Seismic imaging in the eastern Scandinavian Caledonides: Siting the 2.5 km deep COSC-2 borehole, central Sweden.

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Abstract

The Collisional Orogeny in the Scandinavian Caledonides (COSC) project, a contribution to the International Continental Scientific Drilling Program (ICDP), aims to provide a deeper understanding of mountain belt dynamics. Scientific investigations include a range of topics, from subduction-related tectonics to the present-day hydrological cycle. COSC investigations and drilling activities are focused in central Scandinavia where rocks from the mid to lower crust of the orogen are exposed near the Swedish-Norwegian border. Here, rock units of particular interest occur in the Seve Nappe Complex (SNC) of the so-called Middle Allochthon and include granulite facies migmatites (locally with evidence of ultra-high pressures) and amphibolite facies gneisses and mafic rocks. This complex overlies greenschist facies metasedimentary rocks of the dolerite-intruded Särv Nappes and underlying, lower grade Jämtlandian Nappes (Lower Allochthon). Reflection seismic profiles have been an important component in the activities to image the sub-surface structure in the area. Sub-horizontal reflections in the upper 1-2 km are underlain and interlayered with strong west- to northwest-dipping reflections, suggesting significant east-vergent thrusting. Two 2.5 km deep fully cored boreholes are a major component of the project which will improve our understanding of the sub-surface structure and tectonic history of the area. Borehole COSC-1 (IGSN: http://hdl.handle.net/10273/ICDP5054EEW1001), drilled in the summer of 2014, targeted the subduction-related Seve Nappe Complex and the contact with the underlying allochthon. The COSC-2 borehole will be located further east and investigate the lower grade, mainly Cambro-Silurian rocks of the Lower Allochthon, the Jämtlandian décollement and penetrate into the crystalline basement rocks to identify the source of some of the northwest-dipping reflections. A series of high resolution seismic profiles have been acquired along a composite c. 55 km long profile to help locate the COSC drill holes. We present here the results from this COSC-related composite seismic profile (CSP), including new interpretations based on previously unpublished data acquired between 2011 and 2014. These seismic data, along with shallow drill holes in the Caledonian thrust front and previously acquired seismic, magnetotelluric, and magnetic data, are used to identify two potential drill sites for the COSC-2 borehole.

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1 Introduction

Following the Ordovician closure of the Iapetus Ocean, major Caledonian orogeny involved continent collision and underthrusting of Baltica beneath Laurentia. Subduction-related metamorphism along the Baltica margin was taking place already in the early to middle Ordovician (Gee et al., 2012; Majka et al., 2012) and the initial stages of continent-continent collision are believed to have occurred around 445 Ma (e.g. Ladenberger et al., 2012, 2014). Thrust tectonics, which dominated throughout the collision, resulted in the emplacement of allochthonous units both westwards onto the Laurentian platform of Greenland (Higgins and Leslie, 2000) with displacements of the higher allochthons at least 200 km, and eastwards onto the Baltoscandian platform with displacements of more than 500 km (Gee, 1978).

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Towards the end of Caledonian Orogeny, in the early Devonian, the mountain belt was in many aspects comparable to the presently active Himalaya-Tibet Orogen (Dewey 1969; Gee et al., 2010; Labrousse et al., 2010). Following post-orogenic collapse, extension and deep erosion, the surface of the present day Caledonides cuts through the internal architecture of the paleo-orogen, revealing the nappe structure at mid-crustal depths. The Scandinavian mountains, the Scandes, have long been recognized as an excellent environment to study thrust tectonics (Törnebohm, 1888) and the processes involved in continent-continent collision (Gee, 1975; Hossack and Cooper, 1986).

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Investigations of the Scandinavian Caledonides (Fig. 1) were intensified in the 1970’s (Gee and Sturt, 1985) and our understanding has since then improved through continued geological (e.g. the many contributions in Corfu et al., 2014) and numerous geophysical (e.g. Dyrelius, 1980, 1986; Elming, 1988; Hurich et al., 1989; Palm et al., 1991; Hurich, 1996; Juhojuntti et al., 2001; Pascal et al., 2007; Korja et al., 2008; England and Ebbing, 2012) studies. One key area of investigation (Dyrelius et al., 1980) has been along a profile crossing the mountain belt through the provinces of Jämtland (Sweden) and Tröndelag (Norway). Reflection seismic surveys were conducted along the Central Caledonian Transect (CCT) which stretches from east of the Caledonian thrust front in central Jämtland to the Atlantic coast in western Tröndelag (Hurich et al., 1989; Palm et al., 1991; Hurich, 1996; Juhojuntti et al., 2001). The highly reflective upper crust shows a reflectivity pattern of crustal shortening consistent with surface observations, i.e. imbrication of allochthonous units and folding by major N-S to NE-SW-trending antiforms and synforms.

At the thrust front in central Sweden, Cambrian alum shales, deposited unconformably on the autochthonous crystalline basement, are separated from the overlying Caledonian allochthons by a major décollement (Gee et al., 1978). Comprehensive drilling programs targeting the metalliferous organic-rich alum shales (Gee et al., 1982) in the thrust front south of lake Storsjön reached about 30 km to the northwest, establishing a 1-2° westwards dip of the décollement. At the Caledonian front in central Jämtland, this major detachment coincides with the Caledonian sole thrust (see profile in Fig. 1). We define the main décollement (in Jämtland – the Jämtlandian décollement, at the base of the Jämtlandian Nappes) as the thrust zone that separates all the overlying long-transported allochthons from the underlying less deformed basement. The sole thrust corresponds to the lower limit of Caledonian deformation, i.e. involving both the long-transported allochthons and the underlying crystalline basement in and below the antiformal windows. Along the CCT reflection seismic profile, the sole thrust in the western part (Palm et al., 1991) was inferred to ramp up eastwards and pass into the Jämtlandian décollement, as defined in areas north of Storsjön (Juhojuntti et al., 2001). The sole thrust defined by Palm et al (1991) beneath the Åre Synform and Mullfjället Antiform was inferred to continue westwards to the Swedish-Norwegian border, where it appears to reach a depth of c. 7 km (Hurich et al., 1989); perhaps deeper (Gee, 1988, Hurich 1996), beneath the imbricated crystalline basement of the Skardöra Antiform. This interpretation is in agreement with previous modeling of refraction seismic (Palm, 1984), aeromagnetic (Dyrelius, 1980) and gravity data (Dyrelius, 1985; Elming, 1988). Magnetotelluric measurements along the Swedish section of the CCT profile (Korja et al., 2008), targeting the highly conductive alum shales, further support this interpretation.

A transition from thin-skinned (where deformation is mostly restricted to the allochthonous sediment-dominated units) to thick-skinned tectonics (with deep crustal deformation and basement shortening) is often attributed to large scale detachments and fault systems in the hinterland (Hurich, 1996; Mosar, 2003; Fossen et al., 2014) that are reactivated during post-collisional extension. In the case of the Caledonides, these are late-orogenic and involve NE-SW extension along the axis of the orogen. However, the previous thrusting may well have been influenced by the pre-Caledonian geometry of the rifted and extended Neoproterozoic margin of Baltica (Gee et al., 2012).

Juhojuntti et al. (2001) identified a present day Moho at a depth of c. 45-50 km beneath central Sweden and suggested deep crustal deformation in the subducting Baltica plate. However, the source of the strong reflections observed from within the Paleoproterozoic basement beneath Jämtland remains to be determined. Two potential sources of the reflectivity patterns have been proposed (Palm et al., 1991, Juhojuntti et al., 2001), one being that they are related to the deformation history and the other that they are lithological in origin. Deformation zones could have developed during the Caledonian or Precambrian (Sveconorwegian, c. 1.0 Ga, or older) orogenies. Alternatively, most of the reflections could represent deformed mafic intrusions in the dominantly granitic basement rocks. Dolerite sills

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in the Siljan Ring area, a hundred kilometers to the southeast, are known to generate a similar seismic response (Juhlin, 1990). Dolerite sills and dykes are found to the south (0.95 Ga, Juhlin, 1990; Högdahl et al., 2004) and east (1.25 Ga, Högdahl et al., 2004; Söderlund et al., 2006) of the thrust front of the central Scandinavian Caledonides and also in the Olden Window (Sjöström and Talbot, 1987).

The Collisional Orogeny in the Scandinavian Caledonides (COSC) project (Gee et al., 2010; Lorenz et al., 2011) aims to improve our understanding of collisional orogeny through scientific deep drilling of selected targets in the Swedish Caledonides. COSC is supported by the International Continental Scientific Drilling Program (ICDP) and operates within the framework of the Swedish Scientific Drilling Program (SSDP), which has the objective to investigate fundamental questions of global importance that are well defined in Scandinavia and require drilling.

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The first phase of the project, COSC-1, targeted the lower units of the high grade Seve Nappe Complex (SNC). These rocks that originated along the rifted outer margin of continent Baltica, including the continent-ocean transition (COT) zone (Andreasson, 1994), were partially subducted during the Ordovician and then emplaced hot onto underlying allochthons. COSC-1 was drilled to a depth of 2.5 km with almost 100% core recovery during May to August 2014 (Lorenz et al., 2015). The second phase, COSC-2, involves a second 2.5 km deep borehole that will start in the Lower Allochthon and aims to penetrate the Jämtlandian décollement as well as at least one of the underlying enigmatic basement reflectors. The focus of COSC-2 lies in understanding the thin-skinned thrusting over this detachment horizon, the character of the deformation in the underlying crystalline Fennoscandian basement, and how this foreland deformation relates to the partial subduction of the Baltica margin in the hinterland (e.g. the Western Gneiss Region of southwestern Norway) in the early Devonian (Robinson et al., 2014).

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In 2010, a 36 km long high resolution reflection seismic profile was acquired in the Åre area (Fig. 1) with the purpose of finding the most suitable locations for the two scientific boreholes (Hedin et al., 2012). The location of the COSC-1 borehole was defined from these data (together with logistical considerations), but a location fulfilling the requirements of COSC-2 was not clearly identified. The interpreted Jämtlandian décollement and basement reflections appeared to continue shallowing towards the east and the main seismic profile was therefore extended by about 17 km in 2011 and another c. 14 km in 2014. A substantial gap in the 2011 acquisition was bridged in 2014 by an additional c. 16 km long highly crooked profile south of the 2011 profile (Fig. 2).

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Complementary to the seismic profiling, a magnetotelluric (MT) survey was conducted along the entire seismic profile in 2013 (Yan et al., 2016). Although this also suffered from the need for a diversion and, thus, follows the highly crooked seismic profile, it provides clear

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constraints on the depth to the top of the highly conductive alum shales. In addition, new aeromagnetic data were acquired by the Swedish Geological Survey in 2011, showing prominent features that may be linked with Rätan-type magnetite-rich granites in the basement.

This paper focuses on the interpretation of the recently acquired seismic profiles, together referred to as the COSC seismic profiles (CSP), and the linking of these with the results from the drilling program in the late 1970's and observations from the COSC-1 borehole. In the light of the new geophysical data (reflection seismic, MT and aeromagnetic), we present an updated and extended interpretation of the seismic section from Hedin et al. (2012), along with alternative interpretations of the Jämtlandian décollement and the sole thrust. Based on our interpretations of the CSP data and the goals of the COSC scientific deep drilling project, we propose two candidate locations for the second borehole, COSC-2.

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2 Caledonian geology and the central Jämtland profile

As mentioned above, the Caledonian allochthons in the thrust front of the orogen are separated from the underlying Precambrian crystalline basement by the major Jämtlandian décollement. Along most of the orogenic front in Scandinavia and in the basement windows further west, this décollement is associated with Cambrian black alum shales (Andersson et al 1985) which were deposited unconformably on the basement, prior to thrust emplacement of the overlying nappes. These kerogen-rich shales, with carbon contents up to 15%, acted as a lubricant to facilitate the low angle thrusting of the nappes for hundreds of kilometers onto the continental margin and platform of Baltica.

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The Scandian nappes are commonly grouped into four major assemblages – Lower, Middle, Upper and Uppermost, as originally proposed for the Swedish Caledonides by Kulling (in Strand and Kulling, 1972), depending upon their level in the thrust system (Gee et al., 1985). Baltoscandian platform, inner margin and foreland basin strata dominate the Lower Allochthon. The outer margin and COT assemblages are generally thought to comprise the Middle Allochthon. Iapetus ocean-derived terranes characterize the Upper Allochthon and, at the top (Uppermost Allochthon), fragments of continental margin affinities are inferred to have been derived from Laurentia (Fig. 1). All these allochthons, together, are influenced by late orogenic shortening, with the development of major antiforms and synforms on N-S to NE-SW trending axes. Many of the antiforms expose basement-cover relationships. In western Jämtland, the lithologies that comprise the Lower, Middle and Upper allochthons are well developed and distinct. The tectonostratigraphic level of the exposed rocks increases from east to west.

