Reactivated basement structures and their control on sandstone-hosted Pb-Zn deposit along the eastern front of the Scandinavian Caledonides

Saintilan, Nicolas; Fontboté, Lluís; Stephens, Michael B.; Lundstam, Erik

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Nicolas J.D. Saintilan, Lluís Fontboté
University of Geneva, Department of Earth Sciences, Rue des Maraîchers 13, 1205 Geneva, Switzerland

Michael B. Stephens
Geological Survey of Sweden, Box 670, SE-751 28 Uppsala, Sweden

Erik Lundstam
Boliden Mineral AB, S-776 98 Garpenberg, Sweden

Abstract. The Laisvall stratabound Pb-Zn deposit is hosted in Ediacaran–Cambrian sandstone along the eastern front of the Scandinavian Caledonides. Magnetic lineaments identified using airborne geophysical data correspond to geological features in the Palaeoproterozoic crystalline basement beneath this deposit. Geological modelling of the deposit in 3D space shows a correlation between some of the lineaments defined by magnetic minima and faults in the Ediacaran–Cambrian siliciclastic rocks, which are inferred to be spatially coupled to reactivated faults in the basement. Basement fault reactivation caused syn-sedimentary block faulting and also post-sedimentary and post-mineralisation fault movement. The reactivated faults define two major sets, which are inferred to have conditioned basin architecture and deposition of sediment during Ediacaran–Cambrian time, as N–S to NE–SW basin-parallel and WNW–ESE to NW–SE transfer faults. Lead and zinc grade modelling in 3D space revealed plume-like features that are spatially linked to NE–SW faults, suggesting these were conduits to the mineralizing fluids. These conduits and the location of the Laisvall ore bodies are spatially linked to inflection areas along magnetic minima. The geometry of the ore bodies is consistent with the presence of sour gas traps in the sandstone aquifers that may provide reduced sulphur for the formation of economic Pb-Zn deposits.

Keywords. Reactivated basement faults, Ediacaran to Cambrian, sandstone, Pb-Zn

1 Introduction

Stratabound, non-stratiform, sandstone-hosted Pb-Zn deposits and minor occurrences are known in Sweden and Norway, along the eastern front of the Scandinavian Caledonides over a distance of more than 1000 km, and include the Laisvall and Vassbo deposits (Stephens, 1986). Mineralisation is hosted by Ediacaran–Cambrian siliciclastic rocks, both in autochthonous sequences beneath the Caledonian thrust nappes resting unconformably on top of Paleoproterozoic crystalline basement (Fennoscandian Shield), and in the lowermost allochthonous units.

The present study is part of a broader project aiming to re-evaluate the role of the basement, the migration flow path, the driving force, the precipitation mechanism, and the age of sandstone-hosted Pb-Zn mineralisation in a tectonically constrained geological framework. It focuses attention on the structural and broader tectonic controls on the spatial occurrence of the Laisvall stratabound Pb-Zn deposit, hosted in autochthonous sandstone. The Laisvall deposit was an underground mine operated by Boliden Mineral AB until it closed down in 2001. Mineralisation was discovered in 1939 and mining operation started in 1941 (Grip, 1954). As a result of 70 years of mining activity, 64.3 Mt of ore at 0.6 % Zn, 4.0 % Pb and 9 g/t Ag were extracted (Willdén, 2004).

2 Regional geology

The tectonostratigraphic architecture of the Scandinavian Caledonides resulted from a series of tectonic events in Ordovician–Devonian time that involved convergence of the two plates with continental lithosphere referred to as Baltica and Laurentia. This convergence culminated with collision of these two continents during subduction of the margin of Baltica beneath Laurentia. Several allochthonous thrust nappes, comprising Baltica rift-related, platformal and foreland basinal sequences, oceanic arc and exotic continental terranes were thrust eastward onto Precambrian rocks of the Fennoscandian Shield (Gee 1975; Roberts & Gee, 1985; Stephens 1988; Roberts, 2003).

