THE GEOLOGICAL SOCIETY
OF AMERICA®

Large-scale, flat-lying mafic intrusions in the Baltican crust and their influence on basement deformation during the Caledonian orogeny

Rodolphe Lescoutre[1,†], Bjarne Almqvist[1], Hemin Koyi[1,§], Théo Berthet[1], Peter Hedin[2], Olivier Galland[3], Sonia Brahimi[4], Henning Lorenz[1], and Christopher Juhlin[1]

[1]*Uppsala University, Department of Earth Sciences, Villavägen 16, 752 36 Uppsala, Sweden*
[2]*Geological Survey of Sweden, Villavägen 18, 752 36 Uppsala, Sweden*
[3]*Physics of Geological Processes, the NJORD Centre, Department of Geosciences, University of Oslo, Blindern, 0316 Oslo, Norway*
[4]*Institut de Physique du Globe de Strasbourg, UMR7516, CNRS – University of Strasbourg/EOST, 1 rue Blessig, 67084 Strasbourg Cedex, France*

ABSTRACT

The Fennoscandian Shield in central Sweden displays a complex structural and compositional architecture that is mainly related to the Proterozoic history of the Baltica paleocontinent. In its western parts, the Precambrian basement is covered by the allochthonous rocks of the Caledonide orogen, and direct information about the underlying crust is restricted to a few unevenly distributed basement windows in western Sweden and Norway. In this study, we use preliminary results from the second borehole of the Collisional Orogeny in the Scandinavian Caledonides project (COSC-2), new gravity data, forward gravity, and magnetic modeling and interpretation of seismic reflection profiles to assess the 3-D architecture of the basement. Our results reveal a wide (~100 km) and dense network of mainly flat-lying and saucer-shaped dolerites intruding the volcanic and granitic upper crustal rocks of the Transscandinavian Igneous Belt. Similar intrusion geometries related to 1.2 Ga dolerites can be recognized in the Fennoscandian Shield. We discuss that the formation of these sill complexes occurred in a lithologically and structurally heterogeneous crust during transtension, which is in disagreement with the current understanding of sill emplacement that involves crustal shortening, layering, or anisotropy of the host rock. Our seismic interpretation and the structural observations from the COSC-2 drilling show that part of the Caledonian-related basement deformation was localized along the margins of the dolerite sheets. We propose that the dolerite intrusion geometry, akin to a flat-ramp geometry, guided the basement deformation during the Caledonian orogeny.

1. INTRODUCTION

The Fennoscandian Shield in central Sweden is composed of crust that developed during the Paleoproterozoic Svecofennian orogeny (>1.85 Ga) and which is bordered to the west, along the former continental margin, by granitoids and volcanic rocks of the ca. 1.86–1.65 Ga Transscandinavian Igneous Belt. Major transpressive shear zones with an extensive geologic history (1.85 Ga to <1.2 Ga) transect the area in a mainly NNW–SSE direction, including the Storsjön–Edsbyn Deformation Zone and the Hassela Shear Zone (Högdahl et al., 2004). In addition, different generations of Mesoproterozoic mafic intrusions responsible for local magnetic anomalies were mapped in the region (e.g., Gorbatschev et al., 1979, 1987; Söderlund et al., 2005; Greiling et al., 2007; Ripa and Stephens, 2020a). Toward the west, these features abruptly disappear beneath the Lower Allochthon unit of the Scandinavian Caledonides, which marks the present-day NNE–SSW-trending front of the Caledonide orogen (Fig. 1). In this area, the roughly NNE–SSW-striking Caledonian orogenic architecture and the underlying basement appear to be disrupted by the NNW–SSE-trending Grong-Olden basement window and the WNW–ESE-striking Persåsen fault (Fig. 1). However, with the exception of the geology in sporadic antiformal windows and forward gravity and magnetic models revealing the northwestward prolongation of the Transscandinavian Igneous Belt (e.g., Dyrelius, 1980, 1986; Elming, 1988; Skilbrei et al., 2002; Ebbing et al., 2012), little is known about the architecture of the basement beneath the Caledonian nappes and to what degree and in which manner it was affected by the Caledonian orogeny.

The Central Caledonian Transect (Hurich et al., 1989; Palm et al., 1991; Juhojuntti et al., 2001) seismic reflection profile was acquired across central Scandinavia, approximately on a line between Östersund in Sweden and Trondheim in Norway during the late 1980s (Fig. 1). The composite Central Caledonian Transect profile aimed to reveal the architecture of the Caledonian orogen from the foreland in the east to the hinterland in the west. Of particular interest is the depth to the sole thrust in the basement in order to outline the deformation front, both at depth and toward the foreland. It is analogous to the Main Frontal Thrust in the Himalaya-Tibet orogeny and was proposed to transfer the contractional deformation in the hanging wall of a major low-angle thrust fault toward the foreland (e.g., Palm et al., 1991; Gee et al., 2010). Between 2010 and 2015, a high-resolution reflection seismic profile was acquired parallel to a key section of the Central Caledonian Transect during site investigation for the Collisional Orogeny in the Scandinavian Caledonides (COSC) scientific drilling project (Hedin et al., 2012, 2014; Juhlin et al., 2016). This COSC composite seismic profile (CSP) and the Central Caledonian Transect reveal a complex pattern of prominent seismic reflectivity in the upper crust. The origin of these seismic reflections was debated, and interpretations involved either shear zones or mafic intrusions (Hurich et al., 1989; Hauser et al., 1990; Palm et al., 1991; Juhojuntti et al., 2001; Gee

---

Rodolphe Lescoutre https://orcid.org/0000-0002-8185-9110

[†] rodolphe.lescoutre@gmail.com.

[§] Present address: Department of Earth Sciences, Khalifa University, Abu Dhabi, UAE.

GSA Bulletin; November/December 2022; v. 134; no. 11/12; p. 3022–3048; https://doi.org/10.1130/B36202.1; 15 figures; 1 supplemental file.

