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Structural evolution of the VMS-hosting Kristineberg area, Sweden – constraints from structural analysis and 3-D-modelling

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Abstract

Structural mapping and 3-D-modelling with constraints from magnetotelluric (MT) and reflection seismic investigations have been used to provide a geological synthesis of the geometrically complex Kristineberg area in the western part of the Palaeoproterozoic Skellefte district. The results indicate that, like the south-eastern parts of the Skellefte district, the area was subjected to SSE-NNW transpressional deformation at around 1.87 Ga. The contrasting structural geometries between the Kristineberg and the central Skellefte district areas may be attributed to the termination and splaying of a major ESE-WNW-striking high-strain zone into several branches in the northern part of the Kristineberg area. The transpressional structural signature was preferentially developed within the southern of the two antiformal structures of the area, "the Southern antiform", which exposes the deepest cut through the crust and hosts all the economic volcanogenic massive sulphides (VMS) deposits of the area. Partitioning of the SSE-NNW transpression into N–S and E–W components led to formation of a characteristic "flat-steep-flat" geometry defining a highly non-cylindrical hinge of for the Southern antiform. Recognition of the transpressional structural signatures including the "flat-steep-flat" geometry and the distinct pattern of sub-horizontal E–W trending to moderately SW-plunging mineral lineations in the deeper crustal parts of the Kristineberg area is of significance for VMS exploration in both near mine and regional scales. The 3-D-model illustrating the outcomes of this study is available as a 3-D-PDF document through the publication website.

1 Introduction

The Kristineberg area in the western part of the Palaeoproterozoic Skellefte district hosts several volcanogenic massive sulphide (VMS) deposits occurring in the Skellefte Group metavolcanic rocks deposited during crustal extension at 1.89–1.88 Ga (Allen et al., 1996; Billström and Weihed, 1996; Montelius, 2005; Skyttä et al., 2011). Crustal evolution of the district has been attributed to two sets of syn-extensional faults which controlled the deposition of the supracrustal units, but also the subsequent compressional overprint during a stage of basin inversion at around 1.87 Ga (Allen et al., 1996; Bauer et al., 2011; Skyttä et al., 2012). Basin inversion has been suggested also for the Kristineberg area (Skyttä et al., 2010), but the relationship between the high-strain zones and the regional structure has not been constrained since the previous studies either had a thematic or local-scale focus (Dehghannejad et al., 2010, 2012b; Skyttä et al., 2010). For these reasons, the present paper aims at modelling the regional-scale three-dimensional structure of the Kristineberg area. In specific, the coupling between the high-strain zones, the occurrence of stratigraphical units, and the geometry of major fold structures are addressed. Furthermore, the paper aims at providing a larger-scale 3-D-framework for the geometrically complex ore lenses (cf. Årebäck et al., 2005). Finally, the results of the study are discussed with the results of recent investigations from further east in the Skellefte district (Bauer et al., 2011; Dehghannejad et al., 2012a) to complement the existing structural synthesis (Skyttä et al., 2012).

Structural mapping and analysis are used to delineate the structural evolution of the study area. The resulting ideas are further developed into 3-D models which nucleate on geological profiles in the vicinity of the Kristineberg deposit, which in turn are based on drillings by Boliden Mineral AB, with support from available seismic interpretations (Dehghannejad et al., 2010). Geophysical interpretations at larger scales (Tryggvason et al., 2006; Malehmir et al., 2007, 2009a, b; Hübert et al., 2009; Garcia Juanatey et al., 2012) are used to further extrapolate the known geological features towards larger depths.

The results of the study are relevant to ore geological research and exploration of Precambrian deposits occurring in poorly-outcropping areas where stratigraphic correlations are hampered by the lack of stratigraphical marker horizons, by strong hydrothermal alteration, and regional metamorphism. More locally, the paper provides new insights into the geological evolution of the Skellefte district where the crustal structure further east differs from that of the Kristineberg area, even though the same

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tectonic events apparently affected the whole district. Outcomes of the investigation are presented in the form of new geological maps and cross-sections of the Kristineberg area, and by a 3-D model comprising the most significant geological surfaces within the area of investigation. The 3-D-model is available in 3-D-PDF-format in the Supplement and may be downloaded through the publication website.

2 Geological setting

2.1 Skellefte district

The Skellefte district (Fig. 1) is an approximately 120 by 30 km wide area loosely defined by the occurrence of the 1.89–1.88 Ga Skellefte Group metavolcanic rocks (Billström and Weihed 1996; Montelius 2005; Skyttä et al., 2011), which are the main host to the VMS deposits in the area (Allen et al., 1996). The base of the Skellefte Group is not exposed, but it is inferred to have deposited as a laterally constrained sequence upon the Bothnian Supergroup metasedimentary rocks (Rutland et al., 2001a, b; Skyttä et al., 2012) which grade upwards into the 1.88–1.87 Ga Vargfors Group metasedimentary rocks (Billtröm and Weihed, 1996; Skyttä et al., 2012). The Vargfors Group is the uppermost stratigraphical unit of the Skellefte district, and was coeval with the subaerial, predominantly volcanic Arvidsjaur Group which is present further to the north (Skiöld et al., 1993).

Intrusive rocks of the Skellefte district define two major periods of intrusive activity at approximately 1.89–1.86 Ga and 1.82–1.78 Ga (Fig. 1; cf. Weihed et al., 2002; Gonzàles Roldán, 2010; Skyttä et al., 2011). The former period comprises the 1.89–1.87 Ga early-orogenic, calc-alkaline granodiorites-tonalites and gabbros (Phases GI and GII of the Jörn intrusive complex), and the 1.88–1.86 Ma alkaline granites-syenites-monzonites of the Perthite-monzonite-suite (including Jörn GIII and GIV). The younger period comprises the 1.82–1.78 Ga minimum melt S-type granites (Skellefte-Härnö

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suite), and the 1.80–1.78 Ga coarse-porphyritic, A- to I-type granites, monzonites and diorites (Revsund suite).

The structural evolution of the Skellefte district was largely controlled by a complex fault pattern that developed during early crustal extension (Allen et al., 1996; Bauer et al., 2011). The earliest tectonic deformation has been inferred at 1.89–1.87 Ga (Lundström et al., 1997, 1999; Lundström and Antal, 2000, Rutland et al., 2001a, b) and was constrained to the deeper crustal levels, tentatively attributed to ductile crustal extension synchronous with the volcanism higher-up in the crust (Skyttä et al., 2012). The subsequent compressional deformation at 1.87 Ga was characterized by coaxial deformation due to SSW-NNE shortening within the upper parts of the crust (Skyttä et al., 2012). In contrast, the deeper parts of the crust experienced higher-strain non-coaxial deformation under SSE-NNW transpressional conditions, either due to strain partitioning during the 1.87 Ga event or due to a new compressional event at 1.86 Ga (Skyttä et al., 2012). Mineral lineations within the upper, coaxial domain are steep to sub-vertical, and show significantly more gentle plunges within the lower, non-coaxial tectonic domain (Bauer et al., 2011; Skyttä et al., 2012). South-dipping reverse shear zones currently separate the above crustal domains in most parts of the Skellefte district (Dehghannejad et al., 2012a; Skyttä et al., 2012).

The youngest deformation phase at 1.82–1.80 Ga (Weihed et al., 2002) has been attributed to approximately E–W shortening, and was characterized by reverse shearing along steeply-dipping, approximately N–S striking high-strain zones (Bergman Weihed, 2001). However, their generation has been attributed to syn-volcanic crustal extension, with a later history of reactivation(s) during compressional deformation (Skyttä et al., 2010, 2012; Bauer et al., 2011).

Metamorphic peak conditions reached partial melting in the south-eastern part of the district (Lundström et al., 1997), whereas sub-solidus PT-conditions at ~3 kbars and ~600 °C prevailed in the Kristineberg area (Kathol and Weihed, 2005). The metamorphic peak in the eastern and southern parts of the Skellefte district was associated with the oldest deformation event pre-dating the approximately 1.88 Ga intrusions

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(Lundström et al., 1997, 1999). In the western and central parts of the district, the metamorphic peak was late- to post-tectonic with respect to the upright main folding (Årebäck et al., 2005; Skyttä et al., 2012). Most of the crustal evolution models suggest that the Skellefte district is a remnant of a volcanic arc accreted towards the Karelian craton in the NE (Weihed et al., 2002). However, the subduction-zone configurations show significant variations (Hietanen, 1975; Gaál, 1990; Juhlin et al., 2002).

