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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 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 Weiher, 1996; Montelius, 2005; Skyttä et al., 2011). Crustal

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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 (Billström and Weihed, 1996; Skyttä et al., 2012). The Vargfors Group is the uppermost stratigraphical unit of the Skellefte district, and was coeval with the sub-aerial, 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 Ga 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-porphyratic, 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 curvilinear 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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northern flank of the Southern antiform. The orientation of resistor “R11” 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.

5 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
10 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
15 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
20 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; Hübner 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,
25 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

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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
5 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
10 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
15 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
20 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
25 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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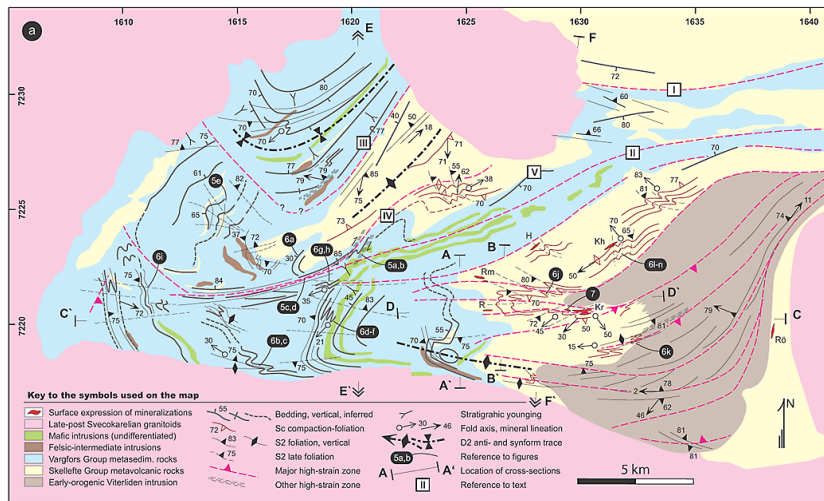


Fig. 2a. Kristineberg area geology. Modified after Kathol et al. (2005) and Skyttä et al. (2009). Cross-sections A–A', B–B' and C–C' are shown in Fig. 4. "Hi-Res" and "Profile 2" in Dehghannejad et al. (2010) are located along cross-sections B–B' and D–D', respectively. E–E' and F–F' indicate the locations 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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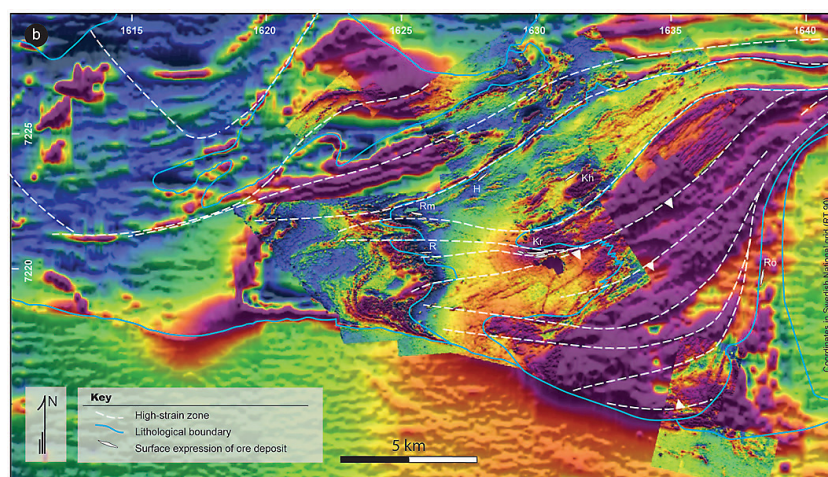


Fig. 2b. Total magnetic map of the Kriberg area (aeromagnetic covering the whole figure, source SGU; ground magnetic map for the central parts, source Boliden Mineral AB).

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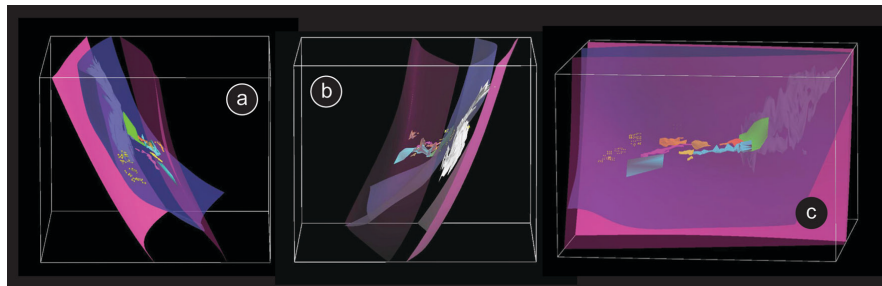


Fig. 3. Geometry of the Kristineberg deposit VMS lenses. **(a)** Cross-sectional view towards east. **(b)** Cross-sectional view towards west. **(c)** Longitudinal view towards north. Selected high-strain zones are shown for reference in different shades of magenta (see the Supplement for details). Height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