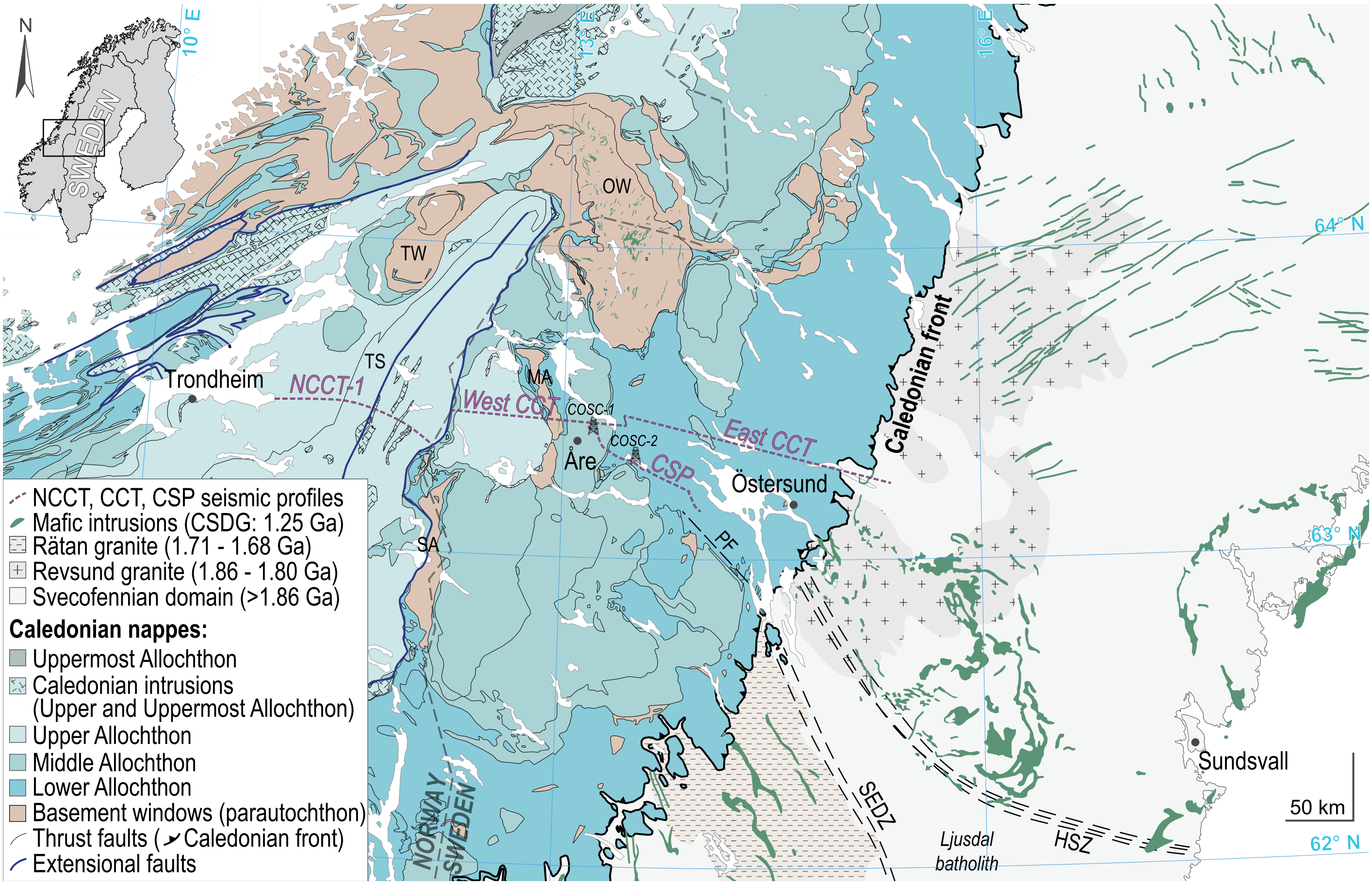


Figure 1. Geologic map of central Sweden and central Norway (modified after Robinson et al., 2014, based on the geologic maps of Lundqvist et al., 1996, and Koistinen et al., 2001) shows the main tectonic and lithological units as well as the location of the composite seismic profile (CSP), Central Caledonian Transect (CCT), and North-Central Caledonian Transect (NCCT)-1 seismic profiles and the Collisional Orogeny in the Scandinavian Caledonides project (COSC)-1 and COSC-2 drill sites. MA—Mullfjället antiform; OW—(Grong-)Olden window; PF—Persåsen fault; HSZ—Hassela Shear Zone; SA—Skardöra antiform; SEDZ—Storsjön–Edsbyn Deformation Zone; TS—Trøndelag synform; TW—Tømmerås window. Map projection: SWEREF99TM (EPSG:3006).

and Stephens, 2020a). The limitations related to the seismic resolution as well as the lack of a coherent geologic model able to discriminate the nature of these prominent seismic reflections hampered further interpretations. As a consequence, the characterization of the deformation related to the Caledonian orogeny, such as the depth of the sole thrust or the amount of crustal shortening in this part of the orogen, remains unsolved.

Two deep (~2.5 km), fully cored boreholes are located along the CSP (COSC-1 and COSC-2, drilled in 2014 and 2020, respectively). They were drilled to obtain a composite geologic profile from the high-grade metamorphic core of the Middle Allochthon through the Lower Allochthon and into the underlying basement of the Fennoscandian Shield. A distinct scientific target was to obtain in situ subsurface information to improve the geophysical interpretations and models. COSC-1 (Fig. 1) is located near the town of Åre and drilled through high-grade rocks of the lower part of the Middle Seve Nappe, where it revealed a substantial shear zone (>800 m of vertical thickness) near the contact between the Middle and Lower Allochthons (Lorenz et al., 2015). COSC-2, located ~20 km to the east, drilled through the sedimentary succession of the Lower Allochthon to determine the depth of the main Caledonian décollement and to define the nature of the seismic reflections in the underlying basement (Hedin et al., 2012; Juhlin et al., 2016, 2021).

The main results of the COSC-2 drilling project (Lorenz et al., 2021; Juhlin et al., 2021) reported in this study highlight the occurrence of a ~240-m-thick dolerite, whose margins are deformed, intruding the basement volcanic rocks. This mafic intrusion is responsible for one of the prominent seismic reflections that is sometimes interpreted as a thrust fault (see e.g., Juhlin et al., 2016). As such, in addition to providing critical information about the lithology of the basement beneath the Caledonian nappes in the central Scandinavian Caledonides (Jämtland region; western-central Sweden), COSC-2 results shed light on the possible origin of the seismic reflectivity pattern in the upper crust. In this study we aim to evaluate whether the seismic reflectivity of the basement can be mostly explained by the occurrence of thick dolerites and if this interpretation can help to reveal Caledonian orogenic structures in the crust. We use preliminary results from the COSC-2 drilling (main lithological units, structures, and geophysical data), combined with a new seismic interpretation, magnetic/gravity maps, and 2-D forward magnetic and gravity modeling, to test this hypothesis and propose a new geologic and tectonic model of the area. We show that, similar to what is observed in the Fennoscandian Shield to the east, the basement underneath the Caledonian nappes of central–western Sweden is composed of a dense and wide network of sills and saucer-shaped intrusions along which deformation at least partly localized during the Caledonian orogeny.