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The Caledonian geology was mapped and compiled at 1:200,000 scale by Strömberg et al. (1984), and described by Karis and Strömberg (1998). Their work provides the basis for the map presented in Fig. 2. The bedrock geology of central and western Jämtland was summarized in the context of the COSC project by Gee et al. (2010). Therefore, we focus the geological overview in this paper on an ESE-WNW directed profile that starts in the crystalline basement just east of Hackås (Fig. 2) and passes through the Jämtlandian Nappes, via Myrviken, where extensive drilling in the 1970´s investigated the alum shales and the Jämtlandian décollement, as far west as Marby. A few kilometers farther west, near Hallen, the new seismic profiles (CSP) start and continue westwards through the Jämtlandian Nappes to merge into the 2010 profile that crosses the Lower Seve Nappe and ends at Byxtjärn, just east of Åre (Fig. 2). The westernmost part of this profile, the Byxtjärn-Liten (BL) reflection seismic profile, was reported on in detail by Hedin et al. (2012).

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Mapping of the many river sections transecting the Caledonian thrust front in the Scandes provided early investigators of the mountain belt with clear evidence of a very gently W-dipping Precambrian basement surface (unconformity), overlain by thin autochthonous Cambrian sandstones and shales (locally also Neoproterozoic sandstones and tillites, and Ordovician limestones), beneath the Jämtlandian décollement. Prospecting for lead and zinc sulphide mineralizations in the sandstones (e.g. Grip, 1960; Saintilan et al., 2015), for example in the Laisvall and Vassbo areas (Fig. 1), provided supporting evidence for these observations. Subsequent, wide-ranging drilling programs by the Geological Survey of Sweden, targeting trace element concentrations in the metalliferous Cambrian Alum Shale Formation (Gee et al., 1982) and, more locally, in directly overlying limestones (Gee et al., 1978) defined the thrust front geometry to extend regularly westwards in the order of 30-40 km towards the hinterland, dipping at an angle of 1-2° to the west-northwest.

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2.1 From the Caledonian front to Marby

In the Myrviken area in central Jämtland (Fig. 2), south of Storsjön, the drilling program (Gee et al., 1982) defined the geometry of an exceptionally thick (up to 180 m) alum shale unit directly overlying the Caledonian sole thrust (here corresponding to the Jämtlandian décollement). Twenty-eight drill holes (all cored) provided the basis for identifying a major low grade uranium, vanadium, molybdenum, and nickel resource in the organic-rich alum shales. Most of the holes also penetrated a thin sandstone-dominated autochthonous Cambrian sedimentary succession overlying late Paleoproterozoic granites of the crystalline basement. Within the allochthonous units, both quartzites, stratigraphically underlying the alum shales, and limestones overlying them, occur in an imbricate stack that comprises the so-called Jämtlandian Nappes of the Lower Allochthon.

The above-mentioned drill holes allow the décollement surface to be mapped in the Myrviken area (Fig. 2) and it shows the typical character of the Caledonian thrust front throughout most of the mountain belt. Interestingly, the fold axes in the allochthon in this area trend approximately N-S instead of NE-SW, possibly due to an anomalous basement high, c. 50 km to the northeast in the Lockne area (Fig. 2), the result of a mid Ordovician meteorite impact (Lindström et al., 1996). Cross-sections through the area of southern Storsjön illustrate the structure of the imbricate stack (Andersson et al., 1985). Figure 3 shows a 25 km long profile trending NW, and partly NNW, from the thrust front near Hackås to Marby (Gee et al., 1982), oriented approximately parallel to the dip of the Jämtlandian décollement. This drill hole-based profile ends about 10 km east of the eastern termination of the Dammån-Hallen (DH) seismic profile. If account is taken of the klippe (tectonic outlier) occurring to the south-southeast of Hackås in the Bingsta area, the Jämtlandian décollement can be inferred to provide a regular surface, dipping about 1 degree west-northwest, over a distance of c. 40 km.

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2.2 From Hallen to Liten

The exposed and near surface bedrock between the village of Hallen and lake Liten is dominated by Ordovician turbidites of the Jämtlandian Nappes. Only in the area of southeastern Liten are younger strata (lower Silurian, including quartzites, limestones, black shales and, perhaps, turbidites) preserved locally in a shallow NW-trending syncline. Together with thick underlying Ordovician turbidites, this Jämtlandian sedimentary succession is folded, regionally, on approximately N-trending axes and apparently imbricated by thrusting that is best exposed to the south of the CSP in the N-plunging Oviksfjällen Antiform. The latter is inferred to be a southern continuation of the Olden Antiform and, as shown on the Strömberg et al. (1984) map, comprises thrust sheets dominated by early Cambrian (perhaps late Ediacaran) quartzites, minor alum shales and subordinate slices of basement-derived felsic volcanic rocks, similar to the porphyritic rhyolites outcropping in the Mullfjället Antiform, to the west of the Åre Synform.

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2.3 From Liten to Byxtjärn

Between Liten and Byxtjärn, near Undersåker, the seismic profile crosses the thrust between the Lower and Middle allochthons. The former is composed of low to sub-greenschist facies Ordovician turbidites, locally passing up into early Silurian strata. In the hanging wall, the Seve Nappe Complex of the Middle Allochthon dips gently westwards in the eastern limb of the Åre Synform. It comprises mainly quartzites and subordinate calcsilicate-rich psammitic gneisses and marbles, with abundant amphibolitized dolerites and gabbros and some, usually isolated, ultramafites. These rocks comprise a highly reflective

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assemblage as found in the seismic investigations over the Åre and Tännfors synforms (Palm et al., 1991) and in the more recent seismic data presented in Hedin et al. (2012). Along the thrust contact between the Seve Nappe Complex and the underlying strongly folded and intensely foliated turbidites of the Lower Allochthon there occurs a sheet of felsic gneisses, locally underlain by a few tens of meters of ductilely deformed Särv Nappe metasandstones and concordant greenstones. Based on the seismic data acquired over the Åre Synform to date (Palm et al., 1991; Hedin et al., 2012, 2016), prominent reflective units that do not crop out in the eastern limb of the synform are expected to be present at depth further west, beneath its central and western parts. Results from the 2.5 km deep COSC-1 borehole show that the reflectivity of the Seve Nappe Complex is due to the contrast between the high metamorphic grade gneisses and amphibolites (Hedin et al., 2016). Some of the reflections originating from below the bottom of the borehole, interpreted not to be part of the Seve Nappe Complex, can be traced towards the east, but do not extend to the surface.

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In the western limb of the Åre Synform and the axial zone of the Mullfjället Antiform, Tiren (1981) mapped a detachment close above the basement and described relationships similar to those in the Caledonian front, i.e. with most of the quartzites, alum shales and overlying turbidites being allochthonous in relation to the underlying Precambrian acid volcanic rocks with their thin unconformable veneer of alum shales and limestones.

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3 Acquisition of the COSC seismic profiles (CSP)

Seismic acquisition parameters for the reflection seismic profiles from 2011 and 2014 were similar to those of the Byxtjärn-Liten (BL) and Kallsjön-Fröå (KF) segments, presented by Hedin et al. (2012) and summarized in Table 1. Crooked line acquisition was necessary along all the profiles due to the need to follow existing roads and paths. In general, an asymmetric split-spread geometry was employed that continuously moved with respect to the source. The acquisition varied slightly from profile to profile (depending on e.g. the terrain, road permissions, etc.). In addition, for the data acquired in 2014, changes were made to the source and recording equipment. The CSP segments that are presented in this paper are summarized below.

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3.1 Byxtjärn-Liten (BL, 2010)

More than 1800 source points were activated along a 36 km long profile (Fig. 2) using a rock-breaking hydraulic hammer (VIBSIST) mounted on a front end loader. Nominal source and receiver spacing was 20 m and a split spread of 360 active channels using 28 Hz geophones was rolled along with the source. In two locations of greater interest, the source point spacing was decreased to 10 m to increase the local fold. No source points were activated at the first 124 receiver locations (in the terrain), or along a few short parts in the western half (no permission to activate the source) resulting in a decreased fold in these areas. The fold along the entire profile therefore shows significant variation (Hedin et al., 2012).

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3.2 *Liten-Dammån (LD, 2011)*

Acquisition of the Liten-Dammån profile used the same VIBSIST source as for the Byxtjärn-Liten profile. Permission to activate the source and plant receivers was not obtained along a nearly 4.5 km stretch of road close to the beginning of this profile, leaving a gap in the acquisition geometry between the Byxtjärn-Liten and Liten-Dammån profiles (Fig. 2). This was partially bridged by using wireless receivers on the western side of the gap, coinciding with the last 1 km of the Byxtjärn-Liten profile, while wired receivers were placed on the eastern side. Source points were activated on both sides of the gap to undershoot it as much as possible. However, complete undershooting was not obtained.

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3.3 *Dammån-Hallen (DH, 2014)*

The main profile of 2014 was the 14 km eastwards extension of the Byxtjärn-Liten and Liten-Dammån profiles, beginning at Dammån and ending south of Hallen (Fig. 2). Acquisition parameters for this profile differed from the Byxtjärn-Liten and Liten-Dammån profiles in that a different source was used, and 28 Hz geophones instead of 10 Hz geophones. More importantly, the source was less powerful. A 400 kg weight-drop mounted on a small Bobcat excavator replaced the VIBSIST source. Previous studies (Sopher et al., 2014; Place et al., 2015) showed that this source could provide enough energy to image the subsurface to the depths of interest for the project, assuming thin Quaternary cover and shallow depths to bedrock.

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3.4 *Sällsjö (S, 2014)*

To resolve the structures not imaged properly in the 4.5 km gap of the Liten-Dammån profile, especially in the uppermost 2 km, a 16 km long profile was designed to fully bridge this gap. Starting at the same location as the Liten-Dammån profile and overlapping with the last 1 km of the Byxtjärn-Liten profile, the Sällsjö profile took a more southern route via the village of Sällsjö before turning north and merging with the Liten-Dammån profile (Fig. 2). Identical acquisition parameters to the Dammån-Hallen profile were used; that is, the same source, recording system and spread.

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4 Processing

Since drilling is targeted to 2.5 km and previous studies have shown source penetration depth generally to be to 5-6 km, only the first three seconds of data, corresponding to c. 9 km, were decoded and processed. For the VIBSIST data of the Byxtjärn-Liten and Liten-Dammån profiles, decoding was performed following Park (1996) and Cosma and Enescu (2001). 400-500 hits per source point were stacked together to generate seismograms with a high S/N ratio. For the data acquired with the weight-drop source along the Sällsjö and Dammån-Hallen profiles, the normally eight hits per source location were stacked together to similarly enhance the S/N ratio of the seismograms. The corresponding seismograms were then used as input to a standard seismic processing package.

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The vertical component data from the 3-component wireless receivers used in the Liten-Dammån profile were extracted and merged with the 1-component receivers. Noisy traces from bad source points (e.g. due to bad weather conditions, bad ground coupling) and receivers (e.g. due to bad ground coupling, instrument malfunction, environmental noise) were then removed prior to subsequent processing.

A smoothly curved crooked Common Midpoint (CMP) line was defined for the Byxtjärn-Liten and Dammån-Hallen profiles to minimize the number of missing traces while still following the acquisition line as closely as possible. Many of the structures in the area are sub-horizontal with a slight dip in the direction of acquisition. Therefore, it is possible (as shown below) to stack the midpoint traces of the Sällsjö profile, despite their far offset, together with those of the Liten-Dammån profile onto a straight CMP line segment between the Byxtjärn-Liten and Dammån-Hallen profiles and obtain a seismic section with coherent reflections.

In general, the processing followed a standard processing sequence (Table 2). However, as the VIBSIST and weight-drop data differed to some extent in their character due to the changed acquisition setups, pre-stack processing was performed separately for the different profiles. Examples of common source gathers from two locations along the profiles, before and after pre-stack processing, are shown in Fig. 4.

Thorough velocity analyses were performed in conjunction with both NMO and DMO corrections. DMO improved the coherency of the reflections along the Byxtjärn-Liten and Liten-Dammån profiles, but did not result in improved coherency along the Sällsjö and Dammån-Hallen profiles. The crookedness of the Sällsjö profile and the generally lower S/N ratio along the Dammån-Hallen profile may explain the lack of improvement. Therefore, when the Liten-Dammån data were jointly processed with the Sällsjö data, as discussed below, no DMO was applied.

After processing the profiles separately, the Sällsjö and Liten-Dammån profiles were merged with the Dammån-Hallen profile to fill in the gap. Given that separate processing of the Sällsjö profile showed generally sub-horizontal reflections to be present below it, or reflections with NW dip (Fig. 5), the Sällsjö data and part of the Liten-Dammån data were projected onto a straight CDP processing line (Fig. 2). Likewise, the southeasterly part of the Liten-Dammån data were combined with the Dammån-Hallen data and processed along a straight CDP line (Fig. 2). Inspection of Fig. 5 shows that this methodology is generally justified even for the highly crooked Sällsjö profile. The general characteristics of the Liten-Dammån profile (Fig. 5a) are maintained in the merged section (Fig. 5c), while the projection of the data from the Sällsjö profile (Fig. 5b) fills in the gap due to the acquisition constraints. Although the details in the merged Liten-Dammån and Sällsjö section may not be accurate, the general structure in the area is well represented.