2.2 Kristineberg area

The supracrustal rocks of the Kristineberg area define the regional-scale Kristineberg antiform which encloses two individual second-order west-plunging antiforms: the Southern antiform cored by the 1.89 Ga Viterliden intrusion (Skyttä et al., 2011), and the Northern antiform by the Skellefte Group metavolcanic rocks (Fig. 2). The antiforms are separated by either a synform (Årebäck et al., 2005) or a large-scale shear zone (Malehmir et al., 2007; Dehghannejad et al., 2010) occurring within the Vargfors Group metasedimentary rocks. Strain within the Kristineberg area was heterogeneously distributed with strong partitioning into curviplanar E–W to NE-SW striking high-strain zones with low-strain tectonic lenses in between (Skyttä et al., 2010). Gently-plunging lineations within the Viterliden intrusion have been attributed to sub-horizontal crustal flow occurring also outside the high-strain zones (Skyttä et al., 2010).The high-strain zones are not penetrative but die out against the reclined hinge of the Kristineberg antiform hinge in the west (Fig. 2; Skyttä et al., 2009). The dip-slip and dextral strike-slip deformation along the E–W shear zones have been attributed to an overall SSE-NNW transpressional tectonic regime within a lower crustal domain (Skyttä et al., 2012).

Four reflection seismic profiles acquired across the area revealed a series of steeply-dipping to sub-horizontal reflections (Malehmir et al., 2007, 2009a; Dehghannejad et al., 2010, 2012b), some of which could be correlated with surface geology, whereas others have been inferred to be generated from more gently-dipping ore-bearing horizons at depth (Dehghannejad et al., 2010). Furthermore, the E–W long-sectional profile shows gently WNW-dipping reflections, interpreted as shear zones transecting the

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eastern part of the Viterliden intrusion (Dehghannejad et al., 2010), in line with the overall westerly inclination of structures through the area. Magnetotelluric (MT) measurements are generally in good agreement with the reflection seismic results (Hübert et al., 2009; Garcia Juanatey et al., 2012).

Two mineralized horizons occur in the Kristineberg area: the upper one comprises the Rävliden, Rävlidmyran and Hornträsk deposits and is located in a typical setting for the Skellefte district VMS deposits, close to the upper part of the Skellefte Group stratigraphy (Fig. 2; Allen et al., 1996; Årebäck et al., 2005). The stratigraphically lower horizon includes the Kristineberg and Kimheden deposits. The 1889 ± 3 Ma minimum age for the ore deposition and volcanism inferred for the deeper parts of the Skellefte Group stratigraphy implies that volcanism may have started prior to the emplacement of the Viterliden intrusion at around 1890 Ma (Skyttä et al., 2011). On the other hand, the 1883 ± 6 Ma age for the Kristineberg hanging-wall rhyolite infers that at least part of the Skellefte Group post-dates the Viterliden intrusion, thus being in contradiction with a model attributing the generation of VMS deposits to heat influx from emplacement of the Viterliden intrusion into the volcanic pile (Galley and Bailes, 1999).

The present-day Kristineberg deposit geometry (Fig. 3) has been attributed to syn-volcanic stratiform sub-seafloor sulphide replacement later followed by tectonic deformation leading to transposition of the main parts of the lenses into moderate to steep southerly dips, and stacking and folding of their present-day deeper parts (e.g. the J-lens; Årebäck et al., 2005). Årebäck et al. (2005) considered the absence of remobilization of A and B lenses, as well as contrasting precursor compositions of the flanking volcanic units indicative of the presence of two separate sulphide sheets prior to deformation. Hence, the model disagrees with the geometrical model by Jolley (2001), but agrees with its kinematic interpretation attributing the deformation to reverse south-dipping shear zones. Reverse shearing was considered responsible for folding of the J-lens and, consequently, the major change in the deposit geometry at approximately the 1000 m level was attributed to the occurrence of a synform core south of the A and B lenses (Årebäck et al., 2005). Skyttä et al. (2009) suggested that localized

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sub-horizontal flow below the 1000 m level in the mine could have contributed to the change in the deposit shape. The Rävliden and Rävlidmyran deposits (Fig. 2) occur as several elongate lenses defining sub-horizontal dips and gentle westerly plunges close to Skellefte Group-Vargfors Group contact.

3 Methodology

3.1 Structural geology

Geological mapping was carried out in an approximately 15 by 30 km area, within the supracrustal rocks occurring in the Kristineberg antiform (Fig. 2a). Due to the small number of outcrops in the area, magnetic maps are used in delineating the major shear zones and contacts between the geological units (Fig. 2b). Microstructural studies from oriented thin sections are used to investigate the development of rock fabrics, and to determine shear senses along the high-strain zones. Structures within the Kristineberg mine vicinity are summarized from geological profiles compiled from drillings by Boliden Mineral AB and by detailed mapping of the surface expression of the north-western part of the deposit (A4 open pit). Reflection seismic results along the "High-resolution" profile of Dehghannejad et al. (2010) are used to constrain the geological interpretation along the same profile (Fig. 4). Recent structural data from the Viterliden intrusion (Skyttä et al., 2010) complements the data set presented in this paper and, together with a more regional overview (Skyttä et al., 2012), allows the kinematic framework for the deformation events to be defined.

3.2 Geological 3-D-modelling

The geological cross-sections (Fig.4) served as the basis for 3-D modelling. The gOcad software platform (Paradigm), supported by the Sparse plug-in (Mira Geosciences), and the MOVE^{TM} software (Midland Valley Exploration Ltd.) are used in model building.

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Source data comprises of surface geology observations, aeromagnetic maps (the Geological Survey of Sweden, SGU), investigation of selected drill holes transecting significant lithological contacts, ground magnetic data, geological cross-sections, plan views, ore lens 3-D-geometries and near-mine 3-D models from Boliden Mineral AB.

Results from the recent MT investigations (Hübert et al., 2009; Garcia Juanatey et al., 2012), reflection seismic profiles (Tryggvason et al., 2006; Malehmir et al., 2007, 2009b; Dehghannejad et al., 2010; Ehsan et al., 2012) and gravity modelling (Malehmir et al., 2009a) are used to constrain the in-depth extent of the major high-strain zones and the most significant geological units.

4 Structural geology

4.1 Overview

The Kristineberg antiform encloses several high-strain zones which typically occur along the steep to overturned antiform limbs, but also as axial surface-parallel to these folds (Figs. 2 and 4). The high-strain zones are typically curvilinear and strike NE-SW to E–W, except for two SE-NW striking high-strain zones in the north-western part of the study area, inferred from the large-scale deflection of bedding planes. The high-strain zones are associated with development of shear fabrics, as well as a variable degree of tectonic transposition of supracrustal units and primary geological contacts (Figs. 2 and 4). All the high-strain zones die out before reaching the hinge of the Kristineberg antiform in the west.

4.2 Observations

Components of both dextral strike-slip deformation (Fig. 5a and b) and reverse dip-slip deformation (Fig. 5c and d) were observed along a high-strain zone separating the Southern and Northern antiforms (Fig. 2). The dip-slip deformation occurred under both ductile and brittle-ductile conditions (Fig. 5c and d; respectively). En-echelon

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patterns of quartz veins locally indicate sinistral strike-slip deformation along the layer-boundaries in the western part of the study area (Fig. 5e).

While the high-strain zones are typically accompanied with asymmetric folds overturned to the north, structures within the tectonic lenses between the high-strain zones range from variably dipping primary depositional contacts (Fig. 6a and b; "I" in Fig. 2) to open upright folds with approximately E–W axial surfaces (Fig. 6c) to tight folds with steep N–S to SW-NE striking axial surfaces (Fig. 6d–h). Except for local overturning in the vicinity of the high-strain zones, sedimentary younging directions are indicative of right-way-up attitude for the sedimentary succession. The folds with N–S to SW-NE striking axial surfaces and the related deformation fabrics within the metasedimentary rocks are overprinted by more localized fabrics (Fig. 6d–h), which locally show a spatial relationship with minor semi-brittle E–W shear zones (Fig. 6i). The foliation of an apparently older generation occurs frequently also without any associated deformation structures (e.g. the area around 5e in Fig. 2). Overprinting relations similar to those within the metasedimentary rocks may be found also within the altered Skellefte Group metavolcanic rocks, where isoclinally folded foliations, sub-parallel with the primary bedding, are obliquely cross-cut by later crenulations (Fig. 6j). The late crenulations define an intensely fanning pattern with strikes ranging from approximately E–W to N–S (the Southern antiform area; Figs. 2 and 6f and k), and vary from semi-penetrative (Fig. 6j) to brittle and spaced (Fig. 6k) in nature. The earliest foliations have been preserved either as inclusion trails in chlorite porphyroblasts (Fig. 6l) or in hinges of rootless isoclinal intrafolial folds (Fig. 6m and n). In contrast to the intensely altered metavolcanic rocks, only one foliation could be found in the less-altered metavolcanic rocks, e.g. in the Northern antiform (Fig. 2).

Mineral lineations are regionally steeply-plunging (Fig. 2). However, the dominant lineation population in the Kristineberg mine vicinity and within the Viterliden intrusion plunges moderately towards south-west (Fig. 2). The SW-plunging lineation has been deformed by late crenulations e.g. in the vicinity of the Kimheden deposit.