At Laisvall, the autochthonous stratigraphy is well developed and preserved underneath a main decollement overlain by allochthonous thrust sheets. The Palaeoproterozoic basement is composed of granite which formed at 1.8 Ga. The basement is overlain by the Ediacaran–Cambrian Laisberg Formation (Nielsen & Schovsbo, 2011) passing upward into the Grammajukku and Middle Cambrian Alum Shale Formations (Rickard et al., 1979; Willdén, 1980). The Laisberg Formation represents a transgressive, sandstone-dominated sequence. Mineralisation is hosted in the Lower and Upper Sandstone horizons in the upper part of the Laisberg Formation. The Grammajukku Formation comprises various shale and siltstone with subordinate sandstone intercalations. The Alum Shale Formation is composed of black pyritic shale (Ljungner, 1950). It is commonly strongly tectonized and provided the main decollement overlain by the allochthonous thrust sheets.

3 Structural and tectonic controls on stratabound, sandstone-hosted Pb-Zn deposits

3.1 Methodology and workflow

Airborne magnetic field data acquired in 2009 by the Geological Survey of Sweden (SGU) for the Laisvall area have been processed as a basis for a detailed lineament interpretation. The geophysical survey was carried out in a west–east direction at the altitude of 60 m. Line and point spacings were 200 m and 7 m, respectively. Scintrex CS2 sensor and radar techniques for magnetic field measurement and a Global Positioning System (GPS) were used. Magnetic field data were acquired at the resolution of 0.1 nT. Data were processed as Geosoft XYZ files and bi-directional gridding was used with a grid cell size equal to point spacing in each area (point spacing gives grid resolution). Linear magnetic anomalies were systematically identified using Total Magnetic Intensity (TMI), First Vertical Derivative (FVD), Analytical Signal (AS), and Tilt Derivative (TDR) maps but always referring back to TMI maps.

The Laisvall deposit was extensively drilled by Boliden Mineral AB for brown-field and subsequent near-field exploration from the 1930´s to the 2000´s. About 1200 boreholes were drilled. Geology and both Pb and Zn grade data in the autochthonous sedimentary rocks are available for 1120 boreholes, 90 % of which are vertical. Information on the location and dynamics of major faults in the mine and in the field were obtained from these legacy data and from the published literature (Lilljequist in Boliden Mineral AB internal reports, unpub. 1965, 1968; Carlson in Boliden Mineral AB internal reports unpub., 1970; Lilljequist, 1973; Rickard et al., 1979; Lucks, 2004). Key profiles were drawn based on new core logging from boreholes carefully selected at the Malå core storage facilities at SGU. This work identified breaks in the stratigraphy and, in combination with the character of the rocks in the drillcore (i.e. core loss, crushed core, probable fault gouge, intensity of fractures, etc), provided a basis for the location of major faults. Delineation of lithological units and of mineralisation grade in 3D space was made using the Leapfrog Mining 3D software after having modelled fault surfaces in the autochthonous sedimentary sequence.