Once processed, the separate profiles were projected onto a single composite profile for interpretation and migration (Fig. 6). Since lateral variations in velocity are only minor, post-stack time migration using a Stolt algorithm (Stolt, 1978) was used. The decision to stack both the Liten-Dammån and Sällsjö profiles on the same straight CDP line parallel with the dip direction is also favorable for 2D migration as this ensures that structures are moved to a more representative subsurface location. The migrated sections were finally time-to-depth converted to generate seismic sections suitable for geological interpretation. A velocity function based on the velocity analyses performed was smoothed to reduce the effects of local lateral variations, despite these being minimal, and used for the depth conversion. Figure 6b shows the section from Fig. 6a after migration and time-to-depth conversion.

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5 Discussion

The interpretation of the Byxtjärn-Liten profile by Hedin et al. (2012) showed that the high grade Seve Nappe Complex corresponds to a highly reflective unit, with a gently west-dipping eastern boundary in the vicinity of Undersåker (CDP 1200 in Fig. 6b), confirming previous evidence from the CCT profiling (Palm et al., 1991) in western Jämtland. Beneath and to the east of the Seve Nappe Complex, a transparent unit (c. 1 km thick) is probably dominated by Ordovician turbidites, and underlain stratigraphically by thin limestones and Cambrian alum shales. More flat-lying reflections are present below these folded low grade metasediments of the Lower Allochthon. The sole thrust was interpreted to be about 4.5 km below the exposed Seve Nappe Complex at Byxtjärn and to shallow eastwards to about 2.5 km in the vicinity of Liten, at CDP 3100 (Hedin et al. 2012). However, relationships to the Jämtlandian décollement were uncertain due to lack of a continuous profile to the Caledonian front and ambiguities in the interpretation of the older CCT profile, where the uppermost crust

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is not so well imaged. The new composite profile (CSP) presented here (Fig. 7) provides additional constraints on the structure, but a unique interpretation is still not possible. Below, we provide some general remarks on the CSP section and the relevance of other geophysical data for its interpretation. We then discuss interpretations of the seismic data, related to both a shallow Jämtlandian décollement, and a deeper sole thrust than the one presented in Hedin et al. (2012). Finally, we discuss two possible locations for the COSC-2 borehole.

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5.1 General characteristics of the COSC composite seismic profile (CSP)

Both the VIBSIST source and weight-drop source generated enough energy to allow the seismic waves to penetrate to at least 9 km depth (Fig. 5). A direct comparison of the sources is not possible since the profile locations, acquisition geometries and the ambient noise conditions were not the same. In general, the VIBSIST source provided higher S/N data than the weight drop source (compare Fig. 5a to Fig. 5b). However, merging of the two data sets generates a section which allows a clear correlation between reflections northwest and southeast of the gap on the Liten-Dammån profile (Fig. 5c). In particular, after merging, it is clear that the sub-horizontal reflection at 0.7 seconds southeast of the gap (to the right of CDP 900 in Fig. 5c) is not connected to the two reflections at 0.4 to 0.6 seconds northwest of the gap (to the left of CDP 350 in Fig. 5c). Furthermore, the two west-dipping reflections at about 1 and 2 seconds (at CDP 1100, Fig. 5a), respectively, southeast of the gap appear to be connected to the sub-horizontal reflections at 1.8 and 2.6 seconds northwest of the gap (Fig. 5a). Note that these reflections are better imaged on the Sällsjö profile with the weight-drop source than on the Liten-Dammån profile with the VIBSIST source (compare Fig. 5a with Fig. 5b at CDP 100 to 300).

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The entire composite profile (Fig. 7) shows generally sub-horizontal reflections in the uppermost 2 km. Below this depth the reflections are mainly northwest dipping, but with some sub-horizontal reflections. An exception is the patchy highly reflective zone in the upper 2 km in the CSP interval from CDP 100 to CDP 1200, which characterizes the Seve Nappe Complex. The west-dipping nature of this boundary is clearly defined from CDP 1100 to CDP 900, but the boundary becomes more diffuse below the central parts of the reflective zone. The diffuse nature of this boundary at depth was verified by the drilling of the COSC-1 borehole to 2.5 km (Lorenz et al., 2015) and the limited 3D seismic survey that was acquired after drilling was completed (Hedin et al., 2016). Between CDP 1100 and 4600 along the CSP, distinct, northwest-dipping reflections are present, some of which can potentially be traced from 7 km depth to the sub-horizontal reflections between 1 and 2 km depth. These dipping reflections appear to merge into the overlying shallower sub-horizontal reflections. Similar dipping reflections were also observed on the CCT profile (Juhojuntti et al., 2001) and

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some of them can be correlated to the CSP by their geometrical patterns in spite of the two profiles being separated by about 20 km. The source of these dipping reflections has previously been discussed (Palm et al., 1991; Juhojuntti et al., 2001; Hedin et al., 2012). Deformation zones, dolerite sheets, or a combination of the two were considered likely candidates. At the southeastern end of the CSP (CDP 4600 to 5500) the data quality deteriorates significantly (Fig. 6) due to the presence of an up to 60 m thick sequence of unconsolidated Quaternary sediments, which severely attenuate the signals and make it difficult to track the reflections beneath them. However, the shallowest sub-horizontal reflection can be traced to about 0.5 km depth at the southeasternmost end of the profile, as can the northwest-dipping reflection at about 6 km. The lack of clear reflections in between these two is due to poor S/N. This reasoning is verified by a comparison with the CCT profile (Fig. 8) on which there are clear northwest-dipping reflections in the equivalent depth interval and in the same structural position along the profile. Note that the Dammån-Hallen profile was not extended further to the southeast due to permitting issues. Even if it had been possible, the thick sequence of unconsolidated sediments, also partly present to the southeast, would probably have made it difficult to acquire good data.

Two important relationships need to be defined – the depth and character of the Jämtlandian décollement, and also the thickness and character of the underlying basement that has been influenced by Caledonian deformation. The drilling in the Myrviken area, southeast of the CSP, clearly defined the Jämtlandian décollement, where Cambro-Ordovician sedimentary rocks are thrust over a thin autochthonous sedimentary cover and the underlying basement shows no evidence of Caledonian deformation. If the geometry of the Jämtlandian décollement in this area (Figs. 2 and 3) is projected into the southeastern end of the CSP, it would be expected to be found at a depth of about 500 m, coinciding with the sub-horizontal reflection found at this depth on the southeastern end of the composite section (Fig. 7). This reflection is not continuous northwestwards to CDP 4800, but rather irregular, perhaps due to the variable quality of the data that was acquired over the thick Quaternary sediments. However, we interpret the reflection at about 0.7 km depth at CDP 4800 along the CSP (Fig. 7) to represent the Jämtlandian décollement that was drilled further southeast in the Myrviken area. This reflection can be fairly reliably traced along the CSP to CDP 3300. Here, it is unclear if the décollement continues along the uppermost reflection at 1.2 km depth to CDP 2900 or along the lower one at 1.7 km depth at CDP 2900. Several lines of evidence indicate that the shallower reflection probably represents the Jämtlandian décollement. On the CCT profile, to the north, the Jämtlandian décollement was interpreted to be at about 1 km depth at an equivalent distance from the Caledonian front. Interpretation of the depth to magnetic basement based on the slope of the magnetic anomalies (using the standard Peter's method, see e.g. Reynolds, 2011) along the

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composite profile (Fig. 7) gives values of about 1.3 km and 1 km at CDPs 3100 and 4100, respectively. Note that an alternative interpretation for the Jämtlandian décollement is that it deepens already at CDP 5200 down to 1 km depth. This alternative will be discussed later in the paper.

The new magnetotelluric (MT) survey along the profile (Yan et al., 2016) provides evidence of a gently undulating surface of the prominent uppermost conductive layer, shown in Fig. 7, this being located at c. 500 m at the eastern end of the CSP, sinking to 600 m at CDP 3800, rising to 400 m at CDP 3500, sinking again to 1100 m at CDP 2700 and then rising again at CDP 1600 to 600 m, before dipping west again beneath the Seve Nappe Complex, west of Undersåker. This undulation fits well with the inferred location of the axes of the synforms and antiforms that are located in the vicinity to the north and south of the CSP line. The highly conductive layer is interpreted to represent the uppermost alum shales. It is therefore possible that the Jämtlandian décollement could be at a depth of about 1.5 km at CDP 2900 along the CSP and, if so, that it shallows to less than 1 km further west at CDP 1500 (Fig. 7) and then deepens at CDP 1300, below the Seve Nappe Complex.

All alternative interpretations accept the evidence for shallow décollements and require a substantially deeper location for the Caledonian sole thrust (e.g. Hedin et al., 2012). In both the Oviksfjällen and Olden antiforms, located to the south and north of the CSP profile, respectively, and apparently crossing it at c. CDP 3300-3500, there is evidence of substantial shortening, with a quartzite-dominated thrust stack in Oviksfjällen and much internal basement deformation in Olden. The Olden Antiform is of particular interest because it contains an upper part of allochthonous basement (Gee, 1980; Robinson et al., 2014) thrust over the Cambro-Silurian sedimentary rocks of the Jämtland Supergroup. The extent to which sedimentary rocks of the Lower Allochthon might be represented at deeper structural levels than those exposed in the Olden and Oviksfjällen antiforms is, at present, impossible to say; MT methods have difficulty in detecting any features below a strong conductor like the alum shales that is so well defined in the overlying décollement levels. Furthermore, the Oviksfjällen and Olden antiforms do not have a strong magnetic signature. The depth extent of the basement reflectivity is on the order of 10 km and presumably originates in magnetic basement, therefore, it is not clear how these antiforms can be linked to the origin of the basement reflections.

5.2 *Interpretations*

In the following section we discuss alternative interpretations along the CSP. The first one, based on Hedin et al. (2012), focuses on the sole thrust and considers even deeper structural levels for the Caledonian deformation. The second considers the Jämtlandian décollement in relation to the location of the uppermost alum shales and the underlying flat-

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Borttaget: In the next section we focus on two alternative interpretations along the CSP. The first one is based on that in Hedin et al. (2012) with a deep main décollement; even deeper sole thrusts are also considered. The second one has a shallower main décollement, more in line with the interpretations presented in Juhojuntti et al. (2001) and Korja et al. (2008).

Borttaget: Note that even if the main décollement was interpreted as shallower in these studies the limit of Caledonian deformation was interpreted to be deep with a sole thrust reaching as deep as 15 km.¶

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lying reflectors in the upper 2 km of the crust, in line with the interpretations presented in Juhojuntti et al. (2001) and Korja et al. (2008). Figure 9 illustrates these interpretations.

In Figure 9a we present the section of Hedin et al. (2012) up to CDP 2900 (the easternmost extent of the Byxtjärn-Liten profile); further east we define a consistent prolongation within the CSP. The sole thrust, in western parts at about 4 km depth, rises eastwards to the flat reflectors at about 2 km depth between CDP 3400 and 4200. It then ramps up to c. 1.5 km and continues at this level to CDP 5100. Here it ramps up again to c. 500 m and extends eastwards into the frontal décollement in the Myrviken area. The flat sections between CDP 3400 and 5100 both underlie hanging-wall west-dipping reflections, which suggests imbrication. The interpretation in Fig. 9a is based on the geology of the Oviksfjällen Antiform where the early Cambrian (to Ediacaran) quartzites dominate, but include some slices of Precambrian volcanic rocks, particularly in the eastern limb of the structure. Even deeper Caledonian deformation cannot be excluded. In this case, the sole thrust would extend from the frontal ramp at CDP 5100-5200 via a flat to CDP 4400, and from there downwards along prominent west-dipping reflections to a flat at c. 5 km depth beneath CDP 3000 where it continues westwards along more gently dipping reflections. This alternative would pass into the flat reflectors beneath the Mullfjället Antiform at c. 7 km depth (Palm et al., 1991) and then perhaps extend beneath the Skardöra Antiform at similar (Hurich et al., 1989) or even greater depths (Gee, 1988). Both these "deep sole thrust" interpretations require that the shallow Rätan-type basement beneath CDP 3400 and farther east, as suggested by the magnetic data, is allochthonous on top of a basement with similar characteristics.

The interpretation presented in Fig. 9b, concentrates on the Jämtlandian décollement beneath the Jämtlandian Nappes and the new geophysical and geological evidence relevant to the uppermost 2 km of the crust. The characteristic feature here is the shallow level of the décollement to the southeast of CDP 1400 and the significant deepening westwards below the Åre Synform. The Jämtlandian décollement is probably accommodated within, or in close proximity to the highly organic-rich Cambrian alum shales that constitute a weak horizon at, or near, the base of the Early Paleozoic Baltoscandian sedimentary succession. In some areas, up to some tens of meters of Ediacaran to lower Cambrian quartzites separate the alum shales from the underlying basement of the Fennoscandian Shield (Andersson et al., 1985). This unit may be locally absent because of the original basement topography, or stripping by the overlying thrust; alternatively, it may be repeated several times within the décollement zone.

The new magnetotelluric (MT) data indicate the presence of a good conductor at c. 1000 m at CDP 2200 and just below 500 m at CDP 4100 (Fig. 10). Below these depths, the reflection pattern in the seismic profile indicates imbricate thrusting above a detachment

Borttaget: Figure 9 shows two possible interpretations of the composite profile, CSP.

