvaal Supergroup) exposed on the farms Leeuwbosch and Cornwall north of Thabazimbi (Limpopo Province, South Africa) host hydrothermal Pb–Ag–Cu–Zn and high-grade hematite iron ore deposits which include the historic Leeuwbosch lead mine. Based on ore petrography, fluid inclusion and stable isotope analyses and geochemical modeling, the structurally controlled, stratabound Leeuwbosch Pb–Ag–Cu–Zn–Fe deposits formed from high salinity NaCl–$CaCl_2$-rich basinal brines with total salinities from 18 to 24 wt.% NaCl equivalent which are similar to those found in the Mississippi Valley Type (MVT) Pb–Zn deposits. The minimum formation temperatures (homogenization temperatures) for the lead deposits range between 120 and 185 °C and the estimated formation conditions are 200 °C at 1 kbar pressure. Stable isotope analyses of gangue siderite and calcite indicate that the deposits formed from base metal-enriched brines derived from recycled seawater with $\delta^{13}C_{vs.\ PDB}$ from 0.46 to 3.17‰ and $\delta^{18}O_{vs.\ SMOW}$ from −2.95 to −1.79‰. Hydrothermal transport of lead and silver as $PbCl_3^-$ and $AgCl_2^-$ respectively took place at mildly acidic pH and elevated fO_2 in the SO_4^{2-} predominance field. Extensive host rock interaction neutralized and reduced the ore fluid to precipitate galena hosting Ag with chalcopyrite and sphalerite. Fluid inclusions in gangue quartz and calcite in the extensive structurally controlled and pervasive stratabound hydrothermal iron ore deposits on the farms Leeuwbosch and Cornwall, chiefly consisting of high-grade hematite with rare relict magnetite, show a wide compositional variability due to episodic fluid mixing and successive hydrothermal activity in the presence of several distinct fluid end members. Total salinities of fluid inclusions in quartz from the hematite deposits range from 9.2 to 39.9 wt.% NaCl eq. with highly variable proportions of NaCl and $CaCl_2$ and minimum formation temperatures are between 100 and 190 °C. The estimated formation conditions for the iron ore deposits are 175 °C and 1 kbar. Stable isotopes of gangue calcite indicate that diagenetic fluids with $\delta^{13}C_{vs.\ PDB}$ from −3.33 to −2.09 and $\delta^{18}O_{vs.\ SMOW}$ from 2.52 to 5.60‰ and a second fluid with $\delta^{13}C_{vs.\ PDB}$ of −7.45 and $\delta^{13}C_{vs.\ PDB}$ of 17.45 were controlling the formation of the hematite deposits. In agreement with oxidized conditions during hematite formation and characteristic host rock alteration patterns traced by carbon and oxygen isotopes, the second low salinity fluid was derived from the overlying Waterberg Group sandstones and played an important role in the formation of the iron ore deposits, in addition to high salinity diagenetic brines. Iron was leached from the BIFs of the Penge Formation, transported as $FeCl^+$ under mildly acidic conditions and likely deposited in response to the oxidation of the iron-bearing fluids. The lead and iron ore deposits formed by combinations of structural controls which influenced the regional fluid flow patterns and fluid compositions, and fluid–rock interaction with reactive carbonate lithologies of the Malmani Subgroup which acted as a sink for metals transported in acidic hydrothermal solutions.

1. Introduction

The Neoarchean to Paleoproterozoic sediments of the Transvaal Supergroup of South Africa host some of the world's largest Superior-type banded iron formation (BIF)-hosted high-grade iron ore deposits and the oldest known Mississippi Valley Type (MVT) carbonate-hosted lead–zinc–fluorite district (Greyling et al., 2001; Huizenga et al., 2006; Kesler et al., 2007; Martini et al., 1995). The extensive iron ore deposits at Sishen in the Griqualand West Basin and Thabazimbi in the Transvaal Basin formed by a combination of hydrothermal and supergene processes which upgraded the original BIFs (Beukes and Gutzmer, 2008; Beukes et al., 2002; Gutzmer, 2006; Gutzmer et al., 2005) (Fig. 1). In general, the hydrothermal upgrading of BIFs to form high-grade iron ore deposits requires the selective leaching of silica from the chert bands and oxidized fluids are necessary to form hematite-dominated