The A4 open pit exposes the western continuation of the A-lens of the Kristineberg deposit (Figs. 2 and 7). The excavated VMS ore occurred as an approximately 10 m thick sheet parallel with the host rocks foliation, striking WNW-ESE and dipping moderately towards SSW (Fig. 7a). Folds deforming the main foliation on both sides of the ore sheet have parallel axes, and are further parallel with the moderately SW-plunging mineral lineation but vary in the attitude of the axial surface. Axial surfaces of the tight folds in the sericite-altered metavolcanic rocks in the stratigraphic hanging-wall to the ore dip moderately towards the west (Fig. 7b). In the footwall, the axial surfaces in the stockwork mineralization dip steeply towards south-east (Fig. 7c) and the fold shape progresses from gentle-open in the east to tight-isoclinal in the west (Fig. 7a). Furthermore, the ore shows local transposition and detachment from the main lens along the axial surface of the folds in the area of the most intense folding. In the western part of the pit, the ore shows an apparent dextral deflection into a steeply west-dipping, NNE-SSW striking high-strain zone which constrains the western extent of the ore (Fig. 7d). The eastern extremity of the ore is not exposed.

Geophysical signatures of the Rökå mineralization occurring east of the Viterliden intrusion infer moderate westerly dips (Boliden Mineral AB; unpublished exploration report). The Hornträsk and Kimheden deposits occurring along the northern limb of the Southern antiform have gentle to moderate plunges towards WSW.

4.3 Structural interpretation

4.3.1 Succession of deformation events; overall geometry and kinematics

Main foliation within the Vargfors Group metasedimentary rocks occurs along the axial surfaces of upright folds (Fig. 6b and c), hence allowing a district-scale correlation with the main fabric of the upper crustal domain of Skyttä et al. (2012). Consequently, the fabric is labelled S2. Since the earliest fabric of the Skellefte Group rocks (Figs. 6j, k and 7b, c) occurs sub-parallel with the primary bedding, is only locally associated with early folds, and experienced a similar tectonic overprinting with the metasedimentary rocks, we attribute the early fabric to gravitational compaction within a pile of altered (meta)volcanic rocks. Consequently, the fabric is labelled Sc, and may regionally be correlated with S1 by Allen et al. (1996) and "compaction-related foliation" by Skyttä et al. (2012). Strike of the axial surfaces of the ductile folds (F2) varies significantly (Fig. 2), but the spaced overprint (Fig. 6f and i–k) confirms that the folds are of the same generation. Furthermore, folds deviating from the characteristic E–W orientation occur predominantly along N–S to NE-SW striking lithological contacts, and suggest that the orientation is not due to timing, but strain partitioning.

We attribute the synchronous development of contrasting structural orientations during D2 to SSE-NNW transpression and to the plunging nature of the Southern antiform. The "normal" transposition of strata into steeply-dipping to overturned attitudes took place along high-strain zones parallel with E-W striking axial surface of the antiform (Figs. 2 and 4a and b), and accommodated the N–S shortening component of transpression. Between the E–W striking high-strain zones, localized development of steeply west to north-west dipping domains (Fig. 6d and e) is attributed to the E–W shortening component of transpression. The localization of the E–W component of transpression is inferred to have nucleated along contacts of rheologically contrasting lithologies when transpressional deformation caused pronounced uplift in the eastern part of the Kristineberg area, eventually leading to the west-plunging orientation of the Southern antiform. As a result, a zonal "flat-steep-flat" -pattern characterized by alternating gentle and steep westerly dips was developed (Fig. 4c). Consequently, the regional-scale fold geometry of the Southern antiform is strongly non-cylindrical with the largest deviation from the gentle westerly plunge within the western reclined hinge of the Kristineberg antiform (Figs. 2 and 4c). Recognition of the above structural pattern suggests that the sub-horizontal tectonic flow within the Viterliden intrusion, as defined by the mineral lineations (Skyttä et al., 2010), is restricted to the domains with gently-dipping structures and E–W striking strike-slip zones.

The spaced crenulations overprinting D2 fabrics have E–W strikes along the low-strain hinge of the Southern antiform (Fig. 6d surroundings). In contrast, within the metavolcanic units close to the Kristineberg and Kimheden deposits, the crenulations show fanning patterns and non-planar geometries (Fig. 2). However, the dominant strike around the E–W orientation suggests that this event took place at a late stage of D2 rather than the regional D3 attributed to E–W shortening (Bergman Weihed, 2001). Consequently, we label the fabric “late-S2” (S2L). The variations and the more north-southerly strikes of S2L north of the Kimheden deposit are attributed to late-D2 shearing within incompetent altered metavolcanic rocks. Although the S2L fabric has a widespread occurrence, the D2L event is considered insignificant in determining the regional structural geometries.

4.3.2 Framework of major deformation zones and geological units

The geological and the high-resolution reflection seismic data (Dehghannejad et al., 2010) indicate that the high-strain zones in the vicinity of the Kristineberg mine and to the west of it have southerly dips down to approximately 2 km below the ground level (Fig. 4). Extrapolation of their extent at depths greater than this depth is constrained by other geophysical data and discussed in Sect. 5.

The major structural change across an E-W striking shear zone in the northern part of the Kristineberg area (“I” in Fig. 2), from approximately E–W trending low-strain structures in the north (Lickorish 2005) to more complex structural signatures in the south, implies that the area to the south of the high-strain zone, i.e. the whole Kristineberg area, occurs in the SSE-NNW transpressional lower crustal domain as defined by Skyttä et al. (2012). The Kristineberg area may be further divided into a coaxial domain (the Northern antiform), and a transpressional domain (the Southern antiform). Characteristic for the coaxial domain are the upright folds with a SW-NE axial surface strike and local occurrence of minor dextral and sinistral shear zones (Fig. 5a, b and e). In contrast, the larger structural versatility and, in specific, development of dextral strike-slip zones characterizes the non-coaxial Southern antiform. As a consequence, we infer that there is a major dip-slip dominated high-strain zone (Fig. 5c and d) located between the Northern and Southern antiforms (“II” in Fig. 2). Interaction between the Southern and Northern antiforms west of the E–W high-strain zone terminations explains the complex structural geometry of the western hinge area of the regional Kristineberg antiform (Fig. 2).

Within the pure shear domain, the overturning of bedding planes north-west of the contact with the metasedimentary rocks ("III" in Fig. 2) suggests that the contact is defined by an inverted normal fault (cf. Bauer et al., 2011). Furthermore, the parasitic synclinal fold on the southern limb of the Northern antiform is attributed to deformation along the shear zone at "IV" in Fig. 2, whereas the contact at "V" is of primary sedimentary nature.

Previously, we inferred that uplift of the core domain of the Southern antiform with respect to its hinge zones was responsible for the plunging nature of the antiform. Furthermore, we inferred that E–W compression and N–S compression acted synchronously in a SSE-NNW transpressive regime. As a consequence, there must be a significant strain gradient with increasing dip-slip displacement from west to east along the high-strain zone "II" in Fig. 2. Analogous to the Southern antiform, the plunging nature of the Northern antiform may be attributed to uplift in the east. Since the Northern antiform exposes a shallower cut through the crust, as shown by the limited area of exposed Skellefte Group metavolcanic rocks within its core, an apparently smaller amount of uplift relative to the Southern antiform was required. This is in line with the general trend of decreasing strain from south to north across the Skellefte district (Kathol and Weihed, 2005; Skyttä et al., 2012). The westerly dip of the Rökå mineralization east of the Viterliden intrusion suggests that the whole Kristineberg area may have experienced tilting towards the west, here attributed to dip-slip movements along the Deppis-Näsliden shear zone in the east (Fig. 1).

4.3.3 Tectonic transposition of the ore deposits

The most apparent implication from the A4 open pit structures is that high-strain zones occurring at high angles to the axis of the Southern antiform may define the lateral extent of individual ore bodies (Figs. 7a and d). Furthermore, zones of pronounced F2

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folds could be significant in transposing of the ore into variable strikes at the scale of individual ore lenses or sets of lenses. Change in the F2 fold geometry from the stratigraphical footwall to the hanging-wall (Fig. 7a) implies that significant deformation was localized either within the ore sheet or along its contacts. Since the axes of the folds on both sides of the ore sheet are parallel with each another, and with the observed mineral lineation, but vary in the axial surface orientation, we infer that the contrasting fold geometries are due to strike-slip dominated shear with a smaller reverse dip-slip component along the WNW-ESE high-strain zone. This interpretation is in line with dextral strike-slip deformation observed along an ENE-WSW high-strain zone within the Viterliden intrusion, directly east of the A4 open pit (Fig. 2; Skyttä et al., 2010).

Applying the dextral strike-slip shearing to the Kristineberg deposit, localized shearing at approximately 1000 m level below the surface is inferred to have caused lateral stretching of the bodies, hence contributing to the transposition of the ore lenses into the gently-plunging orientation at depth (Fig. 3). However, the lack of structural observations to properly cover the whole deposit inhibits any further estimation about the significance of the lateral tectonic movements in transposing the mineralized lenses. The elongate, gently west-plunging ore lenses of the Rävliden and Rävlidmyran deposits will not allow distinguishing whether the reverse south-side-up shearing or the dextral strike-slip deformation was the dominant deformation affecting the ores.

