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Abstract: The scientific drilling project COSC (Collisional Orogeny in the Scandinavian Caledonides), designed to study key questions concerning orogenic processes, aims to drill two fully cored boreholes to depths of c. 2.5 km each at carefully selected locations in west-central Sweden. The first of these, COSC-1, is scheduled for start late spring 2014 and will target the Seve Nappe Complex, characterized by inverted metamorphism and with parts that have evidently been subjected to hot ductile extrusion. In this study available seismic sections have been combined with surface geology to produce a 3D interpretation of the tectonic structures in the vicinity of the COSC-1 borehole. Constrained 3D inverse gravity modelling over the same area supports the interpretation, and the high-density Seve Nappe Complex stands out clearly in the model. Interpretation and models show that the maximum depth extent of the Seve Nappe Complex is less than 2.5 km, consistent with reflection seismic data. The gravity modelling also requires underlying units to comprise low-density material, consistent with the Lower Allochthon, but the modelling is unable to discern the décollement separating the allochthons from the crystalline Precambrian basement.

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The Caledonian Orogen is the result of the collision between the two palaeocontinents Laurentia and Baltica which followed the Ordovician closing of the Iapetus Ocean (Gee et al. 2008). This collision, with Laurentia overthrusting Baltica, began in the Silurian and experienced continued compressive deformation well into the Devonian. This was followed by over three hundred million years of erosion, as well as uplift and extension during the Cenozoic opening of the Atlantic Ocean. The orogen is therefore well exposed today at mid-crustal levels, revealing the interrelation between the different tectonic units and allowing the study of fossilized orogenic processes.

The orogen is dominated by thrust tectonics with long-transported allochthons emplaced westwards on to the Laurentian platform and eastwards on to Baltica. In Scandinavia (Fig. 1a), the Uppermost Allochthon contains fragments from the Laurentian margin resting on top of Iapetus-derived oceanic terranes, including ophiolites and island-arc assemblages (Upper Allochthon). These are thrust on top of units derived from the Baltoscandian margin (Middle Allochthon), which mainly comprises Neo-proterozoic metasedimentary and older crystalline rocks. The Middle Allochthon is characterized by inverted metamorphism. The uppermost units of the Middle Allochthon were metamorphosed under amphibolite, granulite and eclogite facies conditions; some parts were probably partially molten and were involved in hot, ductile extrusion (Gee et al. 2010). The underlying units of the Middle Allochthon are metamorphosed to greenschist facies, and comprise dolerite-intruded sandstones thrust over sandstones and granitic gneisses without dykes. The Lower Allochthon is made up of Ediacaran, Cambrian, Ordovician and Silurian sedimentary successions derived from the continental shelf of Baltica and the Caledonian foreland basin. All of these allochthonous units were thrust on top of the underlying Autochthon, a major décollement separating them from alum shales and the Precambrian crystalline basement.

In the past few decades the crustal structure of the Scandinavian Caledonides has been investigated by a variety of methods, many of which have focused on the central Scandes, for example the so-called Central Caledonian Transect (CCT). The early geophysical surveys along the CCT and adjacent areas included: petrophysical sampling (Elming 1980); aeromagnetic (Dyrelius 1980) and gravimetric (Dyrelius 1986) surveys; and refraction (Palm 1984; Schmidt 2000) and reflection seismic profiling (Hurich et al. 1989; Palm et al. 1991; Juhojuntti et al. 2001). Subsequently, a number of other geophysical surveys have helped refine our
understanding of the Scandinavian Caledonides. One of these, a magnetotelluric investigation (Korja et al. 2008), provided complementary resistivity data on the upper crustal structures. These structures have also been the focus of new seismic surveys in recent years (Hedin et al. 2012). Understanding the internal structure of the orogen, the inverted metamorphism and the ductile transport of subduction-generated nappes is central to our understanding of Caledonian Orogeny. Despite decades

Fig. 1. (a) Tectonostratigraphic map of the Scandinavian Caledonides (based on Gee et al. 2010); (b) topography/bathymetry of northwestern Scandinavia (prepared with GMT); (c) magnetic anomaly map (based on Olesen et al. 2010a, explained in Olesen et al. 2010b); and (d) Bouguer gravity anomaly map (based on Ebbing et al. 2012). Black rectangle is the extent of the geological map in Figure 2, the dashed red and white line is the national borders and the black and white line is the Caledonian front.
of intense geophysical and geological investigations of the Caledonides, resulting in a fairly consistent picture of the subsurface structures, many questions and uncertainties still remain that can only be answered through deep drilling.

The Swedish Deep Drilling Program (SDDDP) was established in 2007 to study fundamental questions of global importance that are well defined in Scandinavia and can be investigated only through drilling. Summaries of proposed drilling projects were presented in a special issue of the Geological Society of Sweden’s journal (GFF) in 2010. The Collisional Orogeny in the Scandinavian Caledonides (COSC) project (Gee et al. 2010) was designed to study not only the Scandinavian Caledonides but also to test different interpretations of collisional orogeny, as proposed and developed for other major orogenic belts such as the Himalayas (e.g. Law et al. 2006) and the western Pacific Izu–Bonin–Mariana arc system (e.g. Tamura et al. 2010).