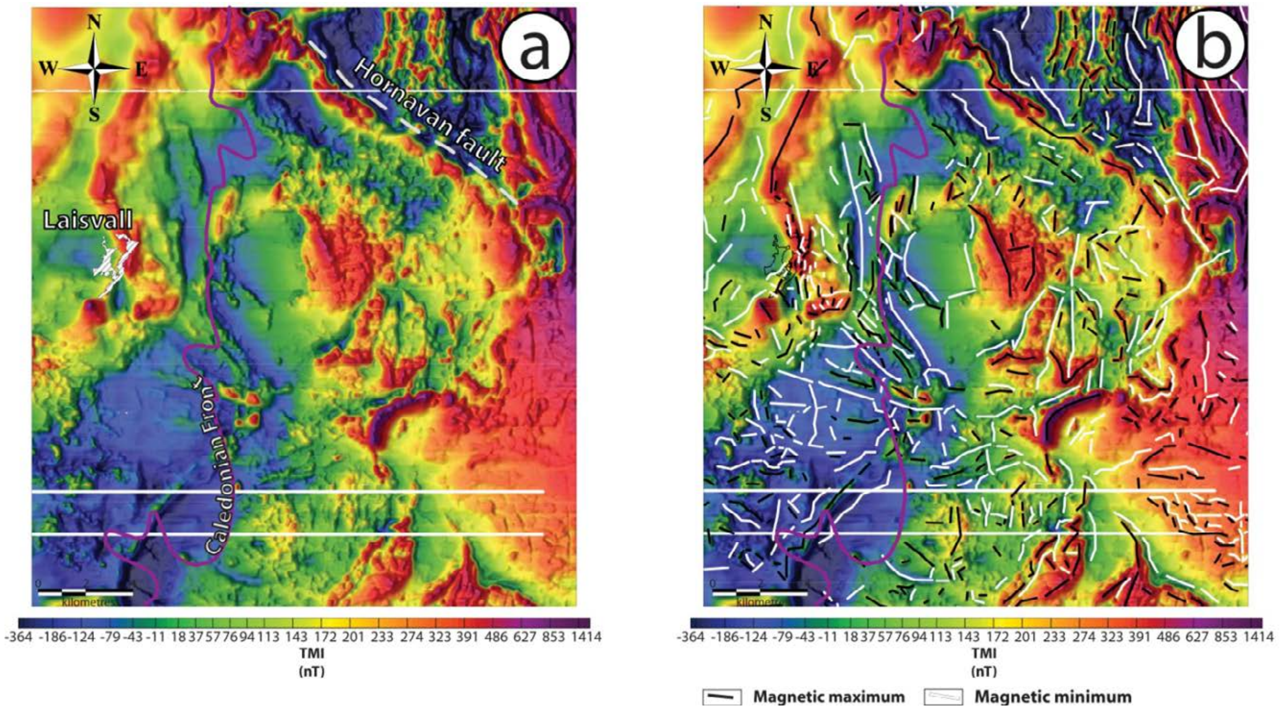

Fig. 1 a) Total Magnetic Intensity (TMI) airborne magnetic map of the Laisvall area. The eastern front of the Scandinavian Caledonides (purple line), the location of the Laisvall deposit and the trace of the fault at the ground surface along Lake Hornavan are shown for reference; b) Linear magnetic anomalies (magnetic minima and maxima) inferred from TMI data. The fault along Lake Hornavan appears as a series of magnetic minima. In the area of the Laisvall deposit, magnetic lineaments show inflection areas where their trend changes from approximately NE–SW to NW–SE. The stratabound Pb-Zn Laisvall deposit is aligned predominantly along magnetic lineaments with a NE–SW trend. The three horizontal white lines are artefacts related to gridding. These do not relate to any magnetic minima.

3.2 Results and discussion

West of the eastern front of the Scandinavian Caledonides (Fig.1a), the Palaeoproterozoic crystalline basement is covered by Ediacaran–Cambrian autochthonous sedimentary rocks and then by allochthonous Caledonian thrust sheets. The trends in magnetic lineaments are the same on both sides of the front and match the regional geological trends to the east in the Fennoscandian Shield, implying that magnetic lineaments correspond to geological features in the basement (Figs. 1a & 1b). Magnetic minima have been classified into two main sets; N–S to NE–SW and WNW–ESE to NW–SE (Fig. 1b).

Magnetic minima correlate with major faults in the Palaeoproterozoic basement. The NW–SE-striking fault that is related to the 200 m deep Lake Hornavan is identified in geophysical data as a series of magnetic minima. Magnetic lineaments show inflection areas where their trend radically changes direction. The autochthonous stratabound Pb-Zn Laisvall deposit is spatially associated with such an inflection area in the basement and mainly follows a NE–SW trend (Fig. 1b).

Faults mapped in the Laisvall area using aerial photographs and field studies have two main orientations, NNE–SSW and NW–SE (Lilljequist, 1973). Some faults cut through both the allochthonous thrust nappes and the autochthonous Ediacaran–Cambrian rocks. Lilljequist (1973) characterized these faults as being related to orogenic collapse. The present work shows that magnetic minima in the Palaeoproterozoic basement correlate with faults in the Ediacaran–Cambrian sedimentary rocks. For this reason, it has been inferred that the faults affecting the cover rocks (and locally the allochthonous thrust sheets) continue downwards into the Palaeoproterozoic basement and represent reactivated basement structures.

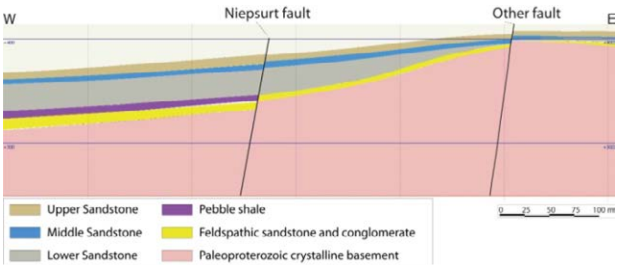

Fig. 2 West-east cross-section through the Niepsurt fault in the Laisvall deposit showing evidence for syn-sedimentary faulting after deposition of the feldspathic sandstone and conglomerate.