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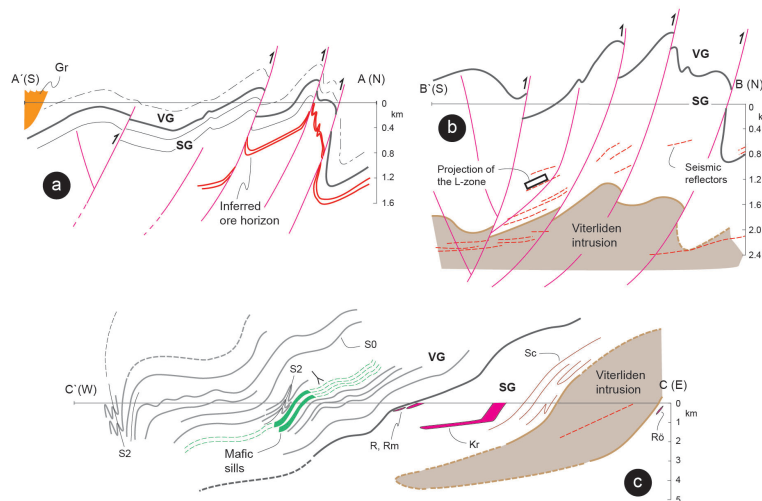


Fig. 4. Geological cross-sections, see Fig. 2a for location. **(a)** Cross-section through the contact zone between the metavolcanic and metasedimentary rocks, Gr = late-orogenic granite, **(b)** cross-section along the “high-resolution” seismic profile in Dehghannejad et al. (2010). See the Supplement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

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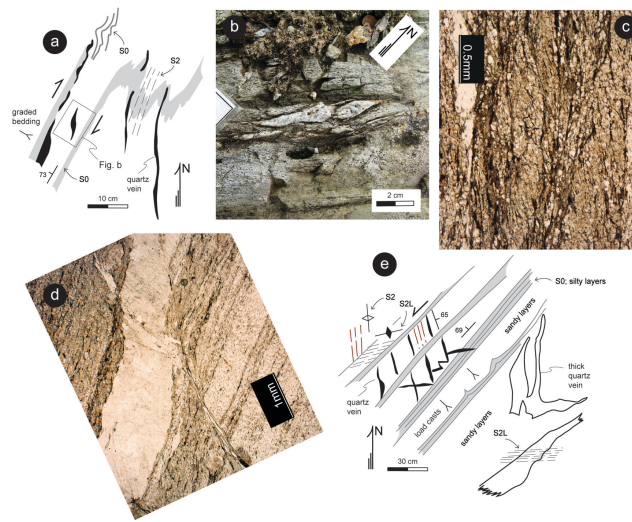


Fig. 5. Shear zone kinematics and fabrics. **(a)** Outcrop sketch illustrating the folding and shearing along the high-strain zone occurring along the southern limb of the Northern antiform. **(b)** Lensoidal quartz vein with asymmetric wings indicative of dextral shear. **(c)** Ductile north-side-up 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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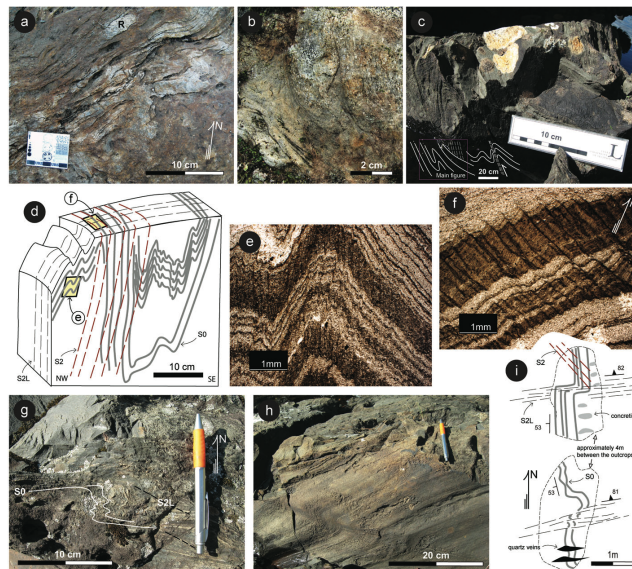