5 Modelling

5.1 The modelling volume, units and workflow

The model covers laterally the 21 × 36 km area shown in Fig. 2 and extends vertically approximately 4 km above and 8 km below the present erosion level (Fig. 8a; Supplemeny). The top/bottom contacts of the following geological units have been modelled as 3-D surfaces: the early-orogenic Viterliden intrusion, the contact between the Skellefte Group metavolcanic rocks and Vargfors Group metasedimentary rocks,

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mafic sills within the Vargfors Group rocks and late- to post-orogenic intrusive rocks. Structural features included in the model are bedding form surfaces within the Vargfors Group rocks to illustrate the structural geometry, axial surfaces of major folds, and high-strain zones. The variation in the attitude of mineral lineations is shown by 3-D arrows each of which represents the dominant orientation of the observed outcrop or group of outcrops. The 3-D-model is provided as a 3-D-PDF file in the Supplement, including a legend and a brief guide helping to explore the model.

Ore lenses from the Kristineberg, Rävliden and Rävlidsmyran deposits were imported into the model as surface sets from the Boliden Mineral AB database. Line intersections of the preliminary geological surfaces along three parallel cross-sections (Fig. 2) were collected and "cleaned" to get seamless line intersections with MOVE™ software. Compilation of the final 3-D-surfaces and export into 3-D-PDF-format (Supplement) was performed by gOcad with the Sparse plug-in.

5.2 Constraints on the 3-D shape of the modelled units from structural geology and regional-scale geophysics

The contact between the Skellefte Group (SG) and Vargfors Group (VG) could be fairly well constrained by drilling data from Boliden Mineral AB along the cross-section shown in Fig. 4a (see also Fig. 8b for location). From this location, the SG-VG contact was extrapolated towards east and west using the apparent dips retrieved from the structural long-section running across the Southern antiform (Figs. 4c and 8c). Furthermore, signatures from the reflection seismic investigation were locally used in constraining the SG-VG contact, as well as along the cross-section shown in Fig. 4b ("N1 reflector" and "Hi-Res profile" in Dehghannejad et al., 2010). The recognized transpressional "flat-steep-flat" geometry was applied when modelling the top contact of the Viterliden intrusion, the SG-VG contact, and structural form surfaces within the Vargfors Group. The eastern contact of the Viterliden intrusion was inferred to have a westerly dip since the Rökå mineralization (Fig. 2) dips towards the west. The northern contact of the Viterliden intrusion is inferred to be sub-vertical, analogous to the overturned

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northern flank of the Southern antiform. The orientation of resistor "RII" by Garcia Juanatey et al. (2012) infers that the E–W "nose" of the intrusion immediately north of the Kristineberg deposit has a moderate to steep westerly plunge (Supplement). The southern intrusion contact is drawn arbitrarily since no data from the area was available.

The Northern antiform was inferred to have a gentle and rather uniform plunge towards south-west until the hinge transects the present erosion level. Further west, field mapping indicates that the antiform deflects into a steeper plunge. The folds within the metavolcanic units are inferred to be upright and approximately symmetric, whereas within the metasedimentary units to the north-west they are asymmetric (Fig. 8d). The interpretation is based on preferential strain partitioning into the metasedimentary rocks and into the high-strain zone separating the metavolcanic and metasedimentary rocks (Bauer et al., 2011). The depth of the SG-VG contact north-west of the Northern antiform is not known and was consequently drawn arbitrarily. For this reason, the difference in the depth of this contact across the transfer faults is illustrative only.

The high-strain zone pattern along the surface has been interpreted from known occurrences along the geological cross-sections (Fig. 4a and b) and from magnetic data. The latter indicates that the majority of the high-strain zones terminate against the west-dipping SG-VG contact or against mafic sills hosted by the Vargfors Group metasedimentary rocks (Fig. 2). The in-depth continuation of the high-strain zones has been interpreted from available MT and seismic data. We interpreted the major north-dipping reflector largely underlying the whole modelling area (Fig. 8e; Tryggvason et al., 2006; Hübert et al., 2009; Garcia Juanatey et al., 2012) as a north-dipping shear zone which flattens and deflects into a more N–S strike towards east. Consequently, the geometry of the zone is in good agreement with the sigmoidal pattern of high-strain zone traces within the Viterliden intrusion and also with the attitude of seismic reflectors observed below or within the intrusion ("W1" and "D1" in Dehghannejad et al., 2010). The large-scale MT-signatures are in line with a northerly dip for the most dominant structural features (Fig. 8e–h). Consequently, the largest high-strain zones bounding the Southern antiform in the south are inferred to have northerly dips. Analogous to the northerly dip of the above high-strain zones, the E-W striking shear zone at "I" in Fig. 2 was considered to dip towards north (Fig. 8d). The larger-scale geophysical signatures in the vicinity of the Kristineberg mine (Fig. 8b, e and f) do not show any distinct predominance towards northerly or southerly dips but are more compatible with steep southerly dips in a smaller scale (Fig. 8a in Garcia Juanatey et al., 2012). Since the local shear zones are known to have southerly dips (Fig. 4a and b), we interpret them as antithetic structures with respect to the major north-dipping structure.

The presence of high-strain zones with opposing dip directions is in good agreement with the box-fold geometry of the Southern antiform (Fig. 2). The greatest uncertainty among the modelled high-strain zones is with "II" in Figures 2 and 8d. The seismic signal in this location is generally weak (Tryggvason et al., 2006) and the MT data may equally well be fitted with northerly or southerly dips (Fig. 8e–h). Since the seismic signatures along the SG-VG contact 2 km south of "II" have southerly dips (Dehghannejad et al., 2010) and the primary sedimentary contact at "V" has a moderate southerly dip, we infer that the major high-strain zone at "II" also has a southerly dip. According to MT data (Fig. 8g) the SG-VG contact between the Northern and Southern antiforms may be inferred to be present at a depth of 700–1500 m. However, due to the uncertainties in constraining the high-strain zone "II" it is impossible to reliably define the 3-D-shape of the contact. The transfer faults in the NW part of the modelling area are inferred from the structural trends along the surface and drawn vertically.

The moderate to steep southerly dip of the contact of the late- to post-orogenic granite south of the Southern antiform has been constrained by the transparent seismic signature in the S-part of the seismic profiles by Tryggvason et al. (2006). This is in line with the presented MT-profiles (Fig. 8e–h). Consequently, we drew the contact of the granite surrounding the Kristineberg antiform as a steeply outwards-dipping surface down to approximately 4 km depth. In contrast, the oval-shaped late- to post-orogenic intrusion transecting the Northern antiform is a sheet-like intrusion with a maximum depth of 600–700 m (Malehmir et al., 2007).

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6 Discussion

The variably striking high-strain zones "I" and "II" (Fig. 2) may be attributed to splaying of the major ESE-WNW striking high-strain zone separating the coaxial and non-coaxial crustal domains further east (Skyttä et al., 2012). Consequently, high-strain zone "I" is the western continuation of this major high-strain zone, whereas "II" is a fault splay separating the Northern and Southern antiforms (Fig. 2). The inferred termination of the major high-strain zone north of the Kristineberg area would also very nicely explain the termination of the faults within the Southern antiform. Furthermore, we attribute the formation of splays responsible for the generation of major plunging antiformal structures in the Kristineberg area, a feature somewhat contrasting to the central parts of the district characterized by sub-horizontal fold hinges (Bauer et al., 2011; Skyttä et al., 2012). The crustal depth within the transpressive domain of Kristineberg is apparently smaller compared with e.g. the Holmträsk domain of Skyttä et al. (2012) since no tectonic S1 foliations characteristic for the non-coaxial domain may be found in Kristineberg. Nevertheless, the tendency towards more flat-lying lineations with increasing depth is common for both the Kristineberg area and the central Skellefte district.

Considering the timing of deformation events, the suggested splaying of a major fault is in favour of the model comprising of one SSE-NNW transpressive event at around 1.87 Ga rather than two separate event with contrasting bulk compression orientations (Skyttä et al., 2012). Furtheremore, the previously observed dextral strike-slip overprint on the dip-slip deformation within the Viterliden intrusion (Skyttä et al., 2010) may now be attributed to progressive SSE-NNW transpression. Recognition of the SSE-NNW transpressional deformational regime and, in specific, the characteristic partitioning between the areas of N–S and E–W compression during D2 suggests that the E–W crustal shortening at around 1.8 Ga (D3 by Bergman Weihed, 2001) was probably due to a new period of SSE-NNW transpression and not a completely new event with a contrasting E–W regional shortening direction. The required N–S component of deformation during the approximately 1.8 Ga transpression is here inferred to reactivation of the inverted WNW-ESE striking high-strain zones.

In district-scale, the northerly dip for the main reflectors within the Kristineberg area (Tryggvason et al., 2006) is contrasting to the southerly dips of reflectors from the central parts of the district (Dehghannejad et al., 2012a). For this reason, we infer that the formation of crustal compartments with opposite polarities previously recognized at a rather local scale (Bauer et al., 2011) may be attributed to the whole district. Consequently, the dip of the major crustal features is inferred to change across the approximately N–S striking Deppis-Näsliden shear zone and Vidsel-Röjnöret shear system (Fig. 1) and possibly also along some of the smaller-scale N–S striking transfer zones (Skyttä et al., 2012).