Major faults have been recognized in the Laisvall mine (Figs. 2–4; Kautsky & Nadok faults in Lilljequist, 1973; Rickard et al., 1979; Lucks, 2004; Kramaviken & Niepsurt faults, this study). They trend NNE–SSW to NE–SW, NNW–SSE or N–S. The detailed 3D modelling carried out in the present study displays facies changes and thickness variations at the meter scale of several sandstone horizons on either side of several faults (e.g. the Niepsurt fault, Fig. 2). The facies distribution indicates syn-sedimentary block movement after deposition of the feldspathic sandstone and conglomerate that represents the erosion surface of the Palaeoproterozoic basement. These findings are consistent with the interpretation that Baltica was intensively peneplained during the Neoproterozoic and completely flat at the dawn of the Cambrian (Nielsen and Schovsbo, 2011).

The main elongation of the Pb-Zn ore bodies is NE–SW, locally changing to NW–SE. In addition, the highest Pb grades are closely centred on the Nadok fault (Figs. 3–4). Ore grades depict plume-like features as recognized in a NW–SE section across the Nadok fault (Fig. 3): i) Pb grades are the highest closer to the fault and diminish away from it, ii) in contrast to the Pb grades, the highest Zn grades are more distal away from the Nadok fault, iii) Pb and Zn grades accumulated preferentially towards the top of the host sandstone aquifers in a similar manner as the variation in grades recognized in several MVT Pb-Zn deposits (e.g., Topla-Mežica deposits in Slovenia; Spangenberg & Herlec, 2006). As in other deposits, this morphology and the available stable isotope data (Rickard et al., 1979 & ongoing work) are best interpreted to correspond to sour gas that formed by heating of kerogen and accumulated by density at the top of host permeable horizons. The gas provided H_2S by thermogenic sulphate reduction to the metal-bearing fluids and triggered subsequent precipitation of Pb-Zn sulphides (Anderson and references therein, 2008).

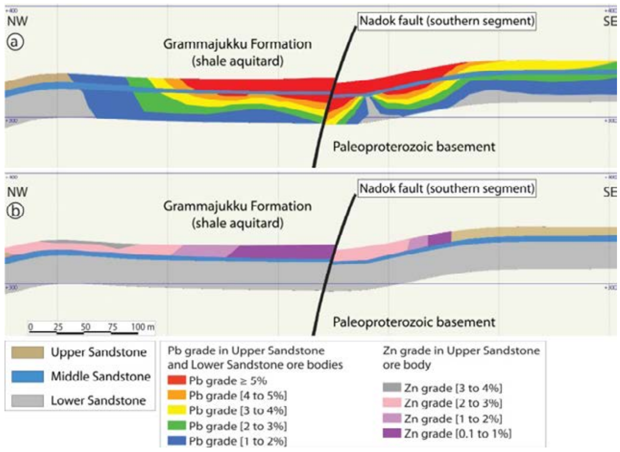

Fig. 3 NW-SE cross-sections through the Nadok fault in the Laisvall deposit; a) distribution of Pb grades in the Upper Sandstone and Lower Sandstone ore horizons of the Laisberg Formation, b) distribution of Zn grades in the Upper Sandstone ore horizon.

4 Conclusions

This multidisciplinary approach has identified the primary role of structures and broader tectonic features in localizing and constraining not only the sedimentary facies distribution but also the origin of the sandstone-hosted Pb-Zn mineralisation at the Laisvall deposit. Magnetic lineaments match geological features in the Palaeoproterozoic basement. Magnetic minima, trending either N–S to NE–SW or WNW–ESE to NW–SE, can be correlated with faults in the autochthonous Ediacaran–Cambrian sedimentary cover rocks. Faults affecting the host sedimentary rocks at Laisvall are interpreted to extend downwards into faults in the underlying Palaeoproterozoic crystalline basement and the latter are inferred to have been reactivated.

The two fault sets (N–S to NE–SW and WNW–ESE to NW–SE) are inferred to have conditioned basin architecture and deposition of sediment during Ediacaran–Cambrian time (syn-sedimentary block faulting) as basin-parallel and transfer faults, respectively. These faults also localized deformation during post-sedimentary and post-mineralisation tectonic regimes.