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horizon. The latter is interpreted as the original, stratigraphic position of the alum shales, which host the Jämtlandian décollement. Within the imbricates, alum shale is brought to a shallower level as indicated by the MT data. This relationship is similar to that observed close to the present Caledonian front (Fig. 3; Gee et al., 1982; Andersson et al., 1985), where successions of alum shales with overlying Lower Ordovician limestones and shales and, further west, underlying quartzites are stacked to several times the original stratigraphic thickness.

5.3 Relationships between the Jämtlandian décollement and mylonites in the Lower Seve Nappe

Close to the northwestern end of the profile, in the Åre Synform, the 2.5 km deep COSC-1 drill hole provides control on the Lower Seve Nappe. At c. 1700 m, the borehole enters a mylonite zone, representing a major thrust at the base of the Seve Nappe Complex. This zone extends to the bottom of the borehole, but a transition to rocks of lower metamorphic grade, possibly from the Särv or Offerdal nappes, occurs at c. 2350 m (Lorenz et al., 2015). Local 3D reflection seismics at the drill site (Hedin et al., 2016) and a VSP survey in the drill hole (Krauß et al., 2015) suggest that the base of the thrust zone is located about 200 m below the bottom of the drill hole. The Särv and Offerdal Nappes are not continuous in the Åre area, but thin and pinch out towards the northeast somewhere below the Åre Synform, as indicated in Fig. 9b. However, farther east the Särv Nappe is present in a klippen (Strömberg et al. 1984). It is also remarkable that, east of the Åre Synform, the fault zone that separates the Lower Seve Nappe from the Lower Allochthon is very narrow (north of CDP 1150), i.e. significantly different from the mylonite zone observed in the COSC-1 borehole. The contact observed at the surface is most likely a W-dipping normal fault that places the Lower Seve Nappe against the Lower Allochthon and, thus, cuts out the tectonostratigraphy in-between. Similar relationships across faults were reported in the area west of Mullfjället in Sweden and Skardöra in Norway (Sjöström et al. 1991, Braathen et al. 2000). Below 2 km depth, the normal fault passes into a highly reflective zone above the interpreted Jämtlandian décollement, which it either cuts or merges into. The borders of the mylonite zone below the Åre Synform (dotted white lines in Fig. 9) trace along the reflectivity pattern eastwards towards location (1) in Fig. 9b, where also they merge into the above-mentioned NW-dipping highly reflective zone above the Jämtlandian décollement. East of location (1), a prominent shallow basement reflection can be traced subhorizontally towards location (2), where it offsets the overlying reflections and continues upwards towards the southeast (broken line in Fig. 9b). It is interpreted as a thrust fault that at location (2) cuts upwards through the Jämtlandian décollement into the alum shale and brings basement with overlying rocks closer to the surface. The position, CDP 3100 and 3500, corresponds well

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with the location of the Oviksfjällen Antiform, which about 10 km south of the seismic profile exposes Ediacaran-Cambrian quartzites in its core (Fig. 2). The nature of the reflectivity above this interpreted thrust fault is ambiguous. Possibly, it is similar to the basement reflections farther down. This would imply that the displacement along this particular reflector is a couple of kilometers, as indicated in Fig. 9b.

For the section of the CSP, we suggest the following geological scenario: The high-grade metamorphic Lower Seve Nappe has a comparatively long tectonothermal history with metamorphism and pegmatite intrusion as early as c. 470 Ma (Li et al. 2014). Its subsequent emplacement as part of the Seve Nappe Complex has caused the penetrative ductile deformation with high internal strain, including gneisses with mylonitic fabric. Thrusting continuously progressed eastwards with the whole nappe stack, including the underlying units of the Middle Allochthon and Lower Allochthon, translated farther towards the foreland on the Jämtlandian décollement in the alum shales.

After metamorphic conditions in the Lower Seve Nappe had decreased considerably, the c. 1 km thick mylonite zone began to develop by continued or resumed movement along the Seve-Särv boundary. The age of the movement on the interpreted normal fault that separates the Lower Seve Nappe from the Lower Allochthon, east of the Åre Synform, is probably Early Devonian, as suggested by Gee et al. (1994) for the Röragen detachment where movement was inferred to have occurred while thrusting was still going on at depth beneath the Vigelen Antiform. This could explain why both the reflective pattern that in the COSC-1 drill hole was related to the Seve mylonite zone and the trace of the normal fault merge into a highly reflective zone that is directly overlying the Jämtlandian décollement at location (1) in Fig. 9b.

While nappe emplacement during Caledonian Orogeny progressed towards the foreland, Baltica was successively underthrusting Laurentia. Thus, it is very likely that also the Baltican basement experienced an eastwards progressing deformation, most likely above a sole thrust and possibly reactivating existing structures in the Proterozoic basement. Major orogen-parallel folding (e. g. Åre Synform and Mullfjället Antiform) occurred above this sole thrust. In the CSP, at least some of the deep reflections (around location 3 in Fig. 9b) are thought to represent this basement deformation.

Additional evidence for some Caledonian deformation is found where reflections present below the interpreted Jämtlandian detachment appear to continue through it and offset the interpreted alum shales. Perhaps the best example of this is between CDPs 2600 and 2800 (Fig. 6) where the "double reflection" may offset the detachment and appears to have disturbed the overlying alum shales.

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Borttaget: The development of the thick mylonite zone might be in part related to the development of the orogen parallel folds. Below the Åre Synform, folding of the main décollement could have translated the foreland directed movement upwards to straighten the deformation zone. At the basement culmination east of the Åre Synform, a similar process seems to have translated the deformation downwards into the basement along the probably pre-existing structure between CDP 1100 and 3100.

Scientific drilling at the COSC-2 site to 2.5 km will investigate and test the above scenario down into the shallow basement. It will sample at least one of the deep reflectors at its shallowest level and define its nature.

5.4 *Locating the COSC-2 borehole*

According to the COSC overall scientific targets, the COSC-2 borehole will investigate the metamorphic and structural evolution from the Lower Allochthon down into the basement of the Fennoscandian Shield. Important questions to be answered by the drilling are (i) what is the nature of the Jämtlandian décollement and where is it located, (ii) is the metamorphic grade inverted in the middle to low grade greenschist facies sedimentary rocks, (iii) were they heated from above, (iv) what lithologies and structures generate the reflections in the Precambrian basement, and (v) what is the timing of deformation at these structural levels?

To reach these goals, the borehole should first drill the turbidites and limestones of the Lower Allochthon, penetrate the uppermost Cambrian alum shales and then continue downwards in the zone of high reflectivity, probably with repetition of thin Ediacaran to Ordovician sedimentary cover (quartzites, alum shales and limestones) and then through the Jämtlandian décollement into the Precambrian crystalline basement, sampling at least a 1 km section of the latter.

Two possible locations for the COSC-2 borehole have been identified on the composite profile (Fig. 10). Option 1 is located along the Byxtjärn-Liten profile at CDP 2200 (Fig. 10a). Assuming that the Jämtlandian décollement has been correctly identified in Fig. 9b, the borehole will penetrate four reflectors in the underlying basement between about 1.5 and 2.2 km depth. A drill hole in this location would investigate the imbricate thrusting above the Jämtlandian décollement, whether the inferred deeper (shallow basement) thrust between CDP 1100 and 3100 is present, and, if not, what then causes the two shallower basement reflections. The two deeper basement reflections can be traced down to about 6 km northwest of the proposed site and appear to offset other reflections on the seismic section (Fig. 7). These two must surely be located in the Precambrian basement. One possible disadvantage with the location is that the separation between these four deeper reflections is small, at least on the present processing, and it may be difficult in the borehole to strictly identify the source to each of the four reflections. However, a combination of new high resolution seismic data and borehole seismic data should allow the source of the reflections to be determined without ambiguity.

Option 2 (Fig. 10b) is at a location (CDP 4100) where the sole thrust appears to be converging upwards towards the Jämtlandian décollement. The drill hole would penetrate the latter, as defined by a zone of flat-lying reflectivity between CDPs 3100 to 5200, at about 500 m depth; as in the Myrviken drill holes, it would be overlain by the shallowest alum shales

Borttaget: Previously, these sub-horizontal to gently northwest dipping reflections have been interpreted as mafic sheets (Palm et al. 1991. Juhojuntti et al., 2001) hosted by Precambrian sandstones, volcanic rocks of Mullfjället type (Gee et al.., 2010),) or other igneous rocks that possibly are related to Trans-Scandinavian Igneous Belt (TIB) granites. This is similar to a setting observed in the autochthon, south of the CSP, where highly magnetic c. 1700 Ma Rätan granites are associated with felsic volcanics and overlain by Precambrian sandstones with mafic volcanics.

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Borttaget: Here, the two interpretations presented in the previous section differ from one another, with the main décollement being shallower in the new interpretation (Fig. 9b).

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Borttaget: It is important to note that a Precambrian reflector may not be drilled if the Hedin et al. (2012) interpretation is correct since the main décollement will then be below the final depth of the borehole. However, we regard this risk as minor, given the evidence from the new MT data and the constraints from the magnetic data.

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the top of which occur at 400 m, based on the MT data. The Jämtlandian décollement is underlain by a duplex structure, about 1 km thick, characterized by more steeply dipping, shorter reflections representing boundaries between Cambrian strata (quartzites and perhaps subordinate alum shales) and fragments of allochthonous Precambrian basement. The basal thrust of the duplex is a well-defined strong sub-horizontal to gently NW-dipping reflection, present across entire Fig. 10b, between 1.3 and 1.9 km depth; this probably corresponds to the Caledonian sole thrust. At 2.2 to 2.3 km depth, a basement reflector that appears to extend westwards to depths of greater than 7 km would be penetrated by this hole. The reflection from this structure is rather weak at the proposed site, but clearly present.

6 Conclusions

An integrated interpretation of the geophysical and drill hole data (CSP, CCT, MT data, aeromagnetics) provides new constraints on the structure in the central part of the Scandinavian Caledonides. The Jämtlandian décollement, as identified in the Myrviken drill holes of the Caledonian thrust front, can be confidently traced westwards along the easternmost 20 km of the CSP, deepening in this section of the profile from about 0.5 km to nearly 1 km. Further west, in our preferred interpretation, the Jämtlandian décollement continues to be relatively shallow, just somewhat greater than 1 km deep, even shallowing on a structural high, before rapidly deepening just east of the Seve Nappe Complex, in the eastern limb of the Åre Synform. The previously acquired CCT profile, together with new MT and magnetic data, are consistent with this interpretation of the Jämtlandian décollement; nevertheless, even somewhat deeper levels are possible.

The extent of Caledonian deformation below the Jämtlandian décollement and influencing the underlying basement, is less easily defined and the location of the Caledonian sole thrust remains enigmatic. It may indeed coincide with the surface defined by Hedin et al. (2012) at c. 4.5 km depth beneath Åre, and then shallow eastwards, ramping up to converge with the Jämtlandian décollement near the end of the CSP and in the Myrviken area. However, deeper levels for the sole thrust beneath the CSP and farther to the west cannot be ruled out. The new data show mainly northwest dipping structures below the uppermost 1-2 km. Many of these structures have a similar pattern as those on the CCT profile located about 20 km to the north, suggesting large lateral continuity of the features out of the plane of the CSP. This is verified by the highly crooked Sällsjö profile in which reflections can be traced more than 5 km to the south of the CSP. A definite interpretation of these NW-dipping reflections is not possible without drilling into them. The reflectivity pattern suggests that they are Caledonian, or possibly reactivated older structures.

Borttaget: imbricate stacks above the main décollement would be

Borttaget: about 400 m as defined by

Borttaget: main

Borttaget: décollement at this location would then correspond to the strong sub-horizontal to gently northwest dipping reflection present across entire Fig. 10b between 1.9 and 1.3 km depth. The

Borttaget: above this strong reflection, but below the alum shales would represent

Borttaget: A weaker dipping reflector, representing the boundary between Cambrian meta-sedimentary rock and allochthonous basement would be penetrated at about 1.2 km.

Borttaget: The new seismic data from the composite profile (CSP), acquired between 2010 and 2013,since 2011 in combination with the previous seismic data from Central Caledonian Transect (2010, the CCT) and profile, MT and magnetic data, and the drill holes in the Myrviken area,

Borttaget: provide

Borttaget: this

Borttaget: main (

Borttaget:)

Borttaget: traced fairly

Borttaget: along

Borttaget: main

Borttaget: may continue

Borttaget: depth, and

Borttaget: data

Borttaget: appear to be

Borttaget: main

Borttaget: . If correct, this requires the structural model presented in Hedin et al. (2012) to be revised. However, it is possible to interpret the main décollement to deepen already near the eastern end of the profile. If so, this deepening would be consistent with the Hedin et al. (2012) structural model. An

Borttaget: main

Borttaget: main

Borttaget: level

Borttaget: for the main décollement

Borttaget: entirely

Borttaget: ¶
Regardless of which interpretation is correct, the

Borttaget: northwest

Two potential locations for the COSC-2 borehole have been identified along the CSP. Drilling at the more westerly site, on the south side of Lake Liten, will penetrate the full Silurian to Ediacaran stratigraphy and allow detailed analysis of the structure of the Jämtlandian décollement, defined by strong flat-lying reflections. It will also penetrate four strong reflections below the interpreted Jämtlandian décollement, allowing identification of the composition, structural characteristics and timing of deformation of these features. Drilling at the alternative site, about twenty kilometers farther southeast, will provide important evidence about the Jämtlandian décollement and possibly also the sole thrust. However, it may fail to provide unambiguous evidence about the character of the typical NW-dipping reflections in the basement, their reflectivity being somewhat diffuse at this potential site. Therefore, we favor the western site for the COSC-2 borehole.