7 Conclusions

The crustal structure of the Kristineberg area may be attributed to SSE-NNW transpression which may be correlated with the formation of the characteristic upright folds in the central Skellefte district at around 1.87 Ga.

Formation of splays at the western termination of a major ESE-WNW high-strain zone (during the transpression) explains the structural geometry with development of two major antiformal structures in Kristineberg. Furthermore, the splays are inferred to divide the area into a coaxial domain (the Northern antiform) and a transpressional domain (the Southern antiform).

The complex geometry of the Southern antiform may be explained by specific strain partitioning during the transpression:

- The N–S component of compression was responsible for the reverse shearing along the approximately E–W striking shear zones.

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– The E–W component of compression affected the low-strain domains in-between, leading to localized and progressive tilting of strata into steeper west-dipping to overturned attitudes.

– As a consequense, a "flat-steep-flat" geometry was developed during one deformation event.

– Dextral strike-slip deformation along the approximately E–W high-strain zones is attributed to the progressive SSE-NNW transpression

We attribute the northerly dip of the main crustal features within the Kristineberg area to formation of crustal compartments with opposite polarities within the scale of the whole Skellefte district.

Recognition of the transpressional strain partioning allows us to suggest that the late-orogenic E–W compression is due to the N–S component of a new period of SSE-NNW transpression starting at around 1.82 Ga.

Supplementary material related to this article is available online at: http://www.solid-earth-discuss.net/4/1281/2012/sed-4-1281-2012-supplement.pdf.

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References

Allen, R. L., Weihed, P., and Svenson, S.-Å.: Setting of Zn-Cu-Au-Ag massive sulfide deposits in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte District, Sweden, Econ. Geol., 91, 1022–1053, 1996.

Årebäck, H., Barrett, T. J., Abrahamsson, S., and Fagerström, P.: The Palaeoproterozoic Kristineberg VMS deposit, Skellefte District, northern Sweden, part I: geology, Miner. Deposita, 40, 351–367, 2005.

Bauer TE, Skyttä, P., Allen, R. L., and Weihed, P.: Syn-extensional faulting controlling structural inversion – Insights from the Palaeoproterozoic Vargfors syncline, Skellefte mining district, Sweden, Precambrian Res., 191, 166–183, 2011.

Bergman Weihed J.: Palaeoproterozoic deformation zones in the Skellefte and the Arvidsjaur areas, northern Sweden, in: Economic Geology Research 1, edited by: Weihed, P., Sveriges Geologiska Undersökning C, 833, 46–68, 2001.

Billström, K. and Weihed, P.: Age and provenance of host rocks and ores of the Palaeoproterozoic Skellefte District, northern Sweden, Econ. Geol., 91, 1054–1072, 1996.

Dehghannejad, M., Juhlin, C., Malehmir, A., Skyttä, P., and Weihed, P.: Reflection seismic imaging of the upper crust in the Kristineberg mining area, northern Sweden, J. Appl. Geophys., 71, 125–136, doi:10.1016/j.jappgeo.2010.06.002, 2010.

Dehghannejad, M., Bauer, T. E., Malehmir, A., Juhlin, C., and Weihed, P.: Crustal geometry of the central Skellefte district, northern Sweden – constraints from reflection seismic investigations, Tectonophysics 20, 87–99, 2012a.

Dehghannejad, M., Malehmir, A., Juhlin, C., and Skyttä, P.: 3D constraints and finite-difference modeling of massive sulfide deposits: The Kristineberg seismic lines revisited, northern Sweden, Geophysics, 77, WC69–WC79, doi:10.1190/GEO2011-0466.1, 2012b.

Ehsan, S. A., Malehmir, A., and Dehghannejad, M.: Re-processing and intepretation of 2D seismic data from the Kristineberg mining area, northern Sweden, J. Appl. Geophys., 80, 43–55, 2012.

Gaál, G.: Tectonic styles of early Proterozoic ore dheposition in the Fennoscandian shield, Precambrian Res., 46, 83–114, 1990.

Galley, A. G. and Bailes, A. H.: The interrelationship between the Viterliden intrusion, synvolcanic alteration, and volcanogenic massive sulphide mineralization, Kristineberg region, Skellefte District, Sweden, CAMIRO, Project 94E07, Draft technical report (unpublished), 71 pp., 1999.

Garcia Juanatey, M., Hübert, J., Tryggvason, A., and Pedersen, L.: Imaging the Kristineberg mining area with two perpendicular magnetotelluric profiles in the Skellefte Ore District, northern Sweden, Geophys. Prospect., doi:10.1111/j.1365-2478.2011.01040.x, in press, 2012.

González-Roldán, M. J.: Mineralogy, Petrology and Geochemistry of syn-volcanic intrusions in the Skellefte mining district, Northern Sweden, Dissertation, University of Huelva, Spain, 2010.

Hietanen, A.: Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian of Finland, J. Res. US Geol. Surv., 3, 631–645, 1975.

Hübert, J., Malehmir, A., Smirnow, M., Tryggvason, A., and Pedersen, L. B.: MT measurements in teh western part of the Paleoproterozoic Skellefte Ore District, Northern Sweden: A contribution to an intergrated geophysical study, Tectonophysics, 475, 493–502, 2009.

Jolley, S.: Structural controls on sulphide remobilisation and deformation: Kristineberg gold mine, Unpublished report 2057 (for Boliden Mineral ab), Rock Deformation Research Group, 37 pp., 2001.

Juhlin, C., Elming, S.-Å., Mellqvist, C., Öhlander, B., Weihed, P., and Wikström, A.: Crustal reflectivity near the Archaean-Proterozoic boundary in northern Sweden and implications for the tectonic evolution of the area, Geophys. J. Int., 150, 180–197, 2002.

Kathol, B. and Weihed, P. (Eds.): Description of regional geological and geophysical maps of the Skellefte District and surrounding areas, Sveriges geologiska undersökning Ba, 57, 197 pp., 2005.

Kathol, B., Weihed, P., Antal Lundin, I., Bark, G., Bergman Weihed, J., Bergström, U., Billström, K., Björk, L., Claesson, L., Daniels, J., Eliasson, T., Frumerie, M., Kero, L., Kumpulainen, R. A., Lundström, H., Lundström, I., Mellqvist, C., Petersson, J., Skiöld, T., Sträng, T., Stølen, L.-K., Söderman, J., Triumf, C.-A., Wikström, A., Wikström, T., and Årebäck, H.: Regional geological and geophysical maps of the Skellefte district and surrounding areas, Bedrock map, Sveriges geologiska undersökning Ba, 57, 1, 2005.

Lickorish, H.: Structural profiles through the Skellefte Belt, northern Sweden, unpublished report for Georange, 38 pp., 2005.

Lundström, I. and Antal, I.: Bedrock map 23 K Boliden, scale 1:50 000, Sveriges geologiska undersökning Ai, 110–113, 2000.

Lundström, I., Vaasjoki, M., Bergström, U., Antal, I., and Strandman, F.: Radiometric age determinations of plutonic rocks in the Boliden area: the Hobergsliden granite and the Stavaträsk diorite, in: Radiometric dating results 3, edited by: Lundqvist, T., Sveriges geologiska undersökning C, 830, 20–30, 1997.

Lundström, I., Persson, P.-O., and Bergström, U.: Indications of early deformational events in the north-eastern part of the Skellefte field. Indirect evidence from geological and radiometric data from the Stavaträsk-Klintån area, Boliden map-sheet, in: Radiometric dating results 4, edited by: Bergman, S., Sveriges geologiska undersökning C, 831, 52–69, 1999.

Malehmir, A., Tryggvason, A., Lickorish, H., and Weihed, P.: Regional structural profiles in the western part of the Palaeoproterozoic Skellefte ore district, northern Sweden, Precambrian Res., 159, 1–18, 2007.

Malehmir, A., Thunehed, H., and Tryggvason, A.: The Paleoproterozoic Kristineberg mining area, northern Sweden: Results from integrated 3D geophysical and geologic modelling, and implications for targeting ore deposits, Geophysics, 74, B9–B22, 2009a.

Malehmir, A., Schmelzbach, C., Bongajum, E., Bellefleur, G., Juhlin, C., and Tryggvason, A.: 3D constraints on a possible deep > 2.5 km massive sulphide mineralization from 2D crooked-line seismic reflection data in the Kristineberg mining area, northern Sweden, Tectonophysics, 479, 223–240, 2009b.

Montelius, C.: The genetic relationship between rhyolitic volcanism and Zn-Cu-Au deposits in the Maurliden Volcanic Centre, Skellefte District, Sweden: volcanic facies, lithogeochemistry and geochronology, Dissertation, Luleå University of Technology, Sweden, 2005.