The COSC project involves drilling two c. 2.5-km-deep fully cored boreholes at carefully selected locations in the Åre–Mörsil area of western Jämtland (Fig. 1). Their combined 5 km tectonostratigraphic sequence begins in the high-grade nappes of the Middle Allochthon and goes through the underlying lower-grade allochthon and basal décollement before reaching deep into the Precambrian basement. The first hole (COSC-1) will focus on the high-metamorphic-grade Seve Nappe Complex (SNC) with its inverted metamorphism and investigate how and to what extent it affected the underlying lower-grade units. The goal with the second hole (COSC-2) is twofold: (1) to penetrate and study in detail the basal décollement, separating the allochthons from the basement; and (2) to drill deep enough into the basement to reach at least one of the prominent deeper reflectors (Gee et al. 2010; Hedin et al. 2012). In preparation for the drilling, new high-resolution 2D reflection seismic profiles were acquired in the Åre–Mörsil area in 2010 (Hedin et al. 2012) in order to obtain more detailed images of the near surface for planning the project and optimally locating the boreholes. Based on these data, a suitable location for the first borehole was identified in the old copper mining area of Fröå, c. 5 km east of Åre (Fig. 2). A location for the second borehole, targeting the décollement and basement further east, has not yet been selected (Hedin et al. 2012).

The reflection seismic interpretation presented by Hedin et al. (2012) was based mainly on the character of the seismic data and their correlation with the older CCT data and surface geology. For a deep drilling project of this scale, targeting specific geological features, it is necessary to have a 3D geological understanding of the environment to be drilled. Gravity measurements acquired in Jämtland over the past 40 years and high-resolution aeromagnetic data, obtained by the Swedish Geological Survey (SGU) in 2011 over the Åre–Mörsil area, provide two essential datasets to further refine and validate the earlier seismic interpretations.

Presented here is a 3D interpretation of the main geological structures in the vicinity of the proposed first drill site COSC-1 based on the 2D seismic reflection profiles, bedrock geology and potential field measurements. Our interpretation is consistent with (1) modelling of the gravity and magnetic data along the seismic profiles using existing petrophysical measurements in the study area; (2) constrained 3D gravity modelling; and (3) the high-density SNC extending down to c. 2–2.5 km along with the presence of low-density material separating it from the underlying basement.

**Geological setting**

The regional geological context of the COSC drilling project has been presented previously by Gee et al. (2010) and Hedin et al. (2012) and this summary focuses on the Åre area of central western Jämtland, where the thrust sheets of the Lower and Middle allochthons dominate the bedrock. In western Jämtland these allochthons are folded by major north–south-trending antiforms and synforms with wavelengths of a few tens of kilometres, which appear to be related to imbrication of the underlying basement (Fig. 2; Palm et al. 1991). The décollement at the base of the Lower Allochthon, as it is defined by drilling in various parts of the Caledonian thrust front (e.g. Gee et al. 1978), dips very gently (1–2°) westwards for c. 50 km into the Offerdal Synform (Fig. 2). On the basis of reflection seismic profiling (Juhojuntti et al. 2001) it is then seen to be arched and imbricated further to the west, the intensity of the imbrication increasing towards the hinterland. The COSC drilling project seeks to better understand both the emplacement of the major high-grade nappes of the Middle Allochthon (Gee et al. 2013) and the character of the lateral shortening in the underlying Lower Allochthon and basement.

The COSC-1 drill hole is located in the eastern limb of the Åre Synform, which is flanked to the west by the Mullfjäll Antiform and to the east by the Olden–Öviksfjäll Antiform. Within the Åre Synform the SNC occupies the highest structural levels; granulite facies migmatises of the Åreskutan Nappe are preserved in a klippe in the hinge of the fold and amphibolite facies gneisses comprise the underlying part of the complex, referred to as the Lower Seve Nappe. This unit is at least 2 km thick in the eastern limb of the synform where it includes
Fig. 2. Bedrock geological map of the Central Caledonides. SA: Skardöra Antiform; TS: Tännforsen Synform; MA: Mullfjället Antiform; ÅS: Åre Synform; OA: Olden–Oviksfjäll Antiform; OS: Offerdal Synform. The small black rectangle shows the extent of the 3D geological interpretation (Figs 5 & 10) and the larger rectangle that of the 3D gravity inversion (Figs 7–9).
a variety of psammitic and calc-silicate-bearing paragneisses and subordinate marbles, abundant amphibolites and some meta-gabbros and ultramafites. In the eastern limb of the synform, the SNC is underlain by thin slices of the Särv and Offerdal nappes thrust over intensely foliated Ordovician and Silurian metasediments of the Lower Allochthon. Cambrian black shales, Cambrian–Ediacaran quartzites and underlying Precambrian felsic volcanic rocks, cropping out a few kilometres south of the seismic profile, are inferred to be present at deeper levels beneath the Äre Synform and to extend westwards into the eastern limb of the Mullfjäll Antiform, where they are well exposed (Strömbäck et al. 1984; Karis & Strömberg 1998).