2. GEOLOGIC SETTING OF CENTRAL SWEDEN

2.1. The Caledonian Orogeny of the Scandinavian Caledonides

The Caledonian orogeny in the Scandinavian Caledonides starts with the closure of the Iapetus Ocean during the Late Cambrian to Ordovician and continues with the collision of the Laurentia and Baltica continents from the Silurian to Devonian (Fig. 2A). This large mountain belt (Fig. 2B) is often compared to the Alpine-Himalayan chain in terms of dimensions (Dewey, 1969) and tectonic evolution (Gee et al., 2010). In the Scandinavian Caledonides, the continent-continent collisional, or Scandian phase (430 Ma, e.g., Corfu et al., 2006), is characterized by the subduction of the extended margin of the Baltican crust beneath Laurentia and the formation of nappes in the collisional wedge. These nappes, whose origins extend from the hyperextended margin of Baltica (Jakob et al., 2019) to the Iapetus oceanic domains and the Laurentian margin, were displaced toward the SE and traveled as far as 700 km onto the Baltoscandian basement (Gee, 1978). Based on structural observations and geochronological data, a recent scenario (Fig. 2C) proposed by Bender et al. (2018, 2019) involves a double subduction of the Baltica rifted margin beneath the Iapetus volcanic arc and the Iapetus oceanic crust beneath the Laurentia continent, which led to a complex, out-of-sequence propagation of the orogenic wedge and eventually to the present metamorphic zonation of the nappe pile.

This nappe pile is divided into major tectonostratigraphic units that are, from top to bottom, the Uppermost, Upper, Middle, and Lower Allochthons (Gee et al., 1985; Roberts and Gee, 1985). They display variable degrees of metamorphism ranging from ultra-high–pressure eclogite in the Middle Allochthon (Seve nappe; Janák et al., 2013) to lower greenschist facies in the Lower Allochthon (Kisch, 1980). The Middle and the Lower Allochthons are derived from the inversion of the former Baltoscandian passive margin (e.g., Gee et al., 2013; Jakob et al., 2019). The Upper Allochthon is derived from the Iapetus Ocean, while the Uppermost Allochthon comprises rocks from the Laurentian margin (Gee et al., 2008). In the Upper and Middle Allochthons, Caledonian deformation is mostly expressed through localized deformation along ductile shear zones, large-scale nappe attenuation, and boudinage of the nappe units (e.g., Young, 2017; Bender et al., 2019). Toward the foreland, structures become more brittle, and deformation of the Lower Allochthon (including the parautochthonous basement) is mostly expressed by thrust duplexes and antiformal nappe stack, which is highlighted by N–S to NW–SE-trending basement windows (Fig. 1; e.g., Rice and Anderson, 2016). However, the amount of displacement of these parautochthonous basement rocks and their overlying Neoproterozoic to Cambrian sedimentary cover (e.g., Gee, 1978, 1980) is poorly constrained (e.g., Greiling et al., 2018; Gee and Stephens, 2020b). Among them, the Olden, Tømmerås, Skardöra, and Mullfjället windows show a low-grade metamorphic assemblage (generally lower to upper greenschist facies, although up to amphibolite facies in the westmost windows) and are affected by folding and local shear zones that are attributed to the Caledonian orogeny (e.g., Gee, 1980; Sjöström and Talbot, 1987; Stel, 1988; Lindqvist, 1990; Gee and Stephens, 2020b). The NNW–SSE-trending antiformal Olden window suggests that a significant orogenic imprint on the basement was made by the occurrence of a major thrust that deforms preexisting mafic intrusions and duplicates similar basement units over >100 km (Stel, 1988; Roberts, 1997). Along this thrust, a deformed and attenuated Ediacaran to Ordovician sedimentary cover is preserved (see the sediments of the Lower Allochthon between basement rocks in the Olden window in Fig. 1). Moreover, the basement and its sedimentary cover were folded and show a strong foliation parallel to the basement-cover interface (Gee, 1980; Sjöström and Talbot, 1987; Sjöström et al., 1996). Finally, syn- to post-orogenic W- to NW-dipping extensional detachment faults that cut across the allochthonous units were reported in various locations and were often associated with basement windows (e.g., Fossen and Rykkelid, 1992; Gee et al., 1994; Hurich and Roberts, 1997; Robinson et al., 2014).

The present-day Caledonian front generally represents the boundary between two distinct tectonic units: in the west, the allochthonous nappes and the parautochthonous basement windows, and in the east, the Fennoscandian Shield, where only little localized Caledonian deformation is known (Lindström et al., 1996). Along the Caledonian front (Fig. 1), the carbon-rich alum shales crop out. These rocks were deposited over a vast area of the Fennoscandian Shield in Cambrian time and are thought to function as the main Caledonian décollement in the external part of the orogen (Gee, 1978, 1980; Andersson et al., 1985).

2.2. Baltica Basement and Basement Windows

Main Lithological Units

In central Sweden, the Fennoscandian Shield is mainly composed of the 1.9–1.87 Ga Svecofennian metavolcanic and granitoid rocks and of ca. 1.86–1.67 Ga monzodiorites to granites of the Transscandinavian Igneous Belt (see details in Högdahl et al., 2004). Subsequently, Mesoproterozoic mafic dikes and sills of various generations have intruded these felsic suites (Fig. 3). The approximately N–S-trending Transscandinavian Igneous Belt (Figs. 1 and 3) comprises alkali-rich granitic plutons and felsic volcanic rocks such as the Revsund granitoid suite (Transscandinavian Igneous Belt-I, ca. 1.86–1.76 Ga; Claesson and Lundqvist, 1995; Delin, 1996; Högdahl, 2000), the Rätan batholith (Transscandinavian Igneous Belt-II, ca. 1.70–1.68 Ga; Wilson et al., 1985; Patchett et al., 1987; Delin, 1996), and the Dala porphyries and granites (Transscandinavian Igneous Belt-II, ca. 1.8–1.7 Ga; Lundqvist and Persson, 1996, 1999; Ahl et al., 1999). The rocks of the Transscandinavian Igneous Belt, and especially the Rätan granite, are the origin of the large magnetic anomaly known as the Jämtland anomaly (Dyrelius, 1980). This magnetic anomaly extends from the Dala Province (its geologic domain corresponds to the Transscandinavian Igneous Belt rocks located in the Sveconorwegian orogenic front in central Sweden; see Fig. 3) to the northwest below the Caledonian nappes and to the Grong-Olden window to the north.