Rutland, R. W. R., Kero, L., Nilsson, G., and Stølen, L. K.: Nature of a major tectonic discontinuity in the Svecofennian province of northern Sweden, Precambrian Res., 112, 211–237, 2001a.

Rutland, R. W. R., Skiöld, T., and Page, R. W.: Age of deformation episodes in the Palaeoproterozoic domain of northern Sweden, and evidence for a pre-1.9 Ga crustal layer, Precambrian Res. 112, 239–259, 2001b.

Skiöld, T., Öhlander, B., Markkula, H., Widenfalk, L., and Claesson, L. Å.: Chronology of Proterozoic orogenic processes at the Archaean continental margin in northern Sweden, Precambrian Res., 64, 225–238, 1993.

Skyttä, P., Hermansson, T., and Bauer, T.: Three Dimensional Structure of the VMS-hosting Palaeoproterozoic Kristineberg Area, Northern Sweden, Proceedings of the 10th biennial SGA meeting, Townsville, Australia, 909–911, 2009.

Skyttä, P., Hermansson, T., Elming, S.-Å., and Bauer, T.: Magnetic fabrics as constraints on the kinematic history of a pre-tectonic granitoid intrusion, Kristineberg, northern Sweden, J. Struct. Geol., 32, 1125–1136, 2010.

Skyttä, P., Hermansson, T., Andersson, J., Whitehouse, M., and Weihed, P.: New zircon data supporting models of short-lived igneous activity at 1.89 Ga in the western Skellefte District, central Fennoscandian Shield, Solid Earth, 2, 205–217, doi:10.5194/se-2-205-2011, 2011.

Skyttä, P., Bauer, T., Tavakoli, S., Hermansson, T., Andersson, J., and Weihed, P.: Pre-1.87 Ga development of crustal domains overprinted by 1.87 Ga transpression in the Palaeoproterozoic Skellefte district, Sweden, Precambrian Res., 206–207, 109–136, 2012.

Tryggvason, A., Malehmir, A., Rodriguez-Tablante, J., and Juhlin, C.: Reflection seismic Investigations in the Western Part of the Paleoproterozoic VHMS-Bearing Skellefte District, Northern Sweden, Econ. Geol., 101, 1039–1054, 2006.

Weihed, P., Billström, K., Persson, P.-O., and Bergman Weihed, J.: Relationship between 1.90–1.85 Ga accretionary processes and 1.82–1.80 Ga oblique subduction at the Karelian craton margin, Fennoscandian Shield, GFF, 124, 163–180, 2002.

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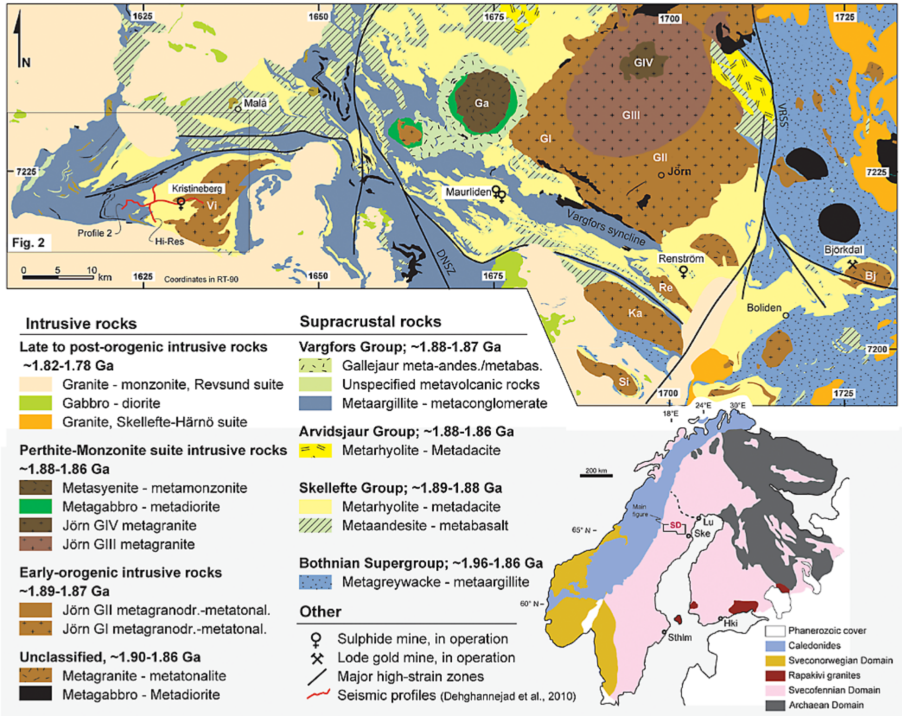

Fig. 1. Inset: generalized Fennoscandian Shield geology. Main map: geological overview of the Skellefte district, as loosely defined by the occurrence of the Skellefte Group metavolcanic rocks, and their immediate vicinity. DNSZ = Deppis-Näsliden shear zone; VRSS = Vidsel-Röjnöret shear system. Intrusions: Vi = Viterliden, Re = Rengård, Ka = Karsträsk, Si = Sikträsk, Bj = Björkliden, GI, GII, GIII, GIV = Jörn type intrusions, phases I–IV. Ore deposits: H = Hornträskviken, Kh = Kimheden, Kr = Kristineberg, R = Rävliden, Rm = Rävlidmyran, Rö = Rökå. Geology after Kathol et al. (2005) and Bergman Weihed (2001).

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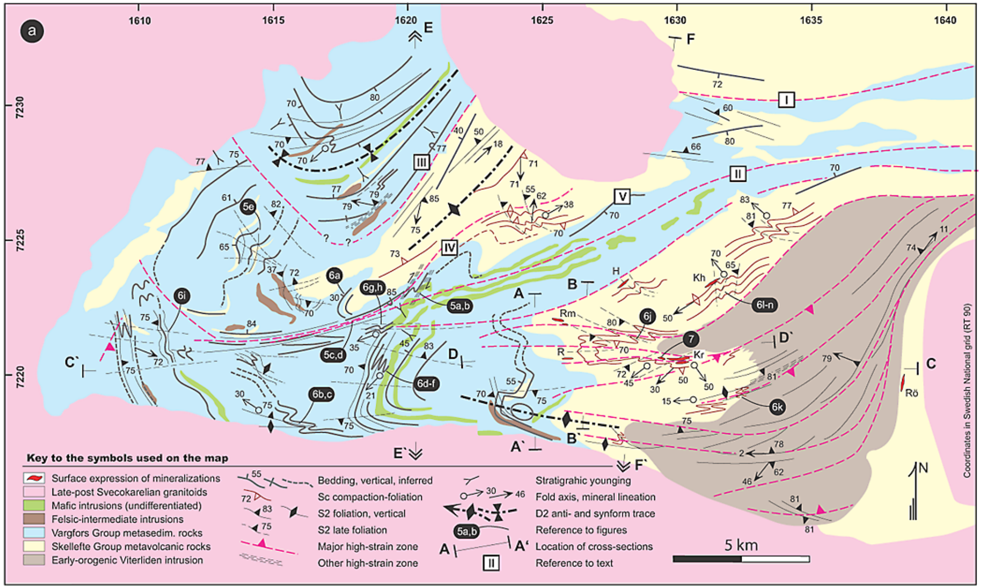

Fig. 2a. Kristineberg area geology. Modified after Kathol et al. (2005) and Skyttä et al. (2009). Cross-sections A–A′, B–B′ and C–C′ are shown in Fig. 4. "Hi-Res" and "Profile 2" in Dehghannejad et al. (2010) are located along cross-sections B–B′ and D–D′, respectively. E–E′ and F–F‘ indicate the locations for "Profile 5" and "Profile 1" in Tryggvason et al. (2006); notice that "Profiles 1 and 5" extend beyond the area of this figure.

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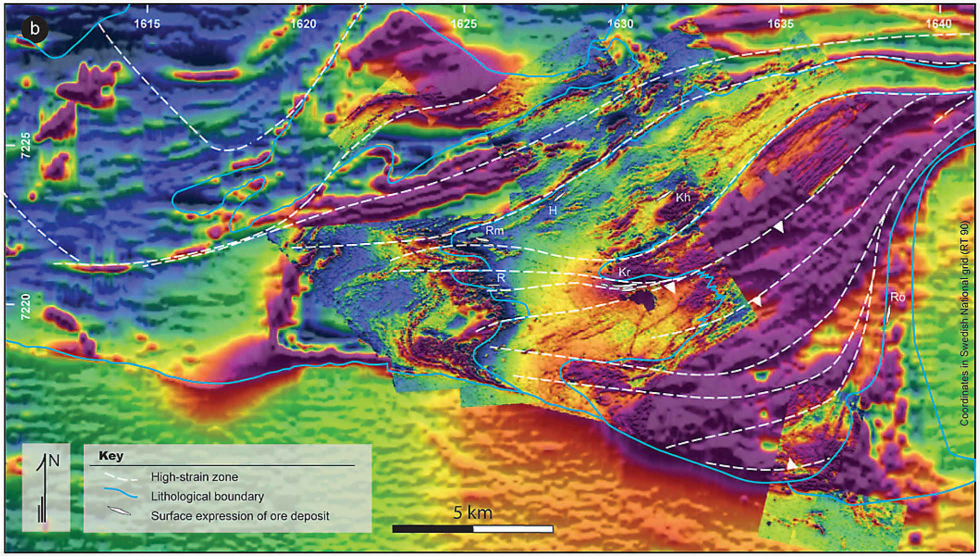

Fig. 2b. Total magnetic map of the Kriberg area (aeromagnetic covering the whole figure, source SGU; ground magnetic map for the central parts, source Boliden Mineral AB).