Mapping and structural analysis of the Olden antiformal window by Sjöström & Talbot (1987) has shown the décollement close above the base ment to be arched over this major fold and the antiform itself to result from further east–west contraction. The deeper structure of the Mullfjället and Olden–Oviksfjäll antiforms has been interpreted from the seismic profiling by Palm et al. (1991) for the former and by Juhojuntti et al. (2001) for the latter. The seismic results across both the Mullfjäll and Olden–Oviksfjäll antiforms show prominent flat reflectors underlying the major folds, consistent with the structural analysis. In the Olden window, the décollement close above the basement passes towards the west down into imbricated basement, providing clear evidence of increasing basement shortening towards the hinterland.

**Geophysical data**

It is well known that potential field data – in this study gravity and magnetic data – have poor depth resolution. When combined with, for example, reflection seismic data and/or geological and petrophysical data, they may, however, yield information about the bulk properties of subsurface materials which other geophysical methods are usually unable to provide (Li & Oldenburg 1998a; Roy & Clowes 2000; Goleby et al. 2002; Martelet et al. 2004; Malchmir et al. 2006, 2007). As with other geophysical methods, to be successful contrasts must exist between geological entities (in this case in density or susceptibility).

The new work presented here integrates existing seismic, gravity and magnetic data with the bedrock geology of the Äre area. Forward and inverse gravity modelling is performed to help test the reflection seismic interpretations and provide further insights into the subsurface geology. Knowledge of the physical parameters of the different lithologies is essential for the potential field integration and data from the literature are used for these purposes. Future studies will involve further sampling both on the surface and, especially, in the COSC-1 borehole.

**Petrophysics**

The petrophysical data for the tectonic units relevant for this work, shown in Table 1, have been compiled from the work presented by Elming (1980). The magnetic susceptibility of most rocks in the area is directly proportional to their magnetite content (Elming 1980), although there may be a small contribution from pyrrhotite. The Caledonian cover nappes are in general (with few exceptions) weakly magnetized and only give rise to local magnetic anomalies (Dyrelius 1980); the rocks of the underlying basement, east of the Caledonian front and beneath the Caledonian cover of west central Sweden, exhibit high magnetic susceptibilities however (Elming 1980). The highest susceptibilities in the area (of the order $10^{-2} - 10^{-1}$ SI units) are found in the magnetite-rich Rätan-type granites of the NW-trending Transscandinavian Igneous Belt (TIB, extensively described by Högdahl et al. 2004), which builds up the crystalline Precambrian basement to the SE of the Caledonian front and which presumably is also underlying the Caledonian cover in western Jämtland. Some granitic rocks within the Lower and Middle Allochthons, as well as some of the dolerites of the Särv Nappe, also have comparatively high susceptibilities ($10^{-3} - 10^{-2}$ SI units). Most other units have susceptibilities of the order $10^{-6} - 10^{-3}$ SI units, including the most strongly magnetized components of the SNC (amphibolites and granulites are in the range $(0.6-12) \times 10^{-4}$ SI units; Table 1). Units of crystalline basement seen in windows through the Caledonian cover (e.g. Mullfjället, Fig. 2) generally have low magnetic susceptibilities that are similar to the Revsund granite of the TIB found to the east of the Caledonian front (present in the Baltoscandian basement in Fig. 2). In general, the Rätan and related granites have low Q-values of c. 0.2 (Elming 1980) with a direction of remanence roughly parallel to that of the present geomagnetic field (Dyrelius 1980). The metasedimentary rocks of the Lower Allochthon also have low Q-values ($<0.15$) while the Q-values of the Seve nappes are generally below 1, but can exceed 10 for some lithologies (Elming 1980).

With regard to density, there is a general tendency within the Caledonian nappes for it to be increasing both upwards in the tectonostratigraphy and with increasing metamorphic grade. The units of the Lower Allochthon generally have densities in the range $2620-2700$ kg m$^{-3}$, the Särv Nappe with its extensive dyke swarms has densities of $2720-2790$ kg m$^{-3}$ (varying with dyke frequency).
Table 1. Density and magnetic susceptibility data from the study area

<table>
<thead>
<tr>
<th>Tectonic unit</th>
<th>Tectonostratigraphy</th>
<th>Average density (kg m$^{-3}$)</th>
<th>Lithology</th>
<th>Mean density (kg m$^{-3}$)</th>
<th>No. samples</th>
<th>Susceptibility of samples ($\times 10^{-5}$ SI units)</th>
<th>No. samples</th>
<th>Susceptibility in situ ($\times 10^{-5}$ SI units)</th>
<th>No. samples</th>
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<td>6–126</td>
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<td></td>
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<td>Feldspathic sandstone</td>
<td>2708</td>
<td>54</td>
<td>1–500</td>
<td>12</td>
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<td>6</td>
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<td></td>
<td>Porphyry (south)</td>
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Compiled from Elming (1980).
and the high-grade SNC with its high content of mafic rocks has mean densities of 2830–2890 kg m\(^{-3}\) (Table 1). In the overlying mainly green- chist facies metasedimentary rocks of the Köl n nappes, the densities once more decrease to a range of 2740–2770 kg m\(^{-3}\) (Table 1). To the east of the Caledonian front the crystalline basement can be divided into a southern unit of higher density, the Råtan granite (c. 2740 kg m\(^{-3}\)), and a northern lower density unit, the Revsund granite (c. 2670 kg m\(^{-3}\)). Crystalline basement with densities and composition similar to those of the Revsund and Råtan granites also occurs further west in windows through the Caledonian cover and in isolated thrust sheets (Elming 1980).