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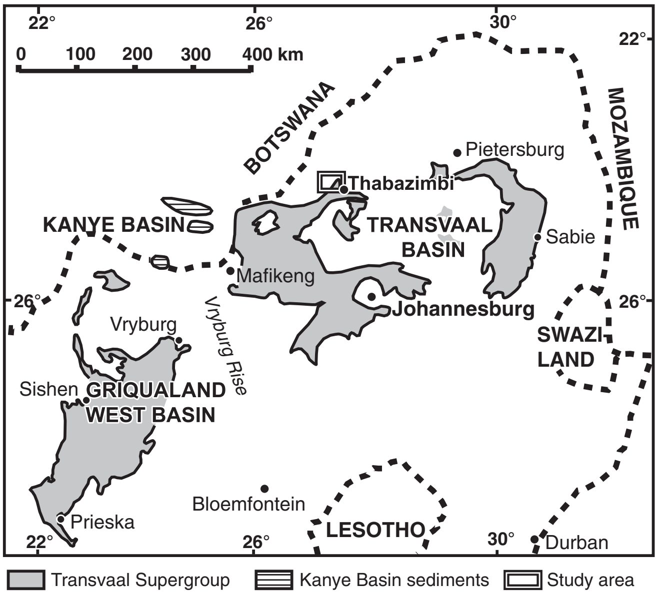

Fig. 1. Outcrop distribution of lithologies of the Transvaal Supergroup sediments in South Africa (after Eriksson et al., 2006).

ore assemblages. Commonly, BIF-hosted iron ore formation is attributed to an early hypogene stage involving alkaline fluids at which magnetite is stable and a later supergene modification stage (e.g. Barley et al., 1999; Taylor et al., 2001). The MVT deposits in the Transvaal Supergroup carbonates form a heterogeneous group with significant variations in their base metal ratios and variable fluid sources which also include possible magmatic contributions (Martini et al., 1995). Examples include the fluorite and Pb–Zn–Ag deposits at Zeerust and Genadendal in the Transvaal Basin which show evidence for a magmatic ore-forming component (Martini et al., 1995) and the sphalerite-dominated Pb–Zn deposits at Pering and Bushy Park in the Griqualand West Basin which were formed by diagenetic processes (Martini et al., 1995). A conspicuous outlier is represented by the Argent lead–silver deposits which are dominated by veins of siderite, galena and sphalerite of probably magmatic origin (Southwood and Viljoen, 1986; Wagner, 1924).

The carbonates and BIFs of the Transvaal Supergroup on the Farms Leeuwbosch and Cornwall in the Thabazimbi District of South Africa host high-grade hydrothermal galena (Pb–Ag–Cu–Zn–Fe) and closely spatially associated hematite deposits which were mined historically (Philpott and Ainslie, 1986). Mineralization occurs as fault-hosted and stratabound replacement bodies in carbonates and BIFs. Following traditional models, Philpott and Ainslie (1986) previously suggested a MVT scenario for the lead mineralization in which hypogene fluids precipitated galena upon fluid mixing, while the iron ore deposits were thought to have formed from surface-derived (supergene) fluids permeating the same structures and lithologies (Philpott and Ainslie, 1986). However, the nature and origin of the ore-forming fluids, the temperature conditions, the role of local and regional hydrothermal events, as well as the precipitation mechanisms were unconstrained. In an effort to test the previous hypotheses and to elucidate the hydrothermal processes which formed high-grade hematite and galena deposits in close spatial association on the Farms Leeuwbosch and Cornwall we conducted a detailed petrographic, fluid inclusion and stable isotope ($\delta^{18}O$, $\delta^{13}C$) study. These data are used to gain insights on the processes which leached, transported and deposited the metals, the fluid–rock ratios, to model the fO_2-pH conditions during mineralization and to identify the relationship between lead and iron mineralization. The results of this study are discussed from a regional perspective with special reference to the Thabazimbi iron ore deposits and the Transvaal Supergroup MVT district. In particular, the distinction between surficial processes and hypogene hydrothermal activity has implications for the future exploration potential in the region.