The Rätan batholith appears in map view as a massive 50 km × 100 km large body surrounded by the rocks of the Dala Province to the south and the Svecofennian supracrustal rocks and the Revsund granite to the north (Mattsson and Elming, 2001b, 2001a). The limit between the Rätan granite and the Dala Province to the south appears either as a shear zone or as an intrusive contact, whereas the contact with the Ljusdal and Revsund granitoids to the north corresponds to the Storsjön–Edsbyn Deformation Zone (Bergman and Sjöström, 1994). The Rätan granite is described as a greyish-red, coarse-grained granitoid with subordinate medium-grained granite, which forms dikes and irregular bodies (Högdahl et al., 2004). Locally, to the north, the Rätan granite is intruded by monzodiorite and monzogabbroic rocks of the "Nordkölen belt," which appear as near-circular positive magnetic anomalies (see section 3.3; Gorbatschev, 1997; Högdahl et al., 2004). Structural measurements in the field and magnetic fabric orientation from

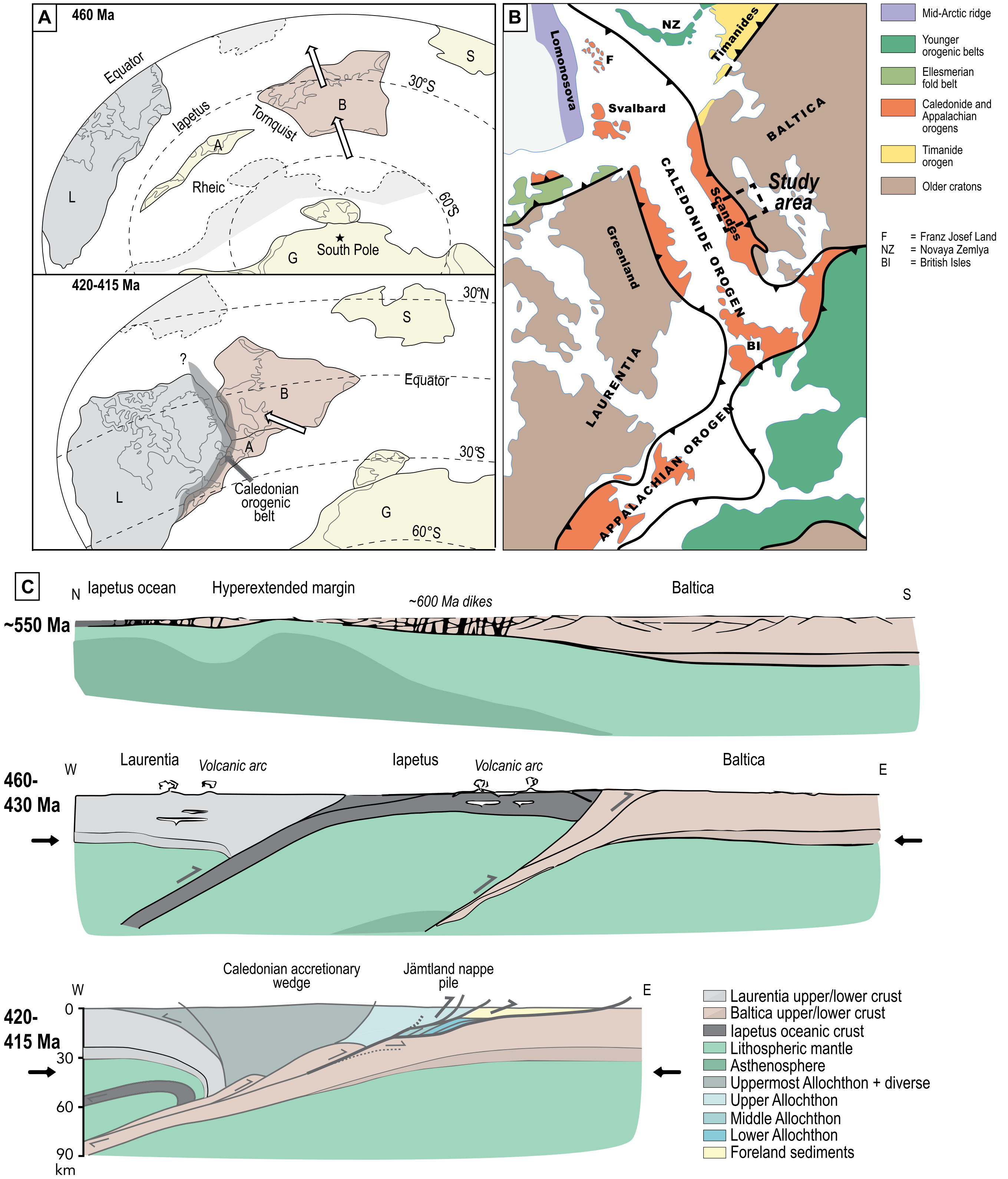


Figure 2. (A) Paleogeographic reconstruction of Baltica and Laurentia at 460 Ma and 420–415 Ma was modified after Corfu et al. (2014) and Cocks and Torsvik (2002). B—Baltica; L—Laurentia; G—Gondwana; S—Siberia; A—Avalonia. (B) The Caledonides at the end of the Mesozoic, prior to the opening of the North Atlantic, from Gee and Stephens (2020a) after Stephens (1988). (C) Schematic cross-sections show the tectonic evolution of Baltica and Laurentia before convergence (ca. 550 Ma) and during the formation of the Caledonian orogeny (460–430 Ma and 420–415 Ma). Modified after Bender et al. (2018, 2019).