Borttaget: would test which of

Borttaget: lake

Borttaget: main

Borttaget: structural interpretations presented here is correct, the shallow main

Borttaget: or a deeper one.

Borttaget: would

Borttaget: reflectors

Borttaget: shallow main

Borttaget: kilometres

Borttaget: . In the event that the Hedin et al. (2012) interpretation is correct then

Borttaget: main

Borttaget: would not be reached by the borehole. At the more easterly site

Borttaget: main décollement would be penetrated at about 1700 m depth. Here,

Borttaget: main décollement is represented by a strong sub-horizontal reflection at about 1.7 km, an excellent drilling target, but its response is of an atypical nature compared to most

Borttaget: other reflections. A more

Borttaget: northwest

Borttaget: reflector is present below, but its

Borttaget: is

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Tables

Table 1. Acquisition parameters for the Byxtjärn-Liten profile (BL, 2010), Liten-Dammån profile (LD, 2011), Sällsjö profile (S, 2014) and Dammån-Hallen profile (DH, 2014).

Profile	BL (2010)	LD (2011)	S (2014)	DH (2014)
Spread Type	Split spread	Split spread	Split spread	Split spread
Number of channels	300-360	330-396	280-360	300-360
Near offset	0 m	0 m	0 m	0 m
Maximum offset	6804 m	9502 m	4633 m	4634 m
Receiver spacing	20 m	20 m	20 m	20 m
Receiver type	28 Hz, 1C	28 Hz, 1C and 3C	10 Hz, 1C	10 Hz, 1C
Source spacing	20 m (10 m)	20 m	20 m	20 m
Source type	VIBSIST	VIBSIST	Weight drop	Weight drop
Hit interval for hammer	100-400 ms	100-400 ms	-	-
Sweeps per source point	3-4	4-5	-	-
Weight drops per source point	-	-	8	8
Nominal fold	150-180	165-200	140-180	150-180
Recording instrument	SERCEL 408 XL	SERCEL 428 XL	SERCEL 428 XL	SERCEL 428 XL
Field low cut	-	-	-	-
Field high cut	-	-	-	-
Sample rate	1 ms	1 ms	1 ms	1 ms
Record length	26 s	29 s	28 s	28 s
Profile length	~36 km	~17 km	~16 km	~14 km
Source points	1807	638	767	626
Data acquired	30/7-13/8, 2010	10-19/10, 2011	18-24/10, 2014	26-30/10, 2014

Table 2. Processing steps and parameters for the Byxtjärn-Liten profile (BL, 2010), Liten-Dammån profile (LD, 2011), Sällsjö profile (S, 2014) and Dammån-Hallen profile (DH, 2014). BL, S+LD and DH were merged prior to migration to form the composite COSC Seismic Profile, CSP.

BL (2010)	LD (2011)	S (2014)	S + LD	DH (2014)
Decoding of Vibsist data	Decoding of Vibsist data	Stacking of weight-drop gathers		Stacking of weight-drop gathers
Manual Trace Edits	Manual Trace Edits	Manual Trace Edits		Manual Trace Edits
Floating datum statics	Floating datum statics	Floating datum statics		Floating datum statics
Refraction static corrections	Refraction static corrections	Refraction static corrections	Data merged	Refraction static corrections
Frontmute	Frontmute		Surgical mute	Frontmute & Surgical mute
Spherical divergence compensation	Spherical divergence compensation	Spherical divergence compensation	Spherical divergence compensation	Spherical divergence compensation
Trace balancing	Trace balancing	Trace balancing	Trace balancing	Trace balancing
Wiener deconvolution	Wiener deconvolution	Spectral Equalization	Wiener deconvolution	Wiener deconvolution
		Notch filter (50 ± 2 Hz)	Notch filter (50 ± 2 Hz)	Notch filter (50 ± 2 Hz)
Band pass filter	Band pass filter	Band pass filter	Band pass filter	Band pass filter
0-1 s 25-50-80-120 Hz 1.25-3 s 20-40-80-120 Hz	0-0.5 s 25-50-100-150 Hz 0.75-1.25 s 20-40-90-135 Hz 1.75-3 s 15-30-80-120 Hz	0-0.5 s 25-50-100-150 Hz 0.75-1.25 s 20-40-90-135 Hz 1.75-3 s 15-30-80-120 Hz	0-1 s 25-50-100-150 Hz 1.25-1.75s 20-40-90-135 Hz 2.25-3 s 15-30-80-120 Hz	0-1 s 25-50-100-150 Hz 1.25-1.75s 20-40-90-135 Hz 2.25-3 s 15-30-80-120 Hz
Airwave filter	Airwave filter			
Median velocity filter 2200, 3200 m s^{-1}	Median velocity filter 2200, 3200 m s^{-1}	Median velocity filter 3100 m s^{-1}	Median velocity filter 1700, 3100 m s^{-1}	Median velocity filter 1700, 3100 m s^{-1}
AGC (200 ms)	AGC (300 ms)		AGC (200 ms)	AGC (500 ms)
Residual static corrections	Residual static corrections	Residual static corrections	Residual static corrections	Residual static corrections
DMO & NMO correction	DMO & NMO correction	NMO correction	NMO correction	NMO correction
CMP stacking	CMP stacking	CMP stacking	CMP stacking	CMP stacking
Coherency filtering (FX-Deconvolution)	Coherency filtering (FX-Deconvolution)	Coherency filtering (FX-Deconvolution)	Coherency filtering (FX-Deconvolution)	Coherency filtering (FX-Deconvolution)
		Zeromute	Zeromute	Zeromute
FK-filter	FK-filter		FK-filter	
Stolt migration			Stolt migration	Stolt migration
Time-to-Depth conversion			Time-to-Depth conversion	Time-to-Depth conversion

Figure Captions

Figure 1. (a) Provenance interpretation of the Tectonostratigraphic Map of the Scandinavian Caledonides, modified from Gee et al. (1985). The star marks the location of the COSC-1 borehole. (b) Schematic cross section (vertical exaggeration x10) along the NW-SE profile in (a), from Gee et al. (2010). The autochthonous basement (light grey) is separated from the Caledonian deformed basement (dark grey) by the Scandian sole thrust.

Figure 2. Bedrock geological map of western Jämtland, based on the bedrock geological map of Sweden, © Geological Survey of Sweden [I2014/00601] and Strömberg et al., (1984), showing the locations of the CSP and CCT seismic profiles, the COSC-1 borehole and the shallow drill holes in the Myrviken area. The location of the geological cross section, shown in Fig. 3, is also indicated.

Figure 3. Geological cross section through the Myrviken area boreholes based on the SGU report on alum shales (Gee et al., 1982), shown at a vertical exaggeration of 10:1.

Figure 4. Two examples of source gathers before and after processing. (a) VIBSIST source gather from the Byxtjärn-Liten profile from the south shore of Lake Liten (Fig. 2) with only trace balancing applied. (b) The same source gather as in (a) after processing. (c) Weight-drop source gather from the Sällsjö profile from the eastern end of Lake Liten with only trace balancing applied. (d) The same source gather as in (c) after processing.

Figure 5. (a) Stacked section from the Liten-Dammån profile acquired in 2011 with the VIBSIST source. (b) Stacked section from the Sällsjö profile acquired in 2014 with the weight-drop source. (c) Data from the Liten-Dammån and Sällsjö profiles processed together and stacked. The plan view maps show the three used CDP stacking lines with the thick black line indicating the CDP stacking line corresponding to the section shown in the same panel. (a) and (c) follow similar CDP stacking lines, while (b) follows a highly crooked CDP stacking line.

Figure 6. (a) Composite stacked section of the CSP. (b) Migrated and depth converted version of (a). The CDP stacking line is shown in Fig. 2 with CDP numbers marked on the map. East of CDP 2850 the weight-drop source was employed.

Figure 7. (a) Total magnetic field along the CSP. The anomalies at about CDP 1800, 3100 and 4100 can be interpreted as due to variations in the magnetic basement at depths of 1.3 km, 1.3 km and 1.0 km, respectively. (b) Migrated and depth converted stack from Fig. 6 shown at a vertical exaggeration of 2:1. The black line marks the depth to the highly conductive layer from MT data as mapped by Yan et al. (2016). An excellent correspondence exists between the base of the uppermost seismically transparent zone

Borttaget: map

Borttaget:) (modified

Borttaget: .,1985

Borttaget: Regional bedrock

Borttaget: CCT seismic profile, the

Borttaget: (Based on the bedrock geological map of Sweden, © Geological Survey of Sweden [I2014/00601] and Strömberg et al., 1984).

Borttaget: example

Borttaget: anomaly

and the mapped conductor. Therefore, the onset of reflectivity below the transparent zone is interpreted to represent the top of the uppermost alum shale. Magnetic data are courtesy of the Geological Survey of Sweden (SGU).

Figure 8. Sections of the CSP (top) and CCT profile (bottom) over approximately the same structural location. The three prominent reflective zones between 1 and 3 seconds on the western halves of the profiles are interpreted to represent the same structures. The transparent zone between 0.5 and 2 seconds on the eastern half of the CSP profile is interpreted as due to poor S/N because of the thick sequence of loose sediments at the surface along this portion of the profile. Although data quality is variable at the equivalent location on the CCT profile, clear reflections are present between 0.5 and 2 seconds. It is likely that with better quality data, clear reflections would also be observed on the eastern half of the CSP between 0.5 and 2 seconds.

Figure 9. Interpretations of the CSP data. In (a) the focus is on the sole thrust. The interpretation west of CDP 2800 is the same as in Hedin et al. (2012) and shows significant basement involved thrusting; farther east, the sole thrust is shown to ramp up to join the Jämtlandian décollement near the thrust front. In (b) the Jämtlandian décollement is shown to dip very gently westwards, lying only a few hundreds of meters below the top of the alum shales, as interpreted from the CSP and the MT data. A second level of detachment may exist in the shallow basement reflectors below CDP 1000 to 3200. Numbers (1), (2) and (3) are referenced in the text.

Borttaget: Two possible interpretations

Borttaget: with a deep main décollement

Borttaget: main

Borttaget: main

Borttaget: much shallower in the west and lies

Borttaget: might

Borttaget: and

Figure 10. (a) Option 1 for the COSC-2 borehole. Here, the Jämtlandian décollement would be penetrated at about 1.3-1.5 km depth, if the interpretation in Fig. 9b is correct. Logistically, it is easier to place the borehole about 1 km to the east. Even at this location, two or three Precambrian reflectors would be penetrated. (b) In option 2 for the COSC-2 borehole, the Jämtlandian décollement would be drilled at about 500 m depth. The structure beneath the Jämtlandian décollement, down to about 1600m, is dominated by a duplex, probably consisting of sedimentary formations and basement-derived imbricates. The basal thrust of the duplex is inferred to coincide with the Caledonian sole thrust. The conductivity profiles shown in the figures are placed at the locations of the MT stations that the inversions were performed for. In (a) the uppermost alum shale would be penetrated at about 900 m depth and in (b) it would be penetrated at about 400 m depth.

Borttaget: corresponding to a location where the two interpretations in Fig. 9 differ significantly.

Borttaget: main

Borttaget: main

Borttaget: 1700

Borttaget: as interpreted in Fig. 9a.