Although not a general rule, there is also a slight covariance between density and magnetic susceptibility of the Caledonian rock units, where higher density rocks have slightly higher magnetic susceptibilities (Elming 1980).

**Potential field data**

Early magnetometric surveys across Scandinavia revealed a vast positive anomaly in the central Caledonides of western Sweden (Dyrelius 1980). East of the Caledonian front, this anomaly correlates with the NW-trending magnetite-rich granites of the TIB, locally overlain by felsic volcanites and Jot nian Dala sandstones, which has led to the interpretation of this unit extending NW beneath a rather thin Caledonian cover (Dyrelius 1980). The western boundary of the anomaly coincides with the western limb of the Skardöra Antiform along the Swedish–Norwegian border, where it drops rapidly to negative flank values (Fig. 1c). The highest values are found in an area just west of the Caledonian front and are likely related to a highly magnetic portion of the basement. Earlier low-resolution (widely spaced) aeromagnetic modelling profiles across the mountain range resulted in interpretations requiring the magnetic granites to be at least 10 km thick (Dyrelius 1980). The high contrast in magnetic susceptibility between the basement and the Caledonian allochthons allows estimates of the depth to the magnetic basement to be made, from several hundred metres to more than 2 km (Dyrelius 1980). Based on the aeromagnetic data, the surface of the magnetic basement was found to be undulating and antiforms and synforms were discovered that are not detectable in the surface geology (Dyrelius 1985).

The magnetic data used in this study (total-field aeromagnetic) were recently (August 2011) acquired by the SGU in a dedicated airborne survey specifically designed to cover the area identified (Fig. 3a) to include the COSC drilling targets (Gee et al. 2010). The dataset consists of 130 acquisition lines flown at a nominal altitude of 60 m with a line and point spacing of 200 and 7 m, respectively. The instrument used was a caesium vapour magnetometer with a resolution of 0.001 nT, resulting in data of high quality. The Earth magnetic intensity is about 51 000 nT in the area, inclination and declination are c. 76° and 4°, respectively (Rukstales & Love 2007). Figure 3a shows the observed total-field magnetic map over a smaller area than that shown for the gravity data, as there are no magnetic data available over the higher elevations of Areskutan and further west. Minimum (in the western part of the study area) and maximum (in the eastern part) magnetic values are 50 660 and 51 552 nT, respectively. The Definitive International Geomagnetic Reference Field (DGRF; averaging 50 550 nT in the study area) was removed from the total-field magnetic data in order to produce the residual anomaly map shown in Figure 3b. With a width of the order 100 km, the positive Jämtland anomaly is not large enough to be included in the DGRF. The Jämtland anomaly, with its positive contribution of the order of 500 nT, therefore still dominates the anomaly map after removal of DGRF, resulting in only positive values in the residual anomaly map (Fig. 3b). Long magnetic east–west-trending lineaments observed in the central and eastern parts of the magnetic map represent high-voltage power lines and a major railway and are not real geological features. An interesting feature in the magnetic data is a north–south-trending boundary between Järpen and Mörsil, neither mapped on the surface nor identified in the seismic sections, implying a sharp boundary between different units or a steeply dipping feature likely related to the magnetic basement.

The mainly east–west variation of crustal thickness across the Scandinavian Caledonides (England & Ebbing 2012) generates a wide negative Bouguer anomaly, aligned along the strike of the mountain belt (Fig. 1d). Although the main variation in this large anomaly can be explained by density variations in the lower crust, some of it (especially on more local scales) must be related to density variations in the upper crust and the thickness of the Caledonian cover (Dyrelius 1985). In the Jämtland area of west-central Sweden, a particularly strong and large negative Bouguer anomaly may be explained by a more than 10-km thick unit of TIB granitic rocks beneath the Caledonian cover (Pascal et al. 2007), although more low-density granites found further SE in the TIB may give a better fit than the previously mentioned Råtan type granites. On an even more local scale, north–south-trending antiforms and synforms folding the undulating basement and Caledonian allochthons are distinguishable in the gravity data (e.g. Elming 1988).
Bouguer gravity data containing more than 300 data point measurements and covering an area of c. 17 000 km², including the target drill site, were compiled from the database of the SGU and earlier measurements (Dyrelius 1985). The gravity data (Bouguer reduced using a standard density of 2670 kg m⁻³) are highly variable with a minimum value of 33 mgal over metasedimentary rocks and a maximum value of 103 mgal over the basement rocks and the high-grade metamorphic rocks.