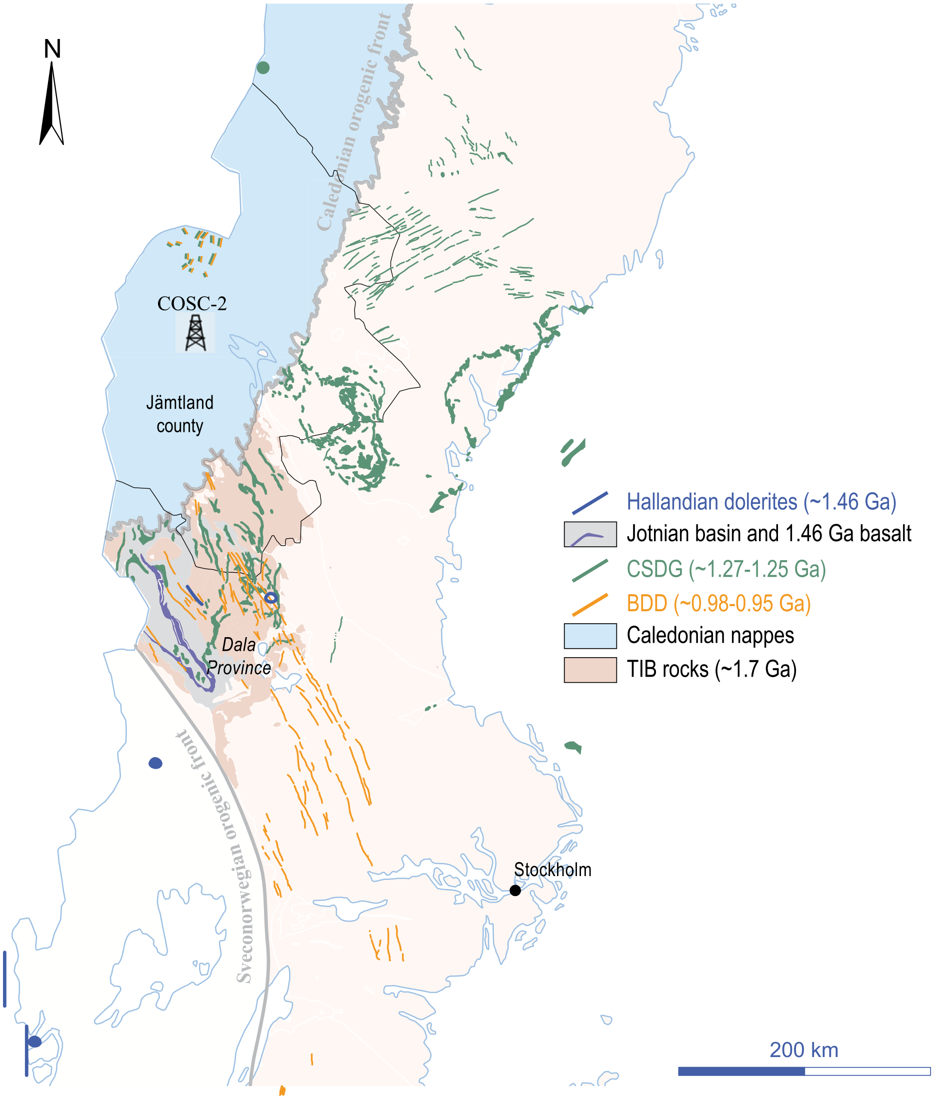


Figure 3. Distribution and age of major mafic intrusions in Central Sweden are shown. Rocks of the Transscandinavian Igneous Belt-II, the Jotnian basin in the Dala Province, and the location of the Collisional Orogeny in the Scandinavian Caledonides project (COSC)-2 borehole are also indicated. Location of the Hallandian Dolerites is from Brander and Söderlund (2009) and Brander (2011), Central Scandinavian Dolerite Group (CSDG) is from Ripa and Stephens (2020a), and the location of the Blekinge–Dalarna Dolerites (BDD) is from Ripa and Stephens (2020b). Dolerites west of the Caledonian front are from Johansson (1980) and Brander et al. (2011). Dolerites of the CSDG are widespread in Central Sweden, whereas the Blekinge–Dalarna Dolerites and the Hallandian Dolerites are mostly reported along the Sveconorwegian orogenic front and in the Dala Province, respectively. The age of the dolerites in Jämtland County west of the Caledonian front is unknown but likely related to the CSDG or the Blekinge–Dalarna Dolerites. Basemap is modified after Ripa and Stephens (2020a).

anisotropy of magnetic susceptibility (AMS) data suggest that the Rätan batholith formed in a transpressional regime along with NW–SE-directed magma flow (Bergman and Sjöström, 1994; Mattsson and Elming, 2001b; Bergman et al., 2006) that was potentially related to back-arc oblique subduction during an early stage of the Gothian orogenic event (1.75–1.55 Ga; Gorbatschev and Bogdanova, 1993; Bergman et al., 2006).

Volcanic porphyries and granites (ca. 1.7–1.6 Ga; Roberts et al., 1999) were observed in basement windows such as in the Olden, Tømmerås, Skardöra, and Mullfjället windows (Fig. 1; Beckholmen, 1978; Gee, 1980; Roberts, 1997). They occur locally as basement slices such as the Östberget porphyries near Östersund and the Caledonian front (Fig. 1; Karis et al., 1998), but with the exception of the Dala porphyries, they have not been described east of the Caledonian front (Fig. 1). These trachytic, porphyritic felsic volcanic rocks, which appear as fine- to medium-grained and are greyish to pink in color, are similar in composition to the ca. 1.7 Ga porphyries of the Dala Province (Roberts, 1997; Lundqvist and Persson, 1999). Their age and chemistry, similar to the Transscandinavian Igneous Belt, suggest a formation nearly coeval with the Dala suite, the Rätan granite, and the activity along the Storsjön–Edsbyn Deformation Zone (Lundqvist and Persson, 1996; Högdahl et al., 2004; Bergman et al., 2006).

Mafic Intrusions

Previous studies have revealed several generations of dolerite intrusions in central Sweden, both in the autochthonous Fennoscandian crust and in the basement windows of the Caledonian nappes (Fig. 3). These can be grouped into separate tectonic events based on age, distribution, and chemistry, as described below from oldest to youngest.

The ca. 1.46 Ga Hallandian dolerites (Fig. 3) occur as fine-grained dikes or sills that locally contain abundant plagioclase megacrysts. In central Sweden, they mostly crop out in the Dala Province (Fig. 3), where they are referred to as the Tuna dolerites and appear as <1-m-thick, N–S- to NE–SW-trending dikes (Söderlund et al., 2005). Other 1.46 Ga mafic intrusions were recognized throughout Sweden and Norway (Brander and Söderlund, 2009), but a clear trend or cluster for their emplacement was not revealed. Based on the age and chemistry of the intrusions, the emplacement of the Hallandian dolerites was proposed to occur in an extensional regime during the Hallandian orogeny (Bingen et al., 2008; Brander, 2011). The latter corresponds to an ill-defined orogenic event that took place between 1.47 Ga and 1.42 Ga to the south-southwest of Fennoscandia and is mainly characterized by granitic magmatism and metamorphism in southeastern Sweden (e.g., Bingen et al., 2008; Brander, 2011). In central Scandinavia, this period is characterized by the deposition of the Jotnian sandstones interbedded with basalt flows (Fig. 3) and was proposed to occur in conjunction with back-arc extension and sag basin formation (Lundmark and Lamminen, 2016) related to northward subduction (e.g., Brander, 2011; Ulmius et al., 2015).

The mildly alkaline mafic intrusions of the Central Scandinavian Dolerite Group (ca. 1.27–1.25 Ga; Gorbatschev et al., 1979) are characterized by medium- to fine-grained rocks of (sub-)ophitic texture and are mainly composed of plagioclase, augite, olivine, biotite, ilmenite, and magnetite (e.g., Elming and Mattsson, 2001). They occur mostly in central Sweden and SW Finland (Fig. 3) and were assigned to five complexes based on slightly different U-Pb baddeleyite ages and spatial distribution (Söderlund et al., 2006): the 1264–1271 Ma Dalarna complex; the 1256–1259 Ma Västerbotten, Ulvö, and Satakunta complexes; and the ca. 1247 Ma Jämtland complex. The Central Scandinavian Dolerite Group intrusions crop out in the porphyries and granites of the Transscandinavian Igneous Belt and Svecofennian domain (Högdahl and Sjöström, 2001), in the Jotnian basins east of the Caledonian front (Bylund and Elming, 1992; Korja et al., 2001; Elming and Mattsson, 2001; Hogmalm et al., 2006), and in basement windows (Brander et al., 2011). They appear as sills that are meter-scale to several hundreds of meters thick and up to a hundred kilometers long, and less often as dikes or lopoliths; they may form saucer-shaped intrusions as observed in the Bothnian Sea (Korja et al., 2001; Buntin et al., 2019). Magmatic signature, age, and mode of emplacement of the Central Scandinavian Dolerite Group have favored the interpretation of a back-arc context in relation to a retreating slab located further west and off the margin of Baltica (Söderlund et al., 2005, 2006; Brander et al., 2011). However, intracratonic rifting related to the break-up of the supercontinent Columbia or a mantle plume hotspot have also been proposed as settings for their formation (see Ripa and Stephens, 2020a, and references therein).