Borttaget: main

Borttaget: rock between 800 m and 1.7 km

Borttaget: interpreted to consist of

Borttaget: structures. Conductivity

Figure 1

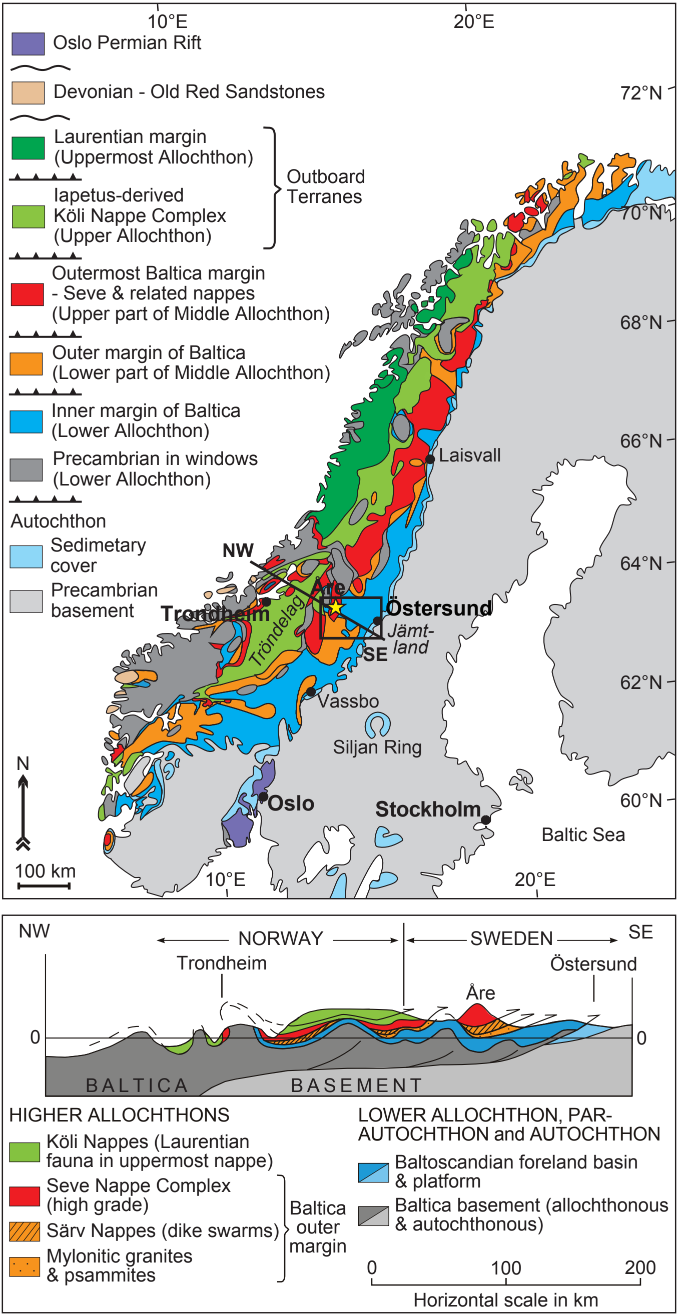

10°E
20°E
Oslo Permian Rift
Devonian - Old Red Sandstones
Laurentian margin
(Uppermost Allochthon)
Iapetus-derived
Köli Nappe Complex
(Upper Allochthon)
Outboard
Terranes
Outermost Baltica margin
- Seve & related nappes
(Upper part of Middle Allochthon)
Outer margin of Baltica
(Lower part of Middle Allochthon)
Inner margin of Baltica
(Lower Allochthon)
Precambrian in windows
(Lower Allochthon)
Autochthon
Sedimetary
cover
Precambrian
basement
72°N
70°N
68°N
66°N
64°N
62°N
60°N
Laisvall
NW
Åre
Trondheim
Tröndelag
Östersund
Jämt-
land
SE
Vassbo
Siljan Ring
N
Oslo
Stockholm
Baltic Sea
100 km
10°E
20°E
NW
NORWAY
SWEDEN
SE
Trondheim
Östersund
Åre
0
0
BALTICA
BASEMENT
HIGHER ALLOCHTHONS
Köli Nappes (Laurentian
fauna in uppermost nappe)
Seve Nappe Complex
(high grade)
Särv Nappes (dike swarms)
Mylonitic granites
& psammites
Baltica
outer
margin
LOWER ALLOCHTHON, PAR-
AUTOCHTHON and AUTOCHTHON
Baltoscandian foreland basin
& platform
Baltica basement (allochthonous
& autochthonous)
0
100
200
Horizontal scale in km

Figure 2

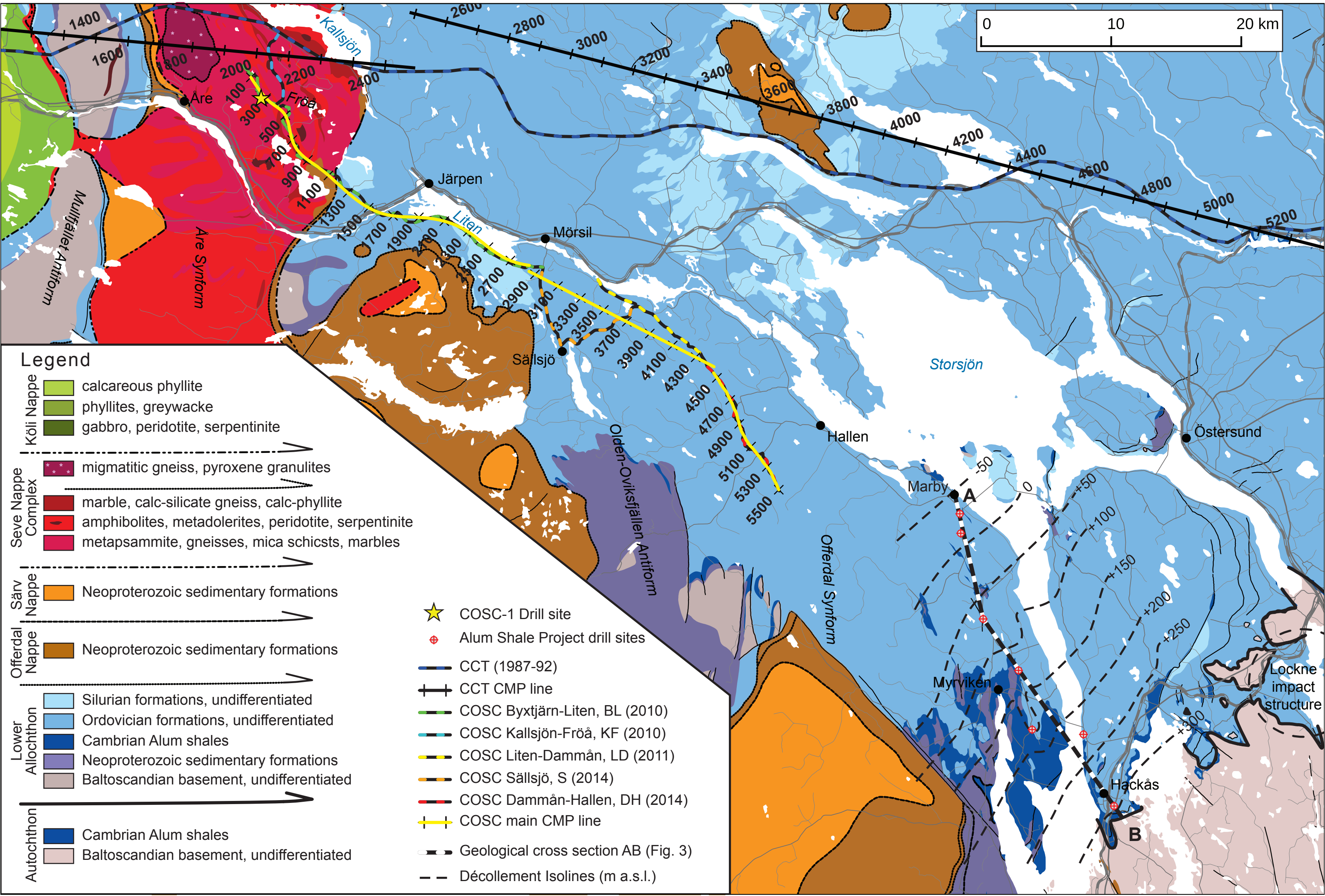
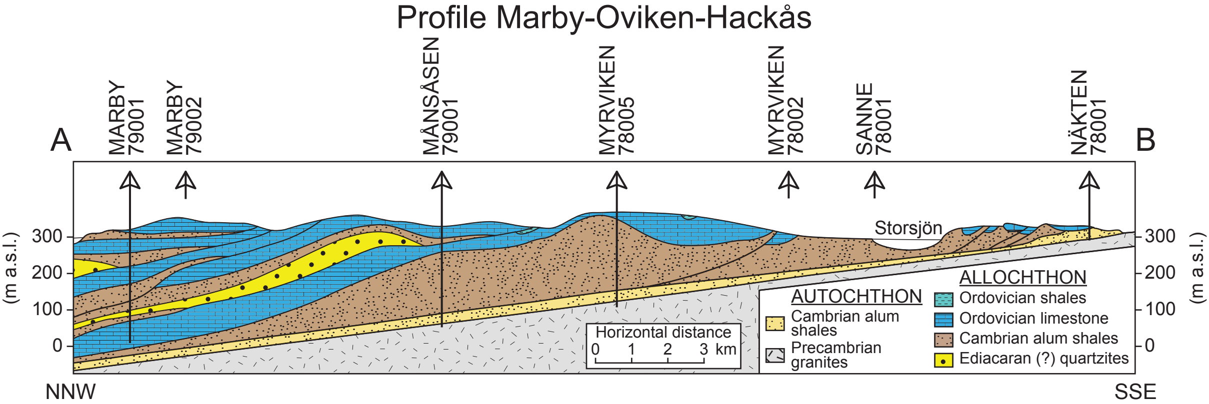

0
10
20 km
Kallsjön
Åre
Fröå
Järpen
Liten
Mörsil
Sällsjö
Hallen
Storsjön
Östersund
Marby
A
Myrviken
Hackås
B
Lockne impact structure
Mullfjället Antiform
Åre Synform
Olden-Oviksfjällen Antiform
Offerdal Synform
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
100
300
500
700
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
5500
-50
0
+50
+100
+150
+200
+250
+300
Legend
Köli Nappe
calcareous phyllite
phyllites, greywacke
gabbro, peridotite, serpentinite
Seve Nappe Complex
migmatitic gneiss, pyroxene granulites
marble, calc-silicate gneiss, calc-phyllite
amphibolites, metadolerites, peridotite, serpentinite
metapsammite, gneisses, mica schicsts, marbles
Särv Nappe
Neoproterozoic sedimentary formations
Offerdal Nappe
Neoproterozoic sedimentary formations
Lower Allochthon
Silurian formations, undifferentiated
Ordovician formations, undifferentiated
Cambrian Alum shales
Neoproterozoic sedimentary formations
Baltoscandian basement, undifferentiated
Autochthon
Cambrian Alum shales
Baltoscandian basement, undifferentiated
COSC-1 Drill site
Alum Shale Project drill sites
CCT (1987-92)
CCT CMP line
COSC Byxtjärn-Liten, BL (2010)
COSC Kallsjön-Fröå, KF (2010)
COSC Liten-Dammån, LD (2011)
COSC Sällsjö, S (2014)
COSC Dammån-Hallen, DH (2014)
COSC main CMP line
Geological cross section AB (Fig. 3)
Décollement Isolines (m a.s.l.)

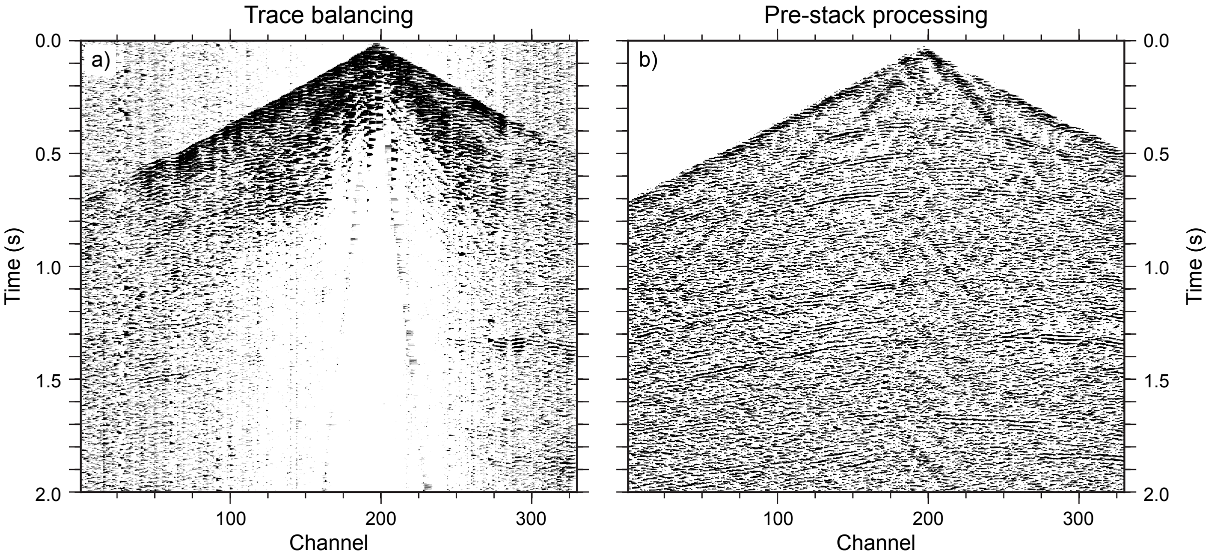
Figure 3



Profile Marby-Oviken-Hackås

Figure 4

Byxtjärn-Liten profile source point 1596 (VIBSIST, 2010)



Sällsjö profile source point 9 (weight drop, 2014)