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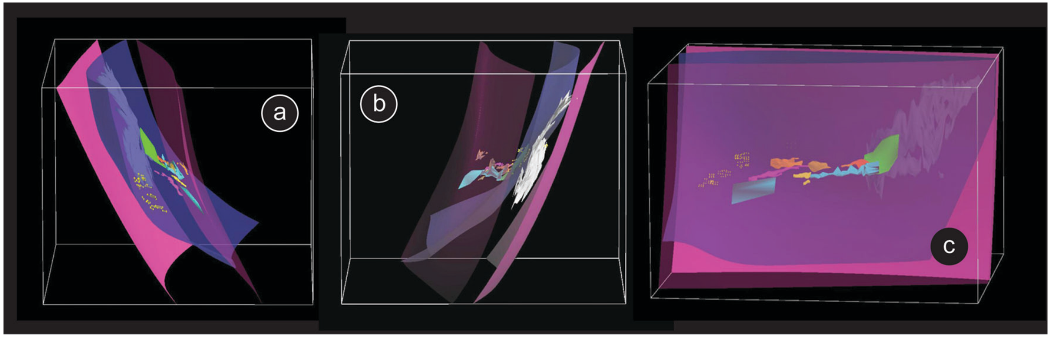

Fig. 3. Geometry of the Kristineberg deposit VMS lenses. **(a)** Cross-sectional view towards east. **(b)** Cross-sectional view towards west. **(c)** Longitudinal view towards north. Selected high-strain zones are shown for reference in different shades of magenta (see the Supplement for details). Height of the bounding boxes are 2.5 km.

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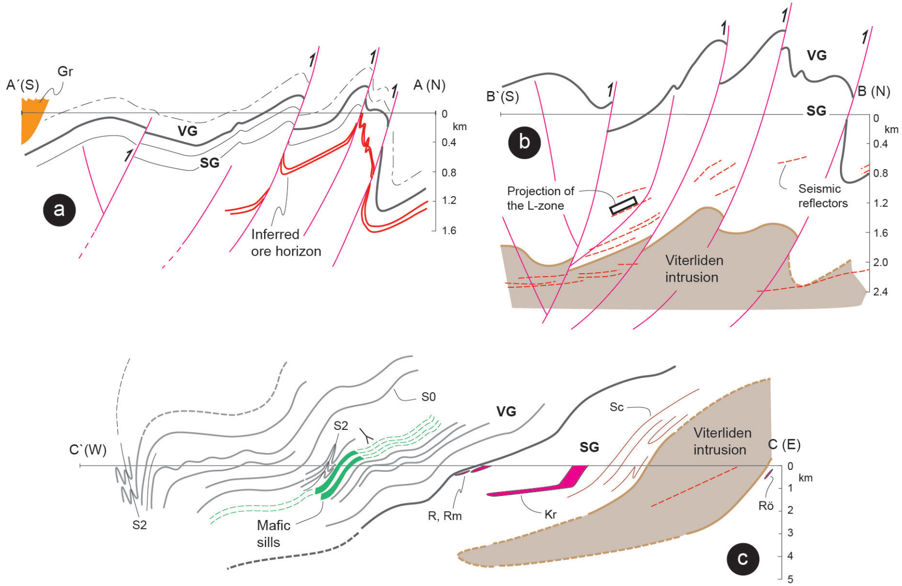

Fig. 4. Geological cross-sections, see Fig. 2a for location. **(a)** Cross-section through the contact zone between the metavolcanic and metasedimentary rocks, Gr = late-orogenic granite, **(b)** cross-section along the "high-resolution" seismic profile in Dehghannejad et al. (2010). See the Supplement for the location of L-zone. **(c)** Longitudinal E–W cross-section. Abbreviations for ore deposits as in Fig. 2.

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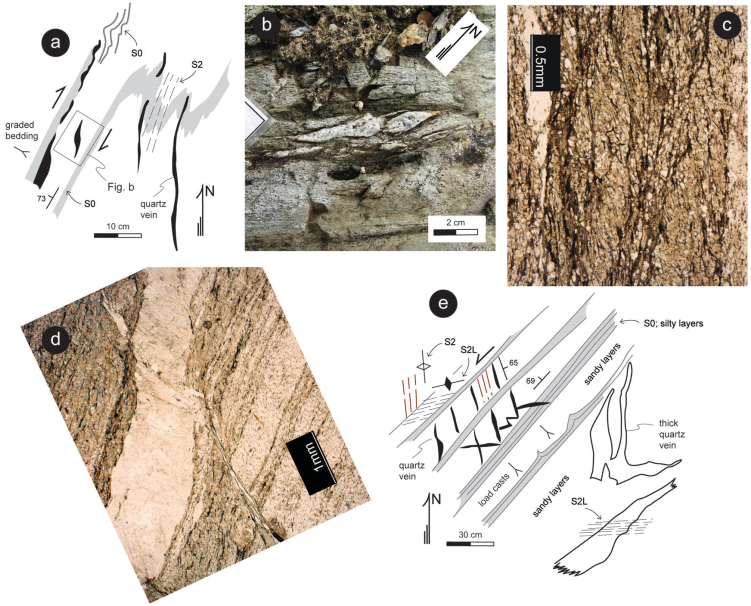

Fig. 5. Shear zone kinematics and fabrics. **(a)** Outcrop sketch illustrating the folding and shearing along the high-strain zone occurring along the southern limb of the Northern antiform. **(b)** Lensoidal quartz vein with asymmetric wings indicative of dextral shear. **(c)** Ductile north-side-up dip-slip movement recorded in metasedimentary rocks occurring along a major sub-vertical high-strain zone. Vertical section, view towards ENE. **(d)** A semi-brittle reverse, south-side-up shear band deforming the sub-vertical foliation and parallel quartz veins, same outcrop as in **(c)**. Vertical section, view towards ENE. **(e)** Outcrop sketch illustrating the en-echelon pattern of quartz veins occurring within thicker sandy units, between laminated silty units, in a metasedimentary succession on the north-west limb of the regional Kristineberg antiform.

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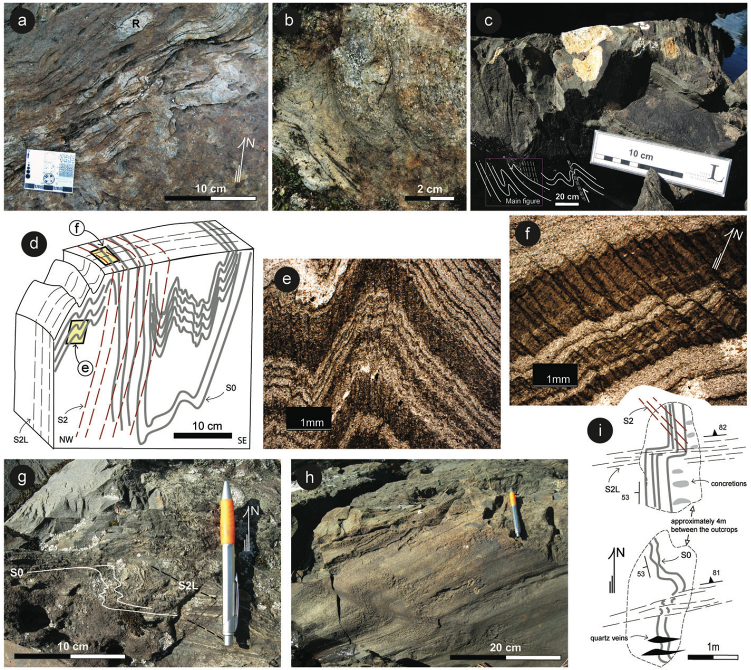