The Blekinge–Dalarna Dolerites (ca. 0.98–0.95 Ga) show similarities in size and mineralogy to those of the Central Scandinavian Dolerite Group, but they are less alkaline and generally contain hypersthene (Gorbatschev et al., 1987; Solyom et al., 1992). Some of the Blekinge–Dalarna Dolerites suffered low-grade greenschist metamorphism (Johansson and Johansson, 1990). They were emplaced during the early Tonian (ca. 0.98–0.95 Ga) and intrude Svecofennian and Transscandinavian Igneous Belt rocks parallel to and eastward of the 700-km-long Sveconorwegian orogenic front in Sweden until they disappear beneath the Caledonian front in the Dala Province (Fig. 3; Bylund and Elming, 1992; Solyom et al., 1992; Patchett et al., 1994; Söderlund et al., 2005). They mostly appear as subvertical dikes that trend north to northwest (Johansson and Johansson, 1990). Due to their spatial and temporal relationship to the ca. 1 Ga Sveconorwegian orogeny, it was suggested that their formation is related to late Sveconorwegian fracturing of the foreland basement due to uplift and exhumation of high-grade metamorphic rocks further west (Johansson and Johansson, 1990; Söderlund et al., 2004).

While these different generations of dolerite intrusions were recognized east of the Caledonian front from geologic mapping and aerial magnetic surveys by the Swedish Geological Survey, the knowledge of their westward extension underneath the Caledonian nappes remains limited to a few field studies in basement windows (e.g., Johansson, 1980; Brander et al., 2011). In the present study area, altered and deformed intrusions in the Olden and Tømmerås parautochthonous basement windows were proposed to belong to the Central Scandinavian Dolerite Group and/or to the Blekinge–Dalarna Dolerites based on geochemical characterization (Johansson, 1980).

Main Structures in Central Sweden

The main structural features in the Baltica basement appear to be the NW–SE- to WNW–ESE-trending Storsjön–Edsbyn Deformation Zone and Hassela Shear Zone (Fig. 1). The former lies mainly between the Rätan granite and the upper crustal rocks of the Svecofennian domain (especially the Ljusdal batholith), while the Hassela Shear Zone delimits the Ljusdal batholith from the metasedimentary and metavolcanic rocks of the Bothnian basin to the north (see details in Bergman and Sjöström, 1994, and Högdahl and Sjöström, 2001). The Hassela Shear Zone corresponds to a steep transpressive dextral shear zone with main ductile activity bracketed between 1.85 Ga and 1.82 Ga (Delin, 1993; Welin et al., 1993; Claesson and Lundqvist, 1995; Högdahl and Sjöström, 2001). On magnetic and geologic maps, the Storsjön–Edsbyn Deformation Zone appears as a 10–20-km-wide and >200-km-long dextral shear zone that affects the Baltica basement (Högdahl et al., 2004; Bergman et al., 2006). While ductile to brittle structures are clearly recorded in the Svecofennian rocks and the Revsund granites within the deformation zone (Högdahl and Sjöström, 2001; Bergman et al., 2006), the nature of the contact (intrusive and/or tectonic) between these rocks and the Rätan granite is ambiguous. In detail, a minimum of four different phases of deformation of different ages (1.85–1.8 Ga, 1.674 Ga, <1.6 Ga, and <1.2 Ga), metamorphic grade, mineral composition, magnetic susceptibility, and deformation mechanisms are described (Bergman et al., 2006, and references therein). While the oldest transpressive shearing along the Storsjön–Edsbyn Deformation Zone and Hassela Shear Zone (1.85–1.8 Ga) may be synchronous to, or followed shortly after, the intrusion of the Revsund granitoids (Högdahl and Sjöström, 2001), the 1.674 Ga deformation along the Storsjön–Edsbyn Deformation Zone could be coeval with the emplacement of the Rätan batholith and the volcanic porphyries of the Dala Province (Bergman et al., 2006). Field observations and mapping show that the Central Scandinavian Dolerite Group (ca. 1.27–1.25 Ga) truncates the mylonites of the Storsjön–Edsbyn Deformation Zone and provides a maximum age for the activity of the shear zone (Mattsson and Elming, 2001b; Bergman et al., 2006). Yet, deformation related to the Caledonian orogeny along the Storsjön–Edsbyn Deformation Zone was proposed based on U/Pb zircon geochronology, whose age of 384 ± 15 Ma and Pb loss was attributed to warm, saline fluid circulation in relation to basement faulting (Högdahl et al., 2001). Moreover, the WNW–ESE-trending Persåsen fault (Fig. 1), which deforms the Upper Ordovician sediments of the Lower Allochthon, was suggested to be related to the westward continuation of the Storsjön–Edsbyn Deformation Zone underneath the Caledonian nappes (e.g., Bergman et al., 2006; Gee and Stephens, 2020b). However, questions remain about the westward extension of the Storsjön–Edsbyn Deformation Zone and Hassela Shear Zone underneath the Caledonian nappes.

3. OBSERVATIONS

3.1. Principal Observations from the Composite and the Central Caledonian Transect Seismic Profiles

Details concerning the acquisition and processing parameters for the Central Caledonian Transect profile are presented in Juhojuntti et al. (2001) and for the CSP profile in Hedin et al. (2012) and Juhlin et al. (2016). Data were acquired along the Central Caledonian Transect in three stages using a dynamite source in the west and a vibrator source for the two eastern stages. Standard common midpoint (CMP) processing was applied with a focus on obtaining good static corrections and careful velocity analysis to provide the most coherent images of reflections. The CSP profile was also acquired in three stages with a hydraulic rock-breaking hammer being used as a source in the first two stages and a 400 kg weight drop mounted on a mini-loader for the last stage. Again, standard CMP processing was applied to the data with a focus on statics and velocity analysis. The sources used for the CSP are weaker than those for the Central Caledonian Transect, but signal penetration is generally good down to at least 3 s two-way time, except for on the easternmost part of the CSP. Velocity analysis showed that the velocity generally increases from ∼5500 m/s in the shallowest parts to ∼6000 m/s at 2–3 s two-way time. Based on this and sonic logging in the COSC-2 borehole, a 1-D velocity function was used for both migration and depth conversion of the data.