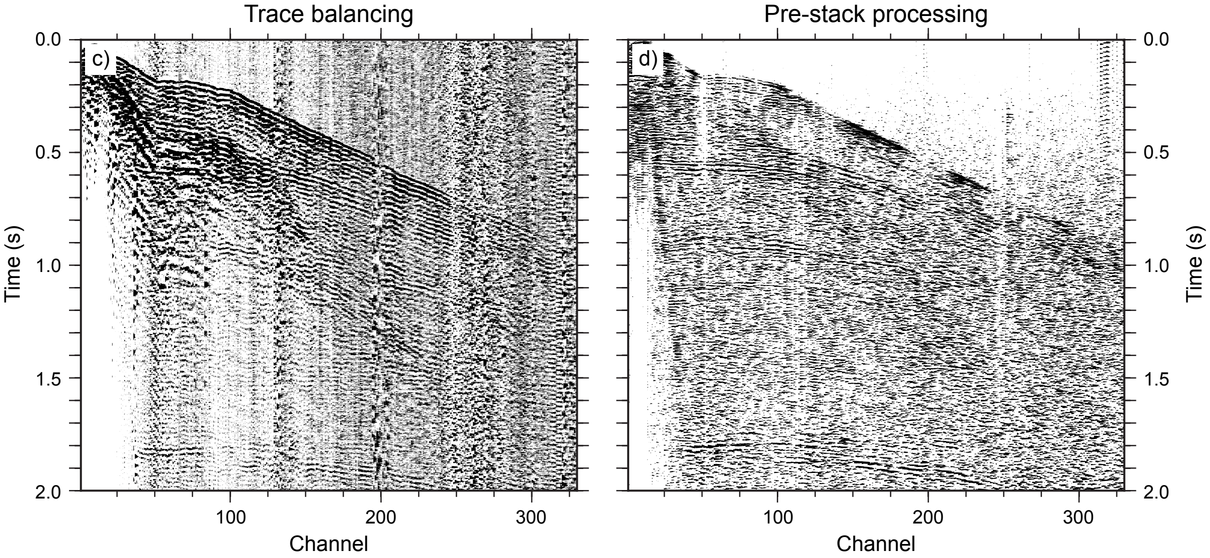


Figure 5

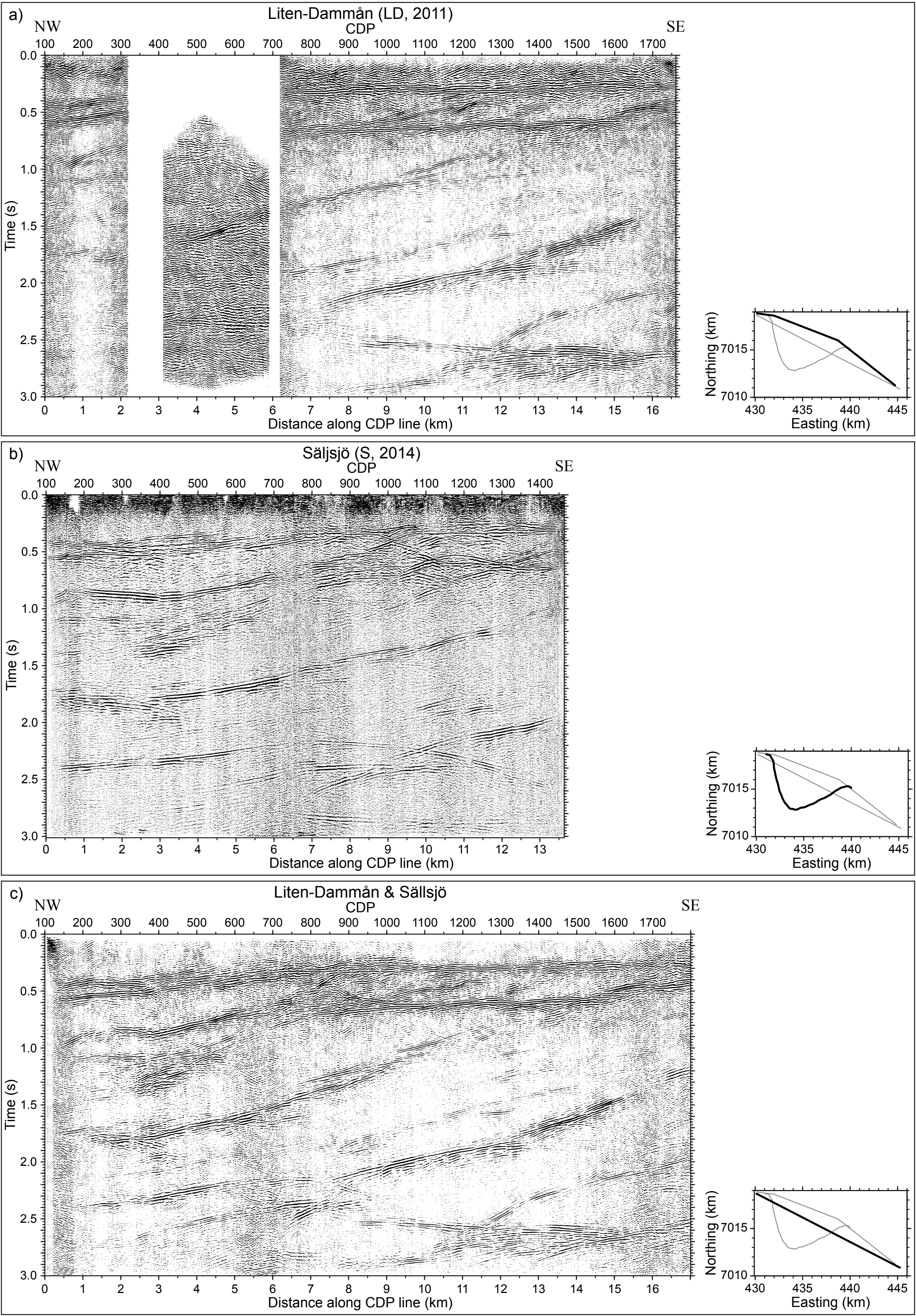

a)
Liten-Dammån (LD, 2011)
NW
SE
CDP
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Distance along CDP line (km)
Northing (km)
7010 7015
Easting (km)
430 435 440 445
b)
Säljsjö (S, 2014)
NW
SE
CDP
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Distance along CDP line (km)
Northing (km)
7010 7015
Easting (km)
430 435 440 445
c)
Liten-Dammån & Sällsjö
NW
SE
CDP
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
Time (s)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Distance along CDP line (km)
Northing (km)
7010 7015
Easting (km)
430 435 440 445

Figure 6

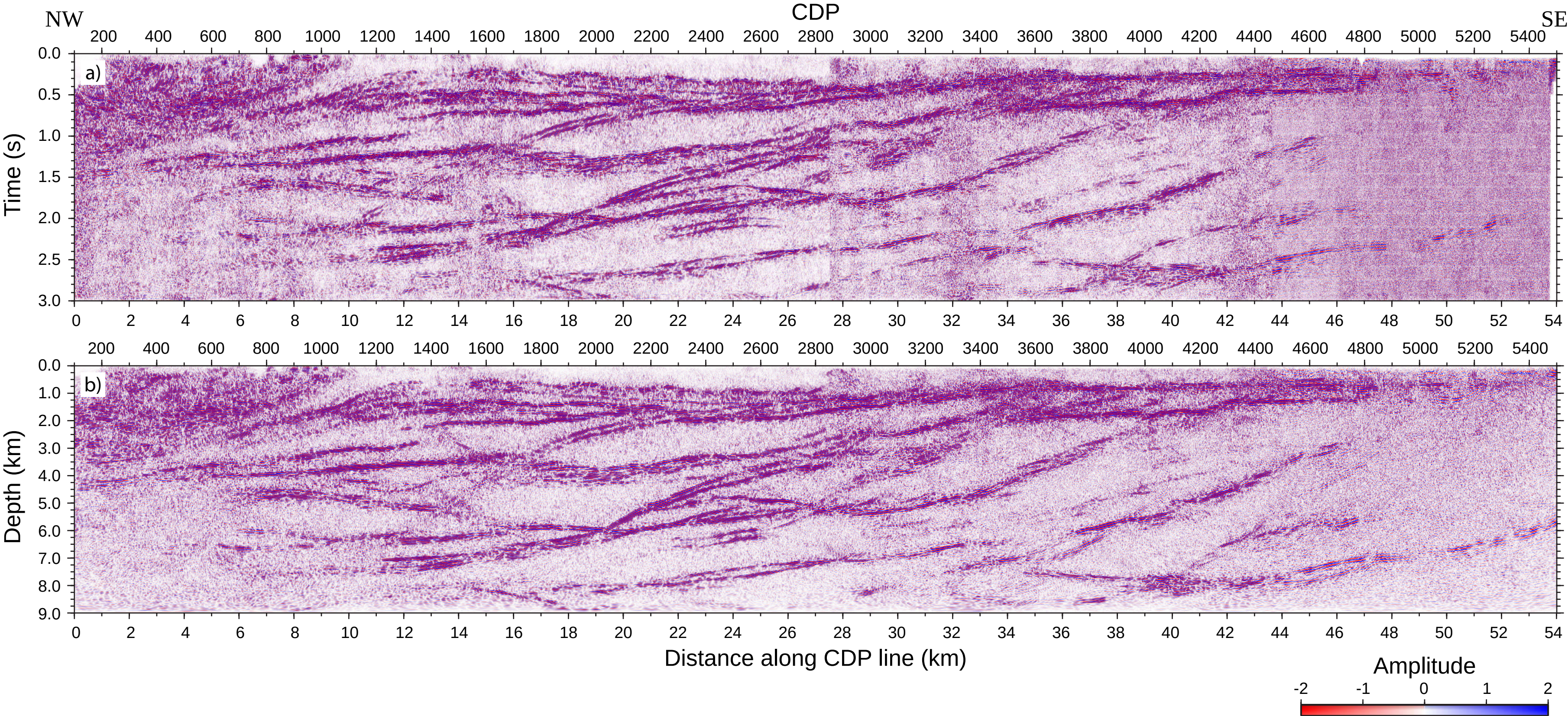

NW
CDP
SE
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
5400
a)
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
b)
Depth (km)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
Distance along CDP line (km)
Amplitude
-2
-1
0
1
2

Figure 7

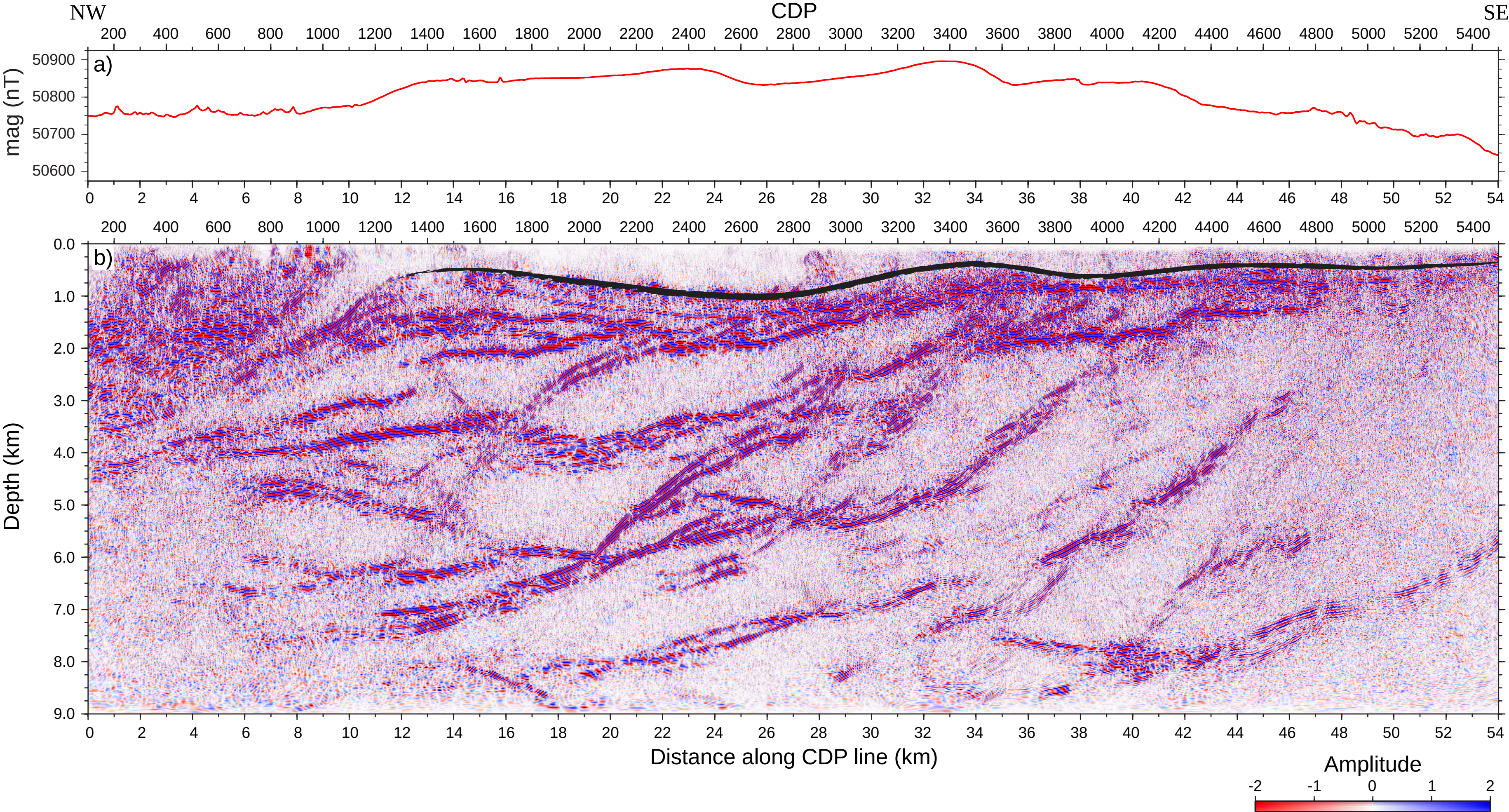

NW
CDP
SE
200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400
a)
mag (nT)
50900
50800
50700
50600
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400
b)
Depth (km)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
Distance along CDP line (km)
Amplitude
-2 -1 0 1 2