Fig. 3. (a) Observed total field aeromagnetic anomaly; (b) residual magnetic field after removal of DGRF; (c) observed Bouguer gravity anomaly; (d) regional gravity field; and (e) Bouguer-residual gravity field. The black rectangle shows the extent of data used in the inversion modelling (Figs 7–9).
of the Seve nappes (see Table 1). Figure 3c shows the Bouguer gravity map used in this study. Gravity highs in both the eastern and western parts of the map reflect the large-scale undulations of units of high-density rocks within the autochthonous basement. The imbricated Precambrian basement units in the major antiforms (e.g. Mullfjället and Olden) are not of Rätian type and are generally associated with local gravity lows. A gravity high in the central part of the map reflects the high-density rocks of the SNC (see Table 1). These gravity data cover a large area (Fig. 3c) and not only allow the separation of the regional field from the residual field (for the modelling), but also provide further insights into the nature of the basement rocks. While there are several methods for separating the regional field from the gravity data (e.g. Li & Oldenburg 1998b, Nabighian et al. 2005; Malehmir et al. 2009), we chose a simple second-order polynomial approach to estimate the regional field (Fig. 3d). The reason for choosing a second-order polynomial was to account for the gravity highs surrounding the study area (Fig. 3a). Figure 3e shows the Bouguer anomaly map after the removal of the regional field. It is clear that most anomalies, the SNC anomaly in particular, are better defined in the residual field than in the observed Bouguer gravity data. As will be shown later, the Bouguer anomaly data were used for 3D inverse modelling. Prior to this, however, we performed 2.5D gravity modelling along the reflection seismic lines using the observed gravity data.

The COSC-1 drill site is located in an area with a relatively low magnetic field (Fig. 3b), but where there is a local high in the Bouguer gravity field (Fig. 3e).

Seismic data

Refraction seismic studies of the Caledonian cover in the central and eastern parts of Jämtland conducted in the 1970s and early 1980s (e.g. Palm et al. 1984) revealed a gently dipping (from less than 1° to a few degrees) basement surface present at depths of a few hundred metres close to the Caledonian front and reaching c. 2 km west of the Åre Synform. An undulating surface was found superimposed on this general dip with amplitudes ranging from 50 to 200 m and wavelengths of c. 3–10 km in both east–west-trending and north–south-trending profiles. According to Dyrelius (1980), and discrepancies could be explained by oversimplified assumptions and variations in magnetic susceptibility and seismic velocities (not necessarily both) within the cover units.

Between 1988 and 1992 an almost 180-km-long reflection seismic profile was acquired from the Swedish border with Norway near Storlien eastwards to the Caledonian front north of Östersund near Lit, and reaching about 20 km fur th er east across the autochthonous crystalline basement (Palm et al. 1991; Juhojuntti et al. 2001). This profile, comprising the CCT together with its westwards continuation in Norway to Trondheimsfjorden and the Norwegian west coast (Hurich et al. 1989), was designed to map the entire crust down to the Moho. Although no clear Moho was defined, the crust was interpreted to be 40–50 km thick in the Jämtland area (Juhojuntti et al. 2001). This was later confirmed by a deep seismic sounding profile (Schmidt 2000), coinciding in its western part with the CCT. Recent passive seismic studies (England & Ebbing 2012) estimate the crustal thickness to be c. 42 km beneath the Jämtland area, consistent with the other seismic data.

The CCT reflection seismic profile revealed a very reflective upper crust with subhorizontal structures that could be attributed both to Precambrian phenomena and to Caledonian deformation (Palm et al. 1991; Juhojuntti et al. 2001). The uppermost levels (down to c. 5 km) of the seismic section correlate well with the surface geology, as well as with the large north–south-trending antiforms and synforms that fold the allochthons and are also seen in the local gravity anomalies. Subhorizontal reflections in the upper crust, dipping c. 1–2° towards the west, can be traced from the Caledonian front to the Norwegian border where they reach a depth of c. 6 km. At the Caledonian front where they project to the surface, and in shallow boreholes just west of the front (Gee et al. 1978; Andersson et al. 1985), these reflections can be shown to correlate with a prominent boundary layer, comprising the surface of the autochthonous Precambrian crystalline basement with its overlying Cambrian cover (mainly alum shales). Within the autochthonous basement, beneath the frontal décollement, prominent reflections define a major antiform. Similar reflections can be traced to the surface east of the Caledonian front where they correlate with gently dipping dolerites intruded into the granitic basement (Juhojuntti et al. 2001). These relationships compare well with the evidence in the Siljan Ring area 150 km further south, where strong reflectivity within the TIB has been tied to 1.0 Ga dolerite intrusions (Juhlin 1990). The strong upper crustal reflectivity in the basement of western Jämtland may therefore be due to dolerite intrusions similar to those in the Siljan area, but subjected to Caledonian or perhaps Sveconorwegian deformation.