Two uncertainties to consider regarding the interpretation of the Central Caledonian Transect and CSP profiles are 3-D and migration effects in the images. Juhlin et al. (2016) showed, by processing the CSP data along different 2-D lines and comparison between the Central Caledonian Transect and CSP profiles, that the structure is reasonably 2-D east of the COSC-2 borehole. Likewise, a profile perpendicular to the CSP profile in the COSC-1 area also shows that the CSP is running approximately perpendicular to strike. Therefore, we consider it reasonable to use the CSP and Central Caledonian Transect profiles as dip lines in the interpretation even though there may still be some minor 3-D effects in the images. During processing, different 1-D velocity functions were tested for migration. These varied by within ± 10% compared to the one actually used. Resulting images showed better focusing on some parts of the profile and poorer focusing on other parts when the function was varied. However, the general structure and offsets in seismic reflections did not change significantly. Therefore, we have some confidence that the offsets we observe in reflections are reasonable representations of true offsets.

Both the CSP and Central Caledonian Transect profiles (Figs. 4A–4B; see location in Fig. 1) display a continuous, shallow, and subhorizontal reflection that is interpreted as the main Caledonian décollement; it is detached in the Cambrian alum shales at its stratigraphic occurrence (see décollement level in Figs. 4A–4B). The depth of the Cambrian alum shale was indirectly inferred on the CSP (Fig. 4A) and the East Central Caledonian Transect (Figs. 4B–4C) profiles based on magnetotelluric and reflection seismic data (Korja et al., 2008; Juhlin et al., 2016; Yan et al., 2017a, 2017b). Underneath the Caledonian nappes, continuous reflections are recognized that are generally hundreds of meters thick and stand out from the relatively transparent seismic background. Roughly parallel double reflections are also observed, in particular on the more recent CSP (e.g., q1 in Figs. 4A–4B). Near the COSC-2 borehole, the upper and lower reflections are of opposite polarity, which is consistent with the double reflection at this location originating from a contrasting impedance layer relative to the more homogeneous host rock. The reflections are gently dipping toward the west on the CSP and East Central Caledonian Transect profiles. In detail, it is possible to recognize a set of flat-lying reflections that often, but not always, appear steeper in the east and become sub-horizontal toward the west. Some of these oblique, west-dipping reflections display a sigmoid shape (e.g., q2 in Figs. 4A–4B). Locally, some sub-horizontal reflections are vertically offset across steeper reflections (e.g., q3 in Fig. 4A). The West Central Caledonian Transect profile shows sub-horizontal to gently east-dipping, locally kinked reflections. On the East Central Caledonian Transect profile (Fig. 4B), a ~40-km-wide, dome-like structure can be recognized underlying thick, prominent reflections that mimic the dome shape (q4 in Fig. 4B). A west-dipping reflection that reaches the surface just east of the dome was interpreted as a dolerite of the Central Scandinavian Dolerite Group and is mapped at the surface (Juhojuntti et al., 2001). Other large, dome-shaped reflections can be observed at very shallow depth in the center of the Central Caledonian Transect profile (e.g., q5 in Fig. 4B). Exactly at 80 km along the Central Caledonian Transect profile (Fig. 4B), this reflection seems to merge with a flat-lying reflection that was formerly attributed to the Cambrian shale décollement (Gee et al., 2010). At ~50 km, between 0 km and 8 km depth, the gently west-dipping reflections rotate upward and appear to be disrupted across a seismically blurred and thin vertical zone that has a droplet shape (q6 in Fig. 4B). Most of the gently west-dipping reflections vanish on the easternmost part of the CSP (from 47 km eastward in Fig. 4A) possibly due to attenuation of the signal by soft sedimentary cover at the surface during seismic acquisition (Juhlin et al., 2016).

In Figure 4C, the velocity model of England and Ebbing (2012), which was computed using receiver functions, is overlain onto the North Central Caledonian Transect/Central Caledonian Transect profiles. The velocity model shows a seismic Moho at ~43 km depth across most of the North Central Caledonian Transect/Central Caledonian Transect profiles. It also highlights a ~10-km-thick lower crust of very high velocity (7.2 km/s) in the eastern part of the profile. Along this high velocity lower crust, a continuous layer extends from 120 km eastward up to the coast of the Bothnian Sea. A separate body between 45 km and 85 km can be distinguished that shifts the velocity boundaries within the middle crust upward.

3.2. Preliminary Results from the COSC-2 Drilling Project

Geologic Description

Preliminary results from the COSC-2 borehole and a first-order interpretation of the CSP are presented in Figures 5A and 5B, respectively. Geologic observations rely on the on-site observations of the authors while drilling (see Lorenz et al., 2021). (A detailed core description is delayed due to the pandemic.) Drilling penetrated the sedimentary cover of the Jämtland supergroup (Gee, 1975b) corresponding to the Lower Allochthon and the porphyries of the (para-)autochthonous basement (Karis et al., 1998). The uppermost ~800 m consist of greywackes and turbidites of the Ordovician–Silurian flysch, which were affected by apparent small-offset, low-angle faults. These units are underlain by ~45 m of strongly deformed dark to black shales with carbonate lenses, which are interpreted as the Cambrian Alum Shale Formation. Below the alum shales, the borehole penetrated a volcano-sedimentary sequence characterized by tuff, coarse-grained sandstones, and conglomerates that were affected by brittle deformation (tectonic breccias and low-angle faults), most likely of Neoproterozoic to Early Cambrian age and equivalent to the Ediacaran–Early Cambrian quartzites of the Sjoutälven Group (Gee et al., 1974; Gee and Stephens, 2020b). At ~1220 m, a zone of brittle deformation marks the transition to volcanic porphyries, which consist of a greyish, very fine-grained matrix containing millimeter-sized mafic xenoliths (e.g., epidote and pyroxene). These porphyries appear to be similar to those encountered in the Mullfjället window ~40 km to the west of the drill site and in basement slices near the Caledonian front (see Östberget porphyries in section 2.2). The porphyry is affected by at least two generations of fractures, which occur as low-angle and steep fractures filled with quartz and/or calcite. Mafic intrusions of a few decimeters thick interrupt the porphyries from ~1300 m down to ~1600 m (see thin green lines in Fig. 5), where a thicker ~240-m-thick dolerite is located. At the base of the thick dolerite, two units of ~4-m-thick porphyries are separated in apparent tectonic contact by a thin layer of dolerite. Below, a ~80-m-thick dolerite occurs and is underlain by porphyries that continue to a total depth of 2276 m and is interrupted only by a single-meter-thick mafic intrusion at 2140 m. Among the dolerites, the smaller intrusions appear generally as greenish and very fine-grained rocks, whereas the core of the thicker intrusions generally displays either plagioclase needles and pyroxenes (subophitic to ophitic texture) with locally abundant very coarse feldspar megacrysts or phaneritic to pegmatitic gabbros. The contacts between the porphyries and the thin dolerites often appear as chilled margins. However, sharp tectonic contacts characterized by (semi-)brittle deformation (cataclastic zones and mylonites) of the porphyries and the dolerite margins are also observed (Fig. 6).