2 . Regional geology

The Transvaal Supergroup comprises a marine basin succession which occupies three outcrop areas that were interconnected at the time of deposition: the Griqualand West and Transvaal Basins in South Africa and the Kanye Basin of Botswana (Eriksson et al., 2006) (Fig. 1). At the base of the sequence, the siliciclastic 2642.2 ± 2.3 Ma old (zircon U–Pb age, Walraven and Martini, cited in Eriksson and Reczko, 1995) Black Reef Formation unconformably overlies the c. 3.0 to 2.8 Ga old Archean granitoid basement of the Makoppa Dome to the northwest of Thabazimbi (Fig. 2) (Anhaeusser and Poujol, 2004; Du Plessis and Clendenin, 1988). The Black Reef Formation is the time-stratigraphic equivalent of the Vryburg Formation in the Griqualand West Basin (SACS, 1980) and consists of quartzites, minor conglomerates, mudstones and a thin layer of shale at the top (Clendenin, 1989).

The overlying strata of the Chuniespoort Group in the Transvaal Basin are the focus of this study (Fig. 3). They consist of dolomitic and locally chert-rich stromatolitic carbonate formations of the Malmani Subgroup, the BIFs of the Penge Formation and, above an erosional unconformity, the siliciclastic Duitsland Formation (Pretoria Group). The carbonates of the Malmani Subgroup can reach thicknesses of up to 2000 m, thinning towards the edges of the Transvaal Basin (Eriksson et al., 2006). A division into five formations based on variable contents of shale, intercalated chert bands and stromatolite morphology was introduced by Button (1973): the basal Oaktree Formation and the successively younger Monte Christo, Lyttleton, Eccles and Frisco formations. Tuff layers in the Oaktree Formation have been dated at 2583 ± 5 Ma and 2588 ± 7 Ma (SHRIMP U–Pb ages for zircon; Martin et al., 1998) and 2550 ± 3 Ma (zircon Pb-evaporation; Walraven and Martini, 1995). Sedimentological models for the Malmani Subgroup and stratigraphic equivalents in the Griqualand West Basin are discussed in Beukes (1986), Eriksson and Reczko (1995), Altermann and Nelson (1998) and Eriksson et al. (2001, 2006).

The Penge Formation is a stratigraphic equivalent to the Kuruman Formation in the Griqualand West basin and is up to 340 m thick at Thabazimbi. It consists of rhythmically banded iron oxide (hematite, magnetite, goethite), iron-silicate (chert, stilpnomelane, minnesotaite), siderite and shale layers in variable proportions (Hälbich et al., 1993). The age of the Penge Formation was determined at 2480 ± 6 Ma (A.F. Trendall, unpublished, cited in Nelson et al., 1999). Above an erosional unconformity the Penge Formation is covered by siliciclastics of the Duitsland Formation. The Transvaal Supergroup is terminated by siliciclastic and volcanic lithologies of the Pretoria Group of which only the basal Timeball Hill Formation (~2.35 Ga, Walraven, cited in Eriksson et al., 1995) is exposed in the study area. The Transvaal Supergroup around Thabazimbi is exposed in several prominent outcrop ranges which form topographic highs (Fig. 2): the east to west striking Thabazimbi Range, extending more than 150 km to the west and c. 50 km to the east from Thabazimbi, and the north–northeast to south–southwest-striking Rousseauspoort Range which pinches out towards the northeast (Fig. 2; Du Plessis and Clendenin, 1988).

To the east and north of the Rousseauspoort Range extending northwards from Thabazimbi, the sandstones of the Waterberg Group form a thick cover sequence, with its basal members unconformably overlying the Transvaal Supergroup (Figs. 2 and 3). The Waterberg Group represents an "unconformity bounded sequence" (WUBS) of siliciclastic units (Cheney and Twist, 1986). Ages of 2054 ± 4 and 2051 ± 8 Ma (SHRIMP U–Pb zircon ages; Dorland et al., 2006) were reported for lavas of the lowermost Waterberg Group. South of the Thabazimbi Range, the Transvaal strata steeply dip to the south below granitic and mafic intrusive rocks of the 2061 ± 2 Ma (Walraven, 1997) to