The seismic profiles acquired for the COSC project (Hedin et al. 2012) provided a much
higher resolution, especially in the near surface, than previously available in this area. Through correlation with the older reflection seismic data and surface geology it was possible to propose an optimal location for the COSC-1 drill site at the western end of the main profile (Figs 2 & 4). This proposed location allows for coring of a thick section of the lower Seve nappes, permitting the study of the inverted metamorphism in detail and also penetration into underlying units. As shown

![Fig. 4.](http://sp.lyellcollection.org/)

Fig. 4. (a) Migrated and depth-converted reflection seismic section along the Byxtjärn–Liten (BL) profile (the main profile) and (b) the interpretation presented by Hedin et al. (2012). (c) 2.5D forward-modelled gravity and magnetic field effect using the geometry of the seismic interpretation in (b). Density and magnetic susceptibility are shown in (b) as kg m$^{-3}$/SI units. The 3D geometry is not taken into account and the calculated gravity and magnetic data deviate somewhat from the observed data. (d) The seismic section in (a) overlain by a section extracted from the 3D gravity inversion.
in Figure 4c, simple 2.5D forward gravity and magnetic modelling based on outwards perpendicular continuation of homogeneous bodies in our seismic interpretations suggests reasonable agreement between the observed data and calculated response. However, the majority of the structures in the study area have 3D geometries that cause deviations in the 2.5D modelling and cannot be neglected, implying that full 3D potential field modelling is required to thoroughly validate the seismic interpretation.

**Magnetotellurics**

The magnetotelluric measurements by Korja et al. (2008) revealed an upper crustal conductive layer, coinciding with the subhorizontal seismic reflections interpreted as the westward continuation of the main Caledonian frontal décollement, consistent with a thin layer of Cambrian cover rich in alum shale. A transition in the near surface into a more resistive western unit was also shown to correlate with the geological boundary between the Lower and the Middle Allochthon, indicating that the lithologies of the latter have higher resistivities.

**3D interpretation and modelling**

**3D interpretation**

The new 2.5D potential field modelling results provide some additional confidence about the earlier seismic interpretations by Hedin et al. (2012). Major reflections in the seismic data were geologically modelled in 3D by combining the 2.5D results with the surface geology, as well as gravity and magnetic maps. Several of the tectonic boundaries seen in the bedrock geology at the surface are easily distinguishable in the magnetic map of the study area, and the gravity data are consistent with the large north–south-trending synclines and anticlines in the area. Some strong reflections in both the newly acquired (Hedin et al. 2012) and older (Palm et al. 1991; Juhojuntti et al. 2001) seismic sections also project to the surface geology in good correlation with the surface geology at the area. Gravity and magnetic anomalies linked to near-surface structures in the surface geology may also give a sense of the thickness of these respective units. Using this as an indication of the 3D geometry, surfaces were created by extending the horizons picked in the seismic sections outwards and adjusting their depth to produce approximate layers tracing the boundaries between adjacent units (Fig. 5c).

The 3D interpretation has been kept as simple as possible, despite the complex sets of reflections observed in several places including the reflective unit interpreted as the Seve Nappe Complex.

**3D gravity inversion modelling**

In the 2.5D potential field modelling (i.e. homogeneous structure perpendicular to the profile) along the seismic profile (Fig. 4), the three-dimensionality of major lithological units was neglected and only a forward modelling approach (i.e. no inversion) was applied. The 2.5D modelling provided a preliminary confirmation of the seismic interpretation, but bias or unrepresentative samples (even internal variations) from the geological units were not accounted for. An unbiased approach slightly controlled by available a priori information was therefore applied. Such a strategy allows any discrepancies between the seismic interpretations (biased by the interpreter) and the potential field data to be checked. For this, we performed 3D inverse gravity modelling taking into account the surface geology, the known density ranges for individual lithological units (Table 1) and the reflection seismic data. The main motivation was to investigate the depth extent of the Seve unit and whether low-density materials underneath it would also be required in the 3D inversion. Magnetic data (Fig. 3a, b) were also considered for the 3D inversion but preliminary inversion results of these data around the COSC-1 drill site were not convincing, mainly because the data cover only a limited area around the site. Estimation of the regional magnetic field was difficult and problems related to edge effects were significant. This problem was not encountered with the gravity data since they cover a much larger area, albeit with lower resolution. Furthermore, large uncertainties when preparing a magnetic model stem from the locally varying composition of the SNC whose different lithologies show significant variation in magnetic susceptibility and remanence. For these reasons, the magnetic inversion results are not presented or discussed here.

Model Vision Pro™ and GRAV3D from the University of British Columbia (Li & Oldenburg 1998a, b) were used for model preparation and inverse modelling, respectively. Figure 6 shows a summary of our 3D gravity inversion strategy. The
most time-consuming part of the procedure was generating a realistic 3D geological model from which the initial density model and the density bounds were derived (Fig. 6). We digitized the geological map of an area covering the Seve Nappe Complex and underlying parts of the Middle Allochthon, Lower Allochthon (east) and Upper Allochthon (west), as well as the felsic volcanites of the Mullfjället Antiform and from that produced the volumetric shape of each individual geological unit. Very small geological units (i.e. surface areas less than 1 km²) were omitted since they were not required by the gravity data. General smoothness constraints were also applied to inhibit wild density contrasts between adjacent cells (see Malehmir et al. 2009).