Stratabound Pb-Zn deposits are spatially associated with inflection areas along magnetic lineaments in the basement. In these areas, magnetic lineaments abruptly change trend from NE–SW to NW–SE. The former corresponds to the main trend of mineralisation in the stratabound Pb-Zn deposit at Laisvall.

Modelling work in 3D space shows plume-like features for Pb and Zn grades demonstrating that the faults with N–S to NE–SW orientation acted as feeders for at least the metal-bearing mineralizing fluids. In addition, mineralisation tends to accumulate towards the roof of sandstone aquifers in a similar manner as described in MVT deposits in other parts of the world.

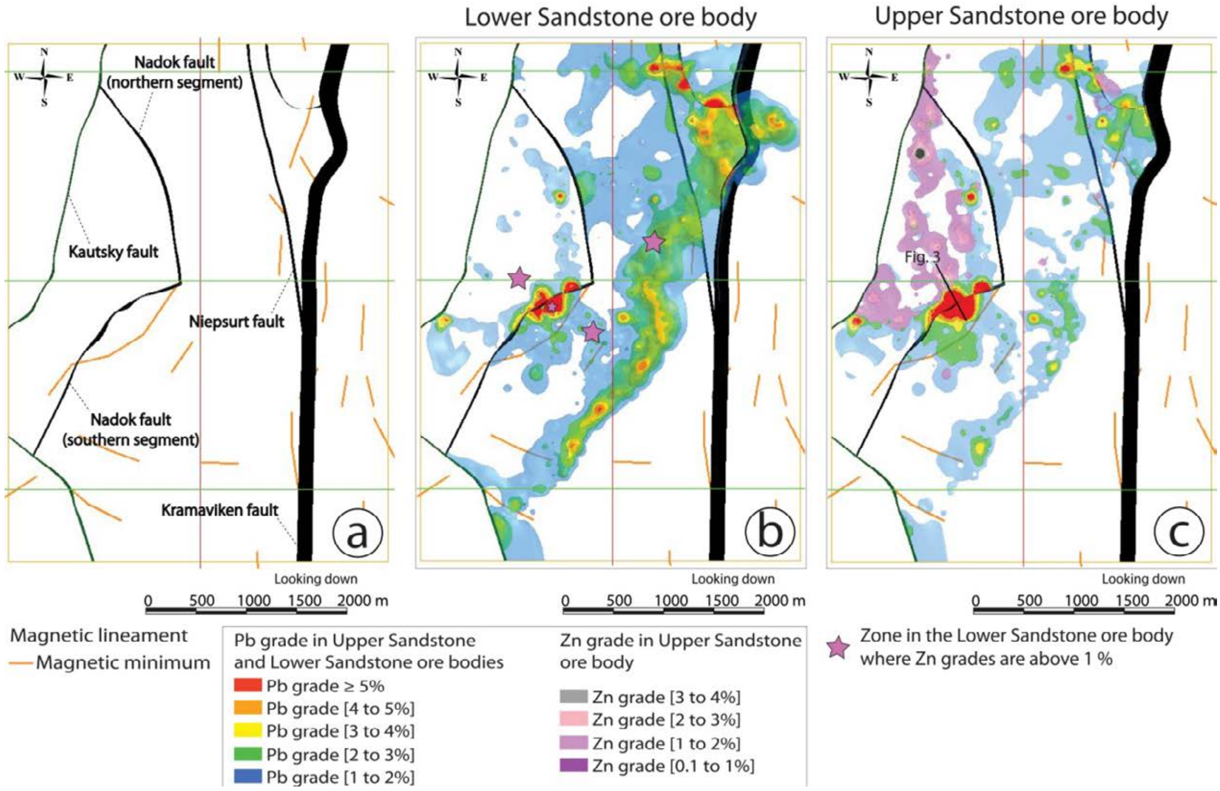

Fig. 4 a) Map showing magnetic minima (brown lines) and faults (black lines) in the Ediacaran–Cambrian siliciclastic cover rocks in the Laisvall mine; b) Pb grade distribution in the Lower Sandstone ore body in the Laisvall mine. Areas with Zn grades above 1% are identified by purple stars; c) Pb & Zn grades in the Upper Sandstone ore body.

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