Figure 8

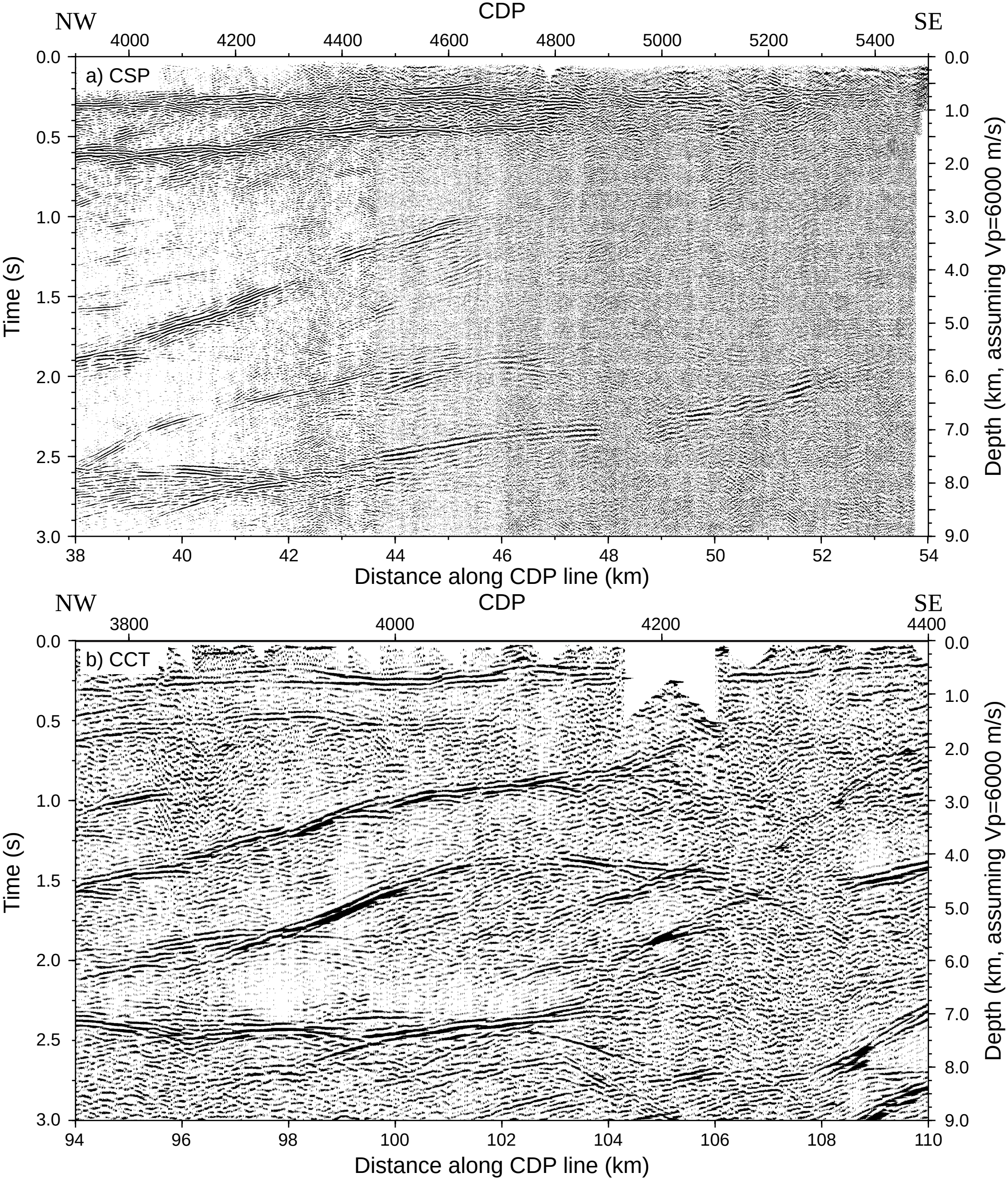

NW
CDP
SE
4000
4200
4400
4600
4800
5000
5200
5400
a) CSP
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Depth (km, assuming Vp=6000 m/s)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
38
40
42
44
46
48
50
52
54
Distance along CDP line (km)
NW
CDP
SE
3800
4000
4200
4400
b) CCT
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Depth (km, assuming Vp=6000 m/s)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
94
96
98
100
102
104
106
108
110
Distance along CDP line (km)

Figure 9

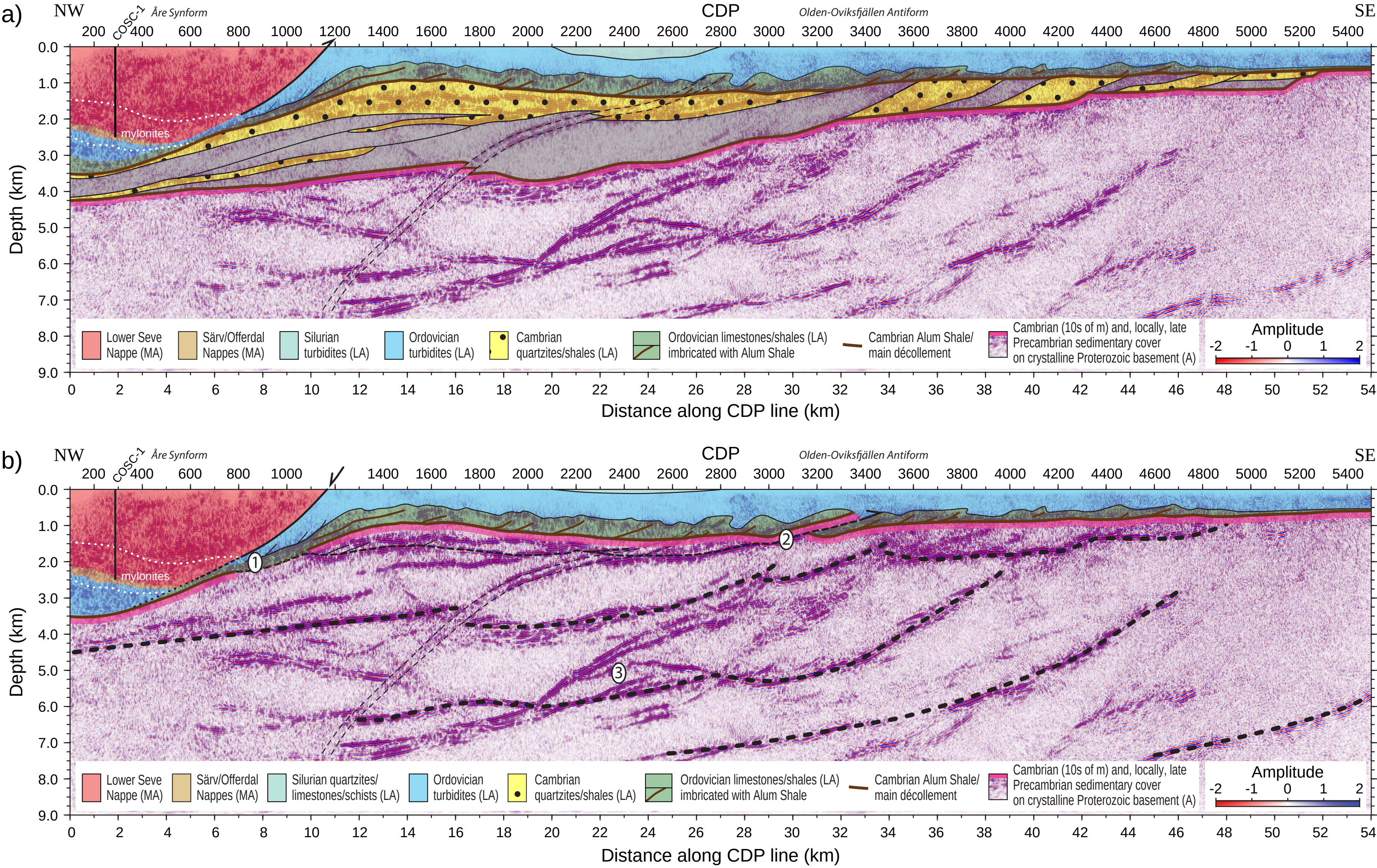
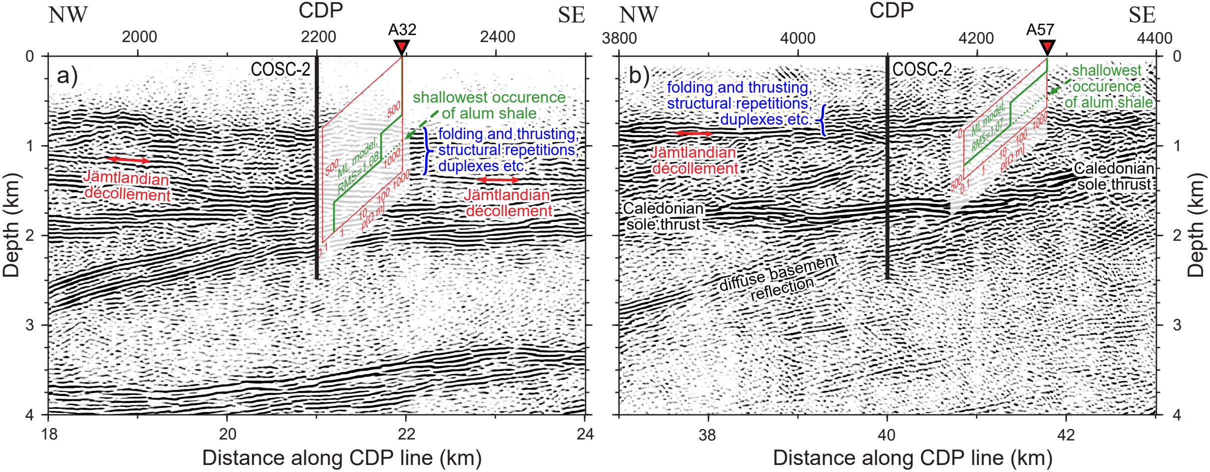

a)
NW
COSC-1
Åre Synform
CDP
Olden-Oviksfjällen Antiform
SE
200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400
Depth (km)
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0
mylonites
Lower Seve Nappe (MA)
Särv/Offerdal Nappes (MA)
Silurian turbidites (LA)
Ordovician turbidites (LA)
Cambrian quartzites/shales (LA)
Ordovician limestones/shales (LA) imbricated with Alum Shale
Cambrian Alum Shale/ main décollement
Cambrian (10s of m) and, locally, late Precambrian sedimentary cover on crystalline Proterozoic basement (A)
Amplitude
-2 -1 0 1 2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
Distance along CDP line (km)
b)
NW
COSC-1
Åre Synform
CDP
Olden-Oviksfjällen Antiform
SE
200 400 600 800 1000 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400
Depth (km)
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0
mylonites
①
②
③
Lower Seve Nappe (MA)
Särv/Offerdal Nappes (MA)
Silurian quartzites/ limestones/schists (LA)
Ordovician turbidites (LA)
Cambrian quartzites/shales (LA)
Ordovician limestones/shales (LA) imbricated with Alum Shale
Cambrian Alum Shale/ main décollement
Cambrian (10s of m) and, locally, late Precambrian sedimentary cover on crystalline Proterozoic basement (A)
Amplitude
-2 -1 0 1 2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54
Distance along CDP line (km)

Figure 10


NW
CDP
SE
2000
2200
2400
A32
a)
COSC-2
500
500
ML model,
RMS=1.08
1000
1000
0.1
1
10
100
1000
ρ[Ω m]
shallowest occurence
of alum shale
folding and thrusting,
structural repetitions,
duplexes etc.
Jämtlandian
décollement
Jämtlandian
décollement
0
1
2
3
4
Depth (km)
18
20
22
24
Distance along CDP line (km)
NW
CDP
SE
3800
4000
4200
A57
4400
b)
COSC-2
folding and thrusting,
structural repetitions,
duplexes etc.
shallowest
occurence
of alum shale
0
ML model,
RMS=1.07
1000
500
0.1
1
10
100
ρ[Ω m]
Jämtlandian
décollement
Caledonian
sole thrust
Caledonian
sole thrust
diffuse basement
reflection
0
1
2
3
4
Depth (km)
38
40
42
Distance along CDP line (km)