Fig. 6. Folds and fabrics within the metasedimentary **(a–i)** and metavolcanic **(j–n)** rocks. Distinction between the structures of successive generations is elaborated in Sect. 4.3.1. However, the final labels for the structures are used in the maps to allow better readability. **(a)** Contact between the Skellefte Group felsic volcanic rock (bottom) and the Vargfors Group metasedimentary rocks (top). Notice the volcanic rip-off clast (F) 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 (S0) 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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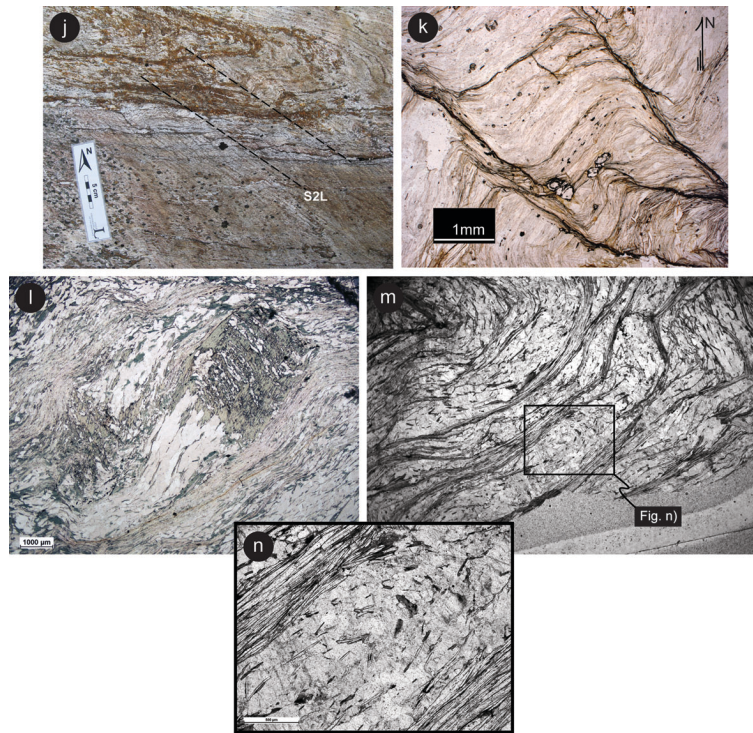


Fig. 6. Continued.

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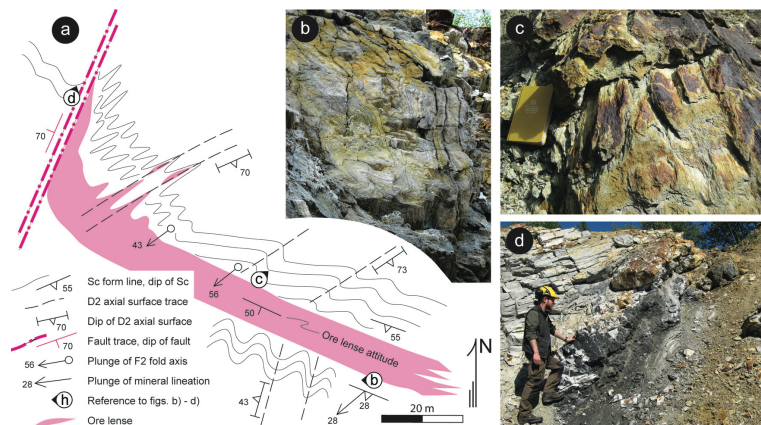


Fig. 7. Structures in the A4 open pit, see Fig. 2 for location. **(a)** Geological overview of the A4 open pit. **(b)** Plunging inclined F2 folds in the sericite-altered stratigraphic hanging-wall to the A4 ore lens. Vertical section, view towards W. Width of view approximately 2 m. **(c)** Plunging upright F2 folds in the stockwork-system mineralization in the stratigraphic footwall to the A4 ore lens. 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 lens. Vertical section, view towards NNE.

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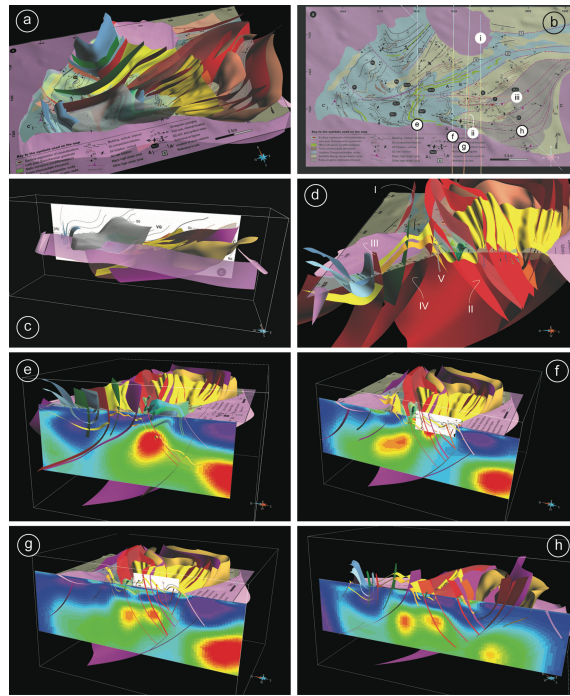


Fig. 8. gOcad screenshots of the 3-D-model over the Kristineberg area, see the Supplement for the related 3-D-PDF file. **(a)** An overview of the model, view towards NNE. **(b)** Location of the cross-sections sliced from 3-dimensional MT models to constrain the in-depth-extension of the modelled geological 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 MT profiles 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.