The inverted model consists of a volume populated with rectangular cells with each cell assigned a physical property (in our case the density contrast from a background of 2700 kg m⁻³). The

Fig. 5. (a) Reflection seismic sections in 3D with picked horizons; (b) bedrock geology and seismic acquisition lines projected to a digital elevation model; and (c) 3D interpreted surfaces separating major tectonic units based primarily on the information in (a) and (b). The legend refers to (a) and (c), where the layers at depth show the base of the respective tectonic units; the bedrock geology of (b) follows the legend of Figure 2. Prepared using the 3D modelling software GOCAD.
volume contains 84 (east–west) × 54 (north–south) × 35 (depth) cells, with each cell having a fixed area of 1 km² in the horizontal plane and the total volume being 84 (east–west) × 54 (north–south) × 7 (depth) km³. The thickness of the cells increases with depth from 25 m at the surface to c. 660 m at the bottom of the model. A priori information about the major geological units, such as their surface geometry, density and depth extent, were incorporated into the inversion and kept relatively fixed (using narrow lower and upper bounds or a fixed model) during the inversion. The bounds were chosen to force the cells to contain what we considered to be reasonable density values for rocks in the study area, namely 2550–3100 kg m⁻³. In regions with no a priori information, no constraints were used and upper and lower bounds were chosen to be wide enough to contain plausible solutions.

Gravity data do not inherently contain depth information. A depth-weighting function was therefore applied to the sensitivity matrix values to balance the natural decay of the resolution kernels with depth. This prevents the inversion from concentrating the density anomalies close to the surface of the model. If a concentration near the surface is envisioned, however, less depth weighting should be applied. By constraining the inversion, the ambiguity of the final model can be reduced (Malehmir et al. 2009).

Inversion was performed iteratively by adjusting the density contrast of the cells while maintaining

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**Fig. 6.** Gravity inverse modelling algorithm.
a constant geometry of the mesh until the complete volume would reproduce the residual Bouguer gravity field (Fig. 3e) within an error misfit of 0.2 mgal. Several tests using various parameters were carried out before the inversion results were finalized. Figure 7 shows the observed residual gravity data (Fig. 7a) and the calculated response from the 3D inversion model (Fig. 7b), indicating a good fit between the two and suggesting a model that satisfies the observed gravity data. Nevertheless, small linear and sharp features in the calculated response are also observed which indicate excess features that are not required by the data and should therefore be neglected in the interpretation. These features are the results of the constrained inversion introduced by the geology and have been partly forced to be there, but are not required by the data. Some of the features are also introduced by the inversion. The observed gravity data are smooth due to the large spacing between the measurements; small geological features, therefore, cannot be resolved. We also carried out unconstrained 3D inversion, but the results were more difficult to interpret.

A series of depth slices from the density model volume are shown in Figure 8. The most striking feature in these depth sections is the high-density region associated with the Seve unit. The model is constrained by seismic data and surface geological observations, resulting in parts of the model appearing rudimentary. From the modelling it is found that the Seve unit (density contrast more than 150 kg m\(^{-3}\)) can extend down to only c. 2.5 km at the location of the COSC-1 drill site. Therefore, in order to match the observed gravity data, low-density materials are required below this depth (Fig. 8d). This is consistent with the seismic and geological interpretation that the high-grade metamorphic SNC has been thrust over the metasedimentary rocks of the Lower Allochthon. It is also interesting to observe that the Seve unit is at its thickest just SW of the COSC-1 drill site (Fig. 8c).

Figure 9 shows 3D views from the gravity model visualized with the location of the proposed COSC-1 drill site, the volumetric geometry of the Seve unit and the available seismic profiles in the study area. In general, there is a good match between the volumetric shape of the SNC and the high-density regions in the model. Although the model is constrained by the available data and our interpretation of subsurface geology, we observe...
Fig. 8. Depth slices from the 3D inversion results at depths (a) 200 m; (b) 700 m; (c) 1700 m; and (d) 2700 m. The blue derrick shows the location of the proposed COSC-1 drill site and the black lines are the seismic acquisition lines (KF: Kallsjön–Fröå profile – the connecting profile; BL: Byxtjärn–Liten profile; CCT: Central Caledonian Transect).

Fig. 9. (a) A 3D view of two vertical slices in the vicinity of the proposed drill site down to a depth of 2600 m. (b) Same 3D view as in (a), but including the geometric body of the Seve unit from the above 3D interpretation (Fig. 5). The blue derrick shows the location of the proposed COSC-1 drill site and the black lines are the seismic acquisition lines (KF: Kallsjön–Fröå profile – the connecting profile; BL: Byxtjärn–Liten profile; CCT: Central Caledonian Transect).
in a few regions of the model that these constraints were rejected by the inversion. This is clear in Figure 9a where an isolated high-density zone is separated from the main density anomaly associated with the Seve unit. These two regions were initially part of a geological body, but the inversion did not accept such geometry and this is the reason for their separation. The high-density region to the west (Fig. 9a) is not required by the data. The inversion results are also consistent with the inwards plunge of the Seve unit in this area, as evident from the comparison with the extracted 3D geological model of the SNC in Figure 9b. The inversion was unable to provide insights into the nature of the basement rocks using the current gravity measurements. This is probably due to these rocks being situated at depths greater than the resolution of the gravity data. An alternative scenario is that their density contrast with the overlying rocks is small, making it impossible to resolve them. Another possible scenario is that their contribution was removed during the regional field separation.