Fig. 6. Folds and fabrics within the metasedimentary **(a–i)** and metavolcanic **(j–n)** rocks. Distinction between the structures of successive generations is elaborated in Sect. 4.3.1. However, the final labels for the structures are used in the maps to allow better readability. **(a)** Contact between the Skellefte Group felsic volcanic rock (bottom) and the Vargfors Group metasedimentary rocks (top). Notice the volcanic rip-off clast (R) in the metasedimentary rock. **(b)** Load casts indicating stratigraphic younging upwards in metasedimentary rocks with sub-horizontal bedding surfaces cross-cut by sub-vertical S2-foliation. Vertical section, view towards NW. **(c)** Cylindrical F2 folds overturned towards south. The inset illustrates the parallel attitude of local reverse shear zones and the S2 foliation. Vertical section, view towards WNW. **(d)** Field sketch of upright, ductile F2 folds overprinted by spaced S2L-foliation. **(e)** S2-foliation developed along the axial surface of an upright F2 fold, see **(d)** for location. Vertical section, view towards NE. **(f)** Asymmetric, spaced S2L crenulation cleavage deforms bedding and the sub-parallel S2 foliation. **(g)** Asymmetric z-shaped F2-folds overprinted by S2L crenulation cleavage in a micaceous domain of a metasedimentary rocks. **(h)** S-shaped F2L-folds developed in a sandy unit of a metasedimentary succession. Vertical section, view towards NNW. **(i)** Stratified metasedimentary rocks displaying a weak oblique S2-foliation, subsequently overprinted by distinct D2L-shear zones, associated with the development S2L shear foliation, transposition of concretions, and syntectonic quartz veining. **(j)** D2l-crenulations overprinting isoclinal F2 folds. **(k)** Composite crenulation and solution cleavage surfaces deforming altered metavolcanic rocks close to the western contact of the Viterliden intrusion. Microphotograph, north upwards in the image. **(l)** Chlorite porphyroblasts with an internal (Sc) foliation occurring at a high angle towards the external main foliation (S2). Microphotograph;approximately horizontal section, north upwards. **(m)** Isoclinal F2-folds deforming the weak older foliation in altered metavolcanic rocks, both overprinted by open NW-SE striking D2L crenulations. Microphotograph, sub-horizontal view, north upwards. Width of view 11 mm. **(n)** Close-up of **(m)** displaying folding of the oldest generation of foliation around the F2 fold hinge. Width of view approximately 2 mm.

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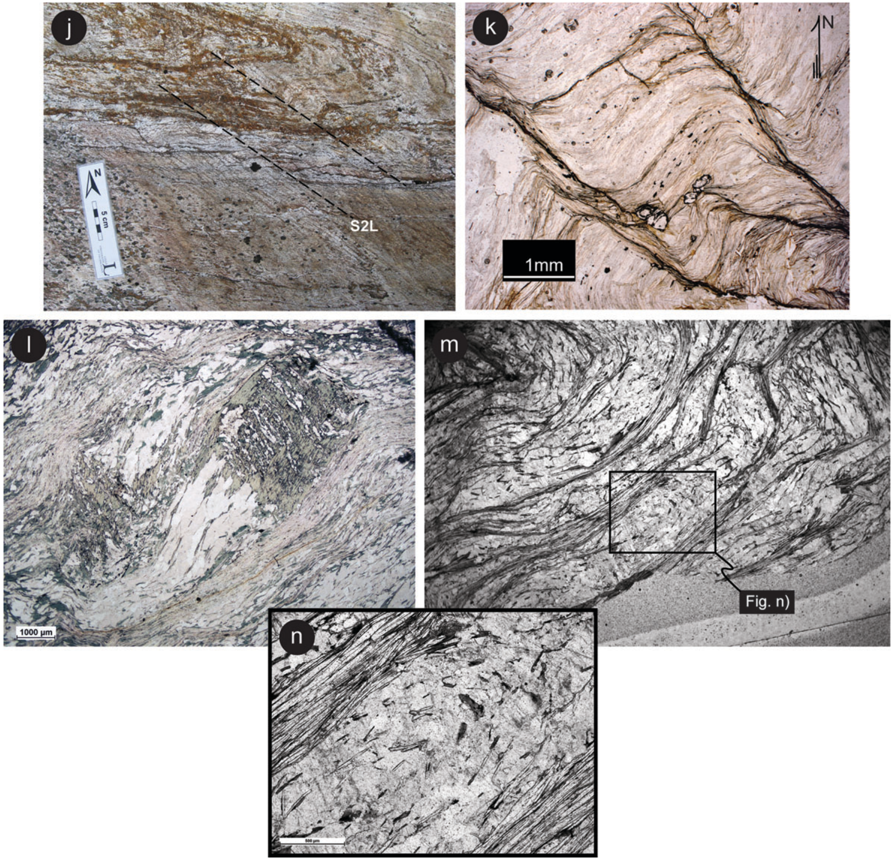

Fig. 6. Continued.

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Structural evolution of the VMS-hosting Kristineberg area

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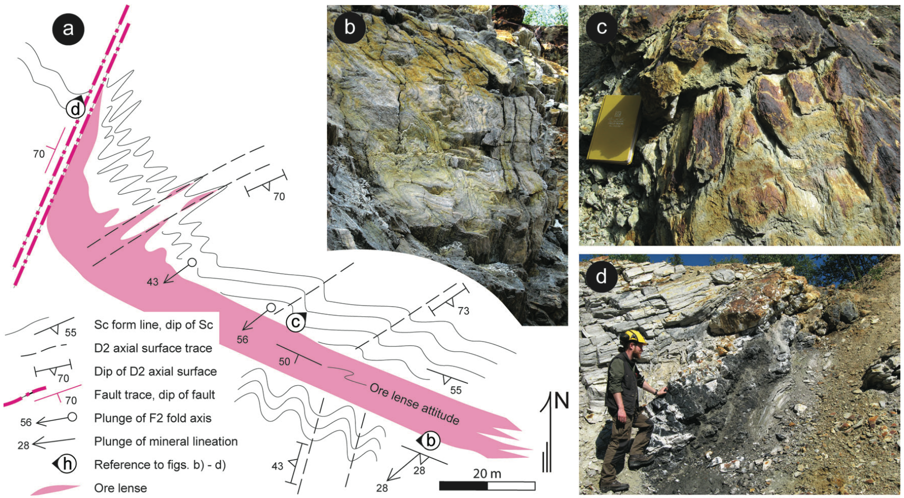

Fig. 7. Structures in the A4 open pit, see Fig. 2 for location. **(a)** Geological overview of the A4 open pit. **(b)** Plunging inclined F2 folds in the sericite-altered stratigraphic hanging-wall to the A4 ore lense. Vertical section, view towards W. Width of view approximately 2 m. **(c)** Plunging upright F2 folds in the stockwork-system mineralization in the stratigraphic footwall to the A4 ore lense. View up-plunge along the fold axes, towards NE. Width of view approximately 80 cm. **(d)** A semi-brittle WNW-dipping high-strain zone constraining the western extent of the A4 ore lense. Vertical section, view towards NNE.

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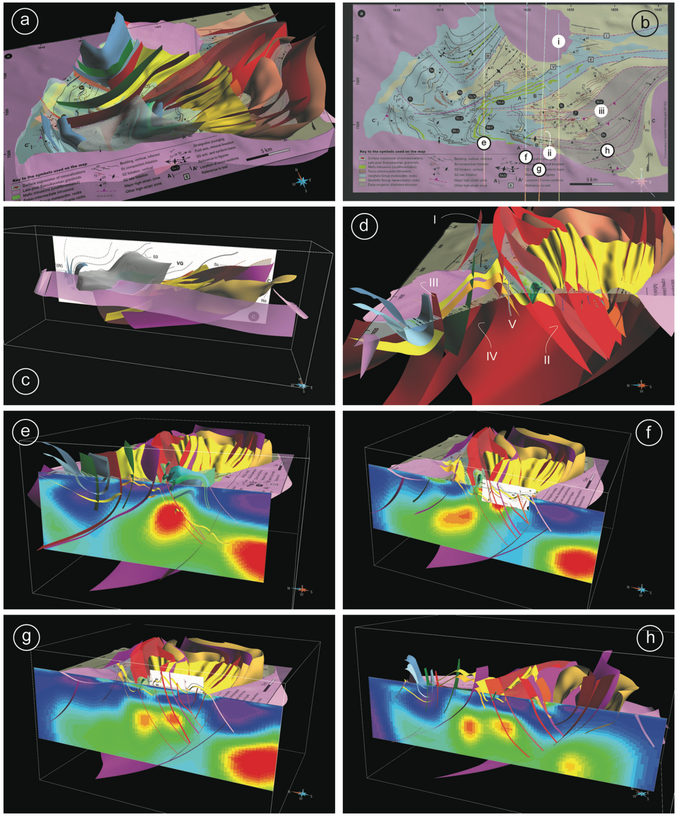

Fig. 8. gOcad screenshots of the 3-D-model over the Kristineberg area, see the Supplement for the related 3-D-PDF file. **(a)** An overview of the model, view towards NNE. **(b)** Location of the cross-sections sliced from 3-dimensional MT models to constrain the in-depth-extension of the modelled geological features of this investigation, see **(e–h)**. ' 'i" is an MT-profile used in constraining the 3-D model but not shown in the figures and "ii" and "iii" are the N–S and E–W-striking MTprofiles in Garcia et al., 2012). **(c)** A long-sectional view highlighting the "steep-flat-steep" geometry along the hinge of the Southern antiform. **(d)** A sliced view with reference to locations "I"–"V" in Fig. 2a. **(e)** "Western" cross-section. **(f)** Section A–A′ in Fig. 2a. **(g)** Section B–B′ in Fig. 2a. **(h)** "Regional cross-section" transecting both the Southern and Northern antiforms.

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