Discussion

The SNC with its inverted metamorphism, the target of the COSC-1 borehole, is today associated with a magnetic low and density high that are easily distinguishable in the magnetic and gravity maps (Fig. 3). Elming (1980) notes that, in the central Caledonides, the density and magnetic susceptibility correlate reasonably well with one another: the denser the rock the higher the susceptibility. However, in the study area of this paper we observe that the magnetic and gravity fields show a negative correlation. We explain this by considering that the gravity high over the SNC is due to the high density of this unit compared to the adjoining units while the magnetic low is not due to the SNC itself, but to the consequence of the magnetic basement (Råtan-type granite) being deeper below this unit. The source of the magnetic signature above the SNC is different from and deeper than the source of the gravity signature. The high metamorphic grade of the SNC also implies that the rocks have exceeded the Curie temperature (>580 °C) and, therefore, that the unit may also have remnant magnetization that is more intense and which differs from the underlying lower-grade rocks, further reducing the magnetic field above it. The 3D gravity inversion results agree roughly with previous geophysical interpretations, but provide more detail and are of higher resolution. The geometry of the high-density SNC from the gravity inversion is close to the presented 3D interpretation (Fig. 9), with the SNC thinning both towards the north and south and being thickest in the area close to the proposed drill site near the hinge of the north–south-trending Aare Synform. The seismic interpretations suggest that the depth to the base of the Lower Seve nappes in the vicinity of the proposed drill site is c. 2.3 km below the surface (Fig. 4c) while the constrained 3D gravity inversion gives a maximum depth of c. 2.5 km (Fig. 4d). The proposed drill site location will therefore provide the longest possible cored tectonostratigraphic section through the lower parts of the SNC, allowing the internal phases of metamorphism in this unit to be studied in detail. As seen in Figure 10, it is expected to penetrate into the underlying units of the Lower Allochthon that may be separated from the SNC by lenses and/or thin sheets of middle allochthonous composition (e.g. Särv or Offerdal). In the geological interpretation, these latter units are missing although their presence is possible at the base of the reflective package that is interpreted as the SNC. This would imply that the targeted Seve nappes may be thinner at the drill site than interpreted from the seismic data. The 3D gravity inversion requires a layer of low-density material separating the high-density SNC from an assumed basement of Råtan-type granite. Its thickness, and hence the depth to the basement surface, is very difficult to resolve through the gravity inversion alone.

Only scientific deep drilling can reveal the nature and composition of the near-surface structures of the Caledonian cover and the underlying autochthonous basement and determine the origin of the complex reflectivity patterns. At the same time, high-quality geophysical and geological data and models are invaluable as they tie borehole data together over large distances and provide an understanding of the large-scale 3D geometry. More potential field data and petrophysical sampling in the vicinity of the COSC-1 drill site, as well as over a wider area, are needed to produce a more highly resolved and accurate model through inversion. The aeromagnetic data are especially limited in terms of their limited areal coverage which is insufficient for producing a convincing 3D inverse model, while the gravity data suffer from sparse sampling. More measurements of magnetic susceptibility and density on outcropping units, as well as better control of the relative amounts of the different lithologies within the SNC, are also needed to better constrain the inverse modelling. A 3D approach to seismic processing (similar to e.g. Malehmir et al. 2011) could help to clarify the nature of some of the complex reflectivity patterns. A magnetotelluric survey to complement the rather sparse regional data presented by Korja et al. (2008), with the potential to allow tracing of the décollement and the middle and lower allochthons
to be distinguished, could help to refine our interpretation and model. In addition, integration of more detailed geological information (e.g. structural information from both previously conducted field studies and from further analysis of seismic data) could help to further constrain the current model.

Conclusions

As an initial stage of planning of the COSC deep drilling project and locating potential drill sites, 2D reflection seismic profiles acquired in 2010 were recently interpreted on the basis of previously acquired geophysical data and surface geology (Hedin et al. 2012). These seismic data and surface geological maps provided the basis for generating a new 3D geological model in the vicinity of the planned COSC-1 drill site. Through integration with potential field data, we tested the validity of this model by 3D inversion of the Bouguer gravity field.

The 3D geometric interpretation of the subsurface structures in the vicinity of the COSC-1 borehole, based mainly on reflection seismic sections and bedrock geology and supported by constrained 3D inversion of gravity data, gives us better control on the structures of interest for the COSC scientific deep drilling project. Complex reflectivity within the Seve Nappe Complex, the main target of the COSC-1 drill hole, suggests internal structures that may complicate the drilling. Although treated as missing in our geological interpretation, a significant component of the lower Middle Allochthon (e.g. Särv or Offerdal nappes) may be present at the base of this reflective package, implying that the Seve nappes may be thinner than suggested by the geological interpretation of the seismic data. Regardless of whether these components are present or not, the maximum depth extent for the Seve Nappe Complex appears to be c. 2.5 km and the unit may be thinner. The proposed drilling location will give the longest possible cored section through the Lower Seve nappes, allowing a thorough study of the structure and metamorphic history of this unit and a better understanding of the Caledonian Orogeny.

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New Zealand was used to process the seismic data. Seismic figures were prepared with GMT from P. Wessel and W. H. F. Smith and GOCAD under academic licence from the GOCAD Consortium and Paradigm. GRAV3D (University of British Columbia, Geophysical Inversion Facility) and Model Vision Pro™ (Encom Technology) were used for processing and modelling the potential field data.

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