Density and Magnetic Susceptibility of Lithological Units

The magnetic susceptibility was measured as part of the COSC-2 downhole survey and is available in the related project data set (Lorenz et al., 2021). The density was measured on drill cores using the Geotek multi-sensor core logger (MSCL; Lorenz et al., 2021). The Ordovician–

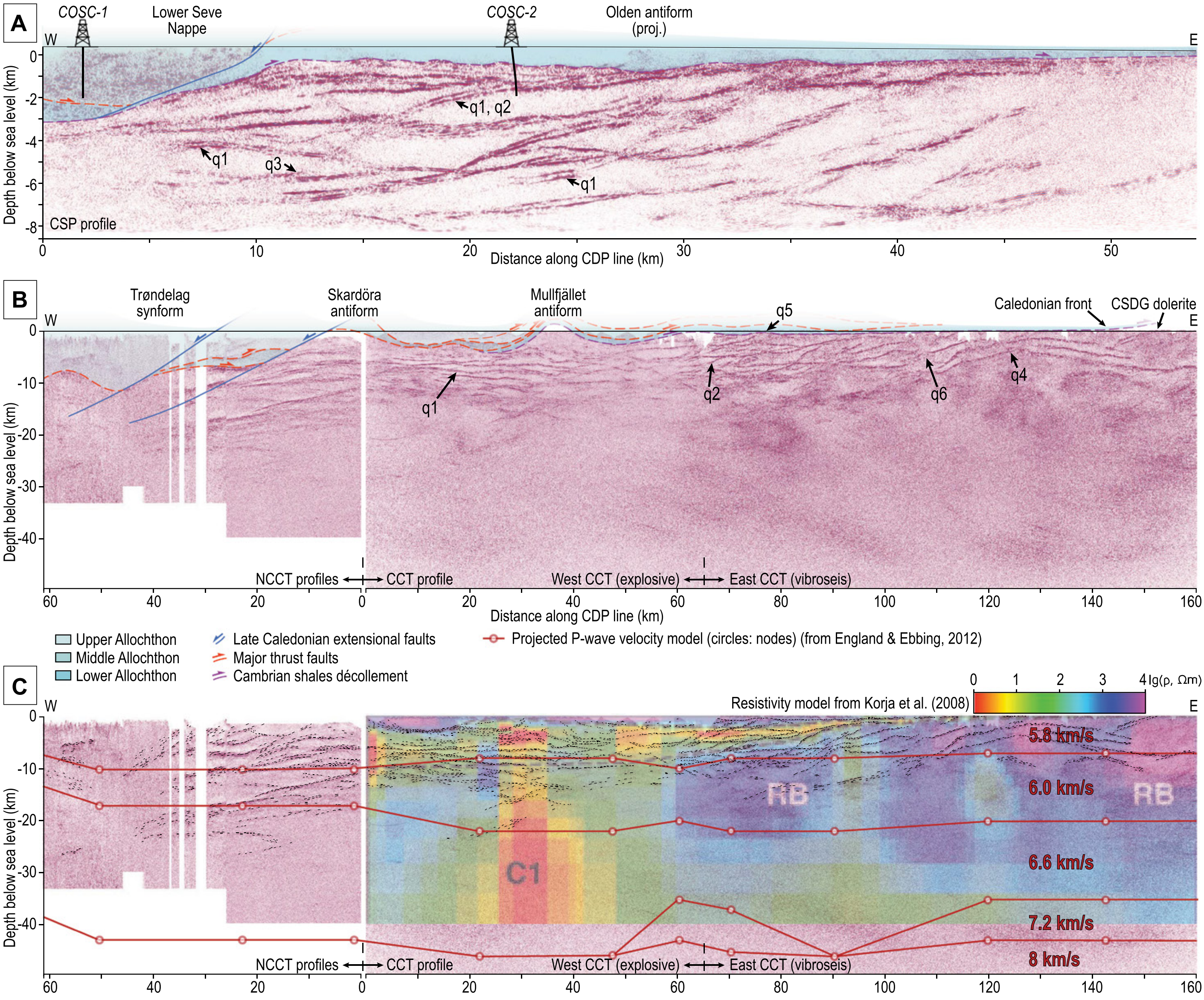


Figure 4. (A) Composite seismic profile (CSP) and (B) Central Caledonian Transect (CCT)/North Central Caledonian Transect (NCCT) seismic profiles with main Caledonian units are shown (after Palm et al., 1991; Hurich, 1996; Juhojuntti et al., 2001; Juhlin et al., 2016). The Collisional Orogeny in the Scandinavian Caledonides (COSC)-1 and COSC-2 project boreholes are projected onto the composite seismic profile (CSP). Labels q1, q2, etc., are discussed in the text. Label q1 shows parallel double reflections; q2 shows west-dipping, sigmoid-shaped reflections; q3 indicates vertically offset sub-horizontal reflections; q4 and q5 show seismic reflections that display a dome shape on the Central Caledonian Transect profile.; q6 indicates the location of a seismically blurred zone. See text for further explanations. The depth migration of the CSP was updated based on the seismic velocity (Vp) measurements acquired during the COSC-2 downhole logging (Lorenz et al., 2021). (C) The velocity profile of England and Ebbing (2012) and the resistivity model of Korja et al. (2008) are overlain on the CCT/NCCT profiles. The resistivity model reveals the depth of the Cambrian alum shales (top of the conductive layer). C1 and RB correspond to conductive and resistive bodies, respectively, identified by Korja et al. (2008). CSDG—Central Scandinavian Dolerite Group.

Silurian succession has a density of 2.77 g/cm^3 and a magnetic susceptibility <0.001 SI, whereas the highly deformed Cambrian alum shales have a lower density of 2.68 g/cm^3 and similar low magnetic susceptibility of <0.001 SI (Fig. 5A). The Neoproterozoic tuffs show a higher density in the sandstone-rich upper unit (~2.75 g/cm^3) than in the conglomerate-rich lower unit (~2.68 g/cm^3), but the two units have indistinguishable magnetic susceptibility, which is in general <0.002 SI. The density and magnetic susceptibility of the porphyries are rather low with a 2.68 g/cm^3 mean of the former and the latter ranging from 0.001 SI up to ~0.005 SI, in accordance with the reported values of Elming (1980) for the Skardöra, Olden, and Mullfjället basement window porphyries. The ~240-m-thick dolerite has an average magnetic susceptibility of ~0.06 SI with decreasing values toward its upper margin. However, thinner intrusions such as the 80-m-thick dolerite (1860–1940 m depth) show lower magnetic susceptibilities (<0.002 SI) with only locally high peak values. Density is similar for all dolerites at, on average, 2.91 g/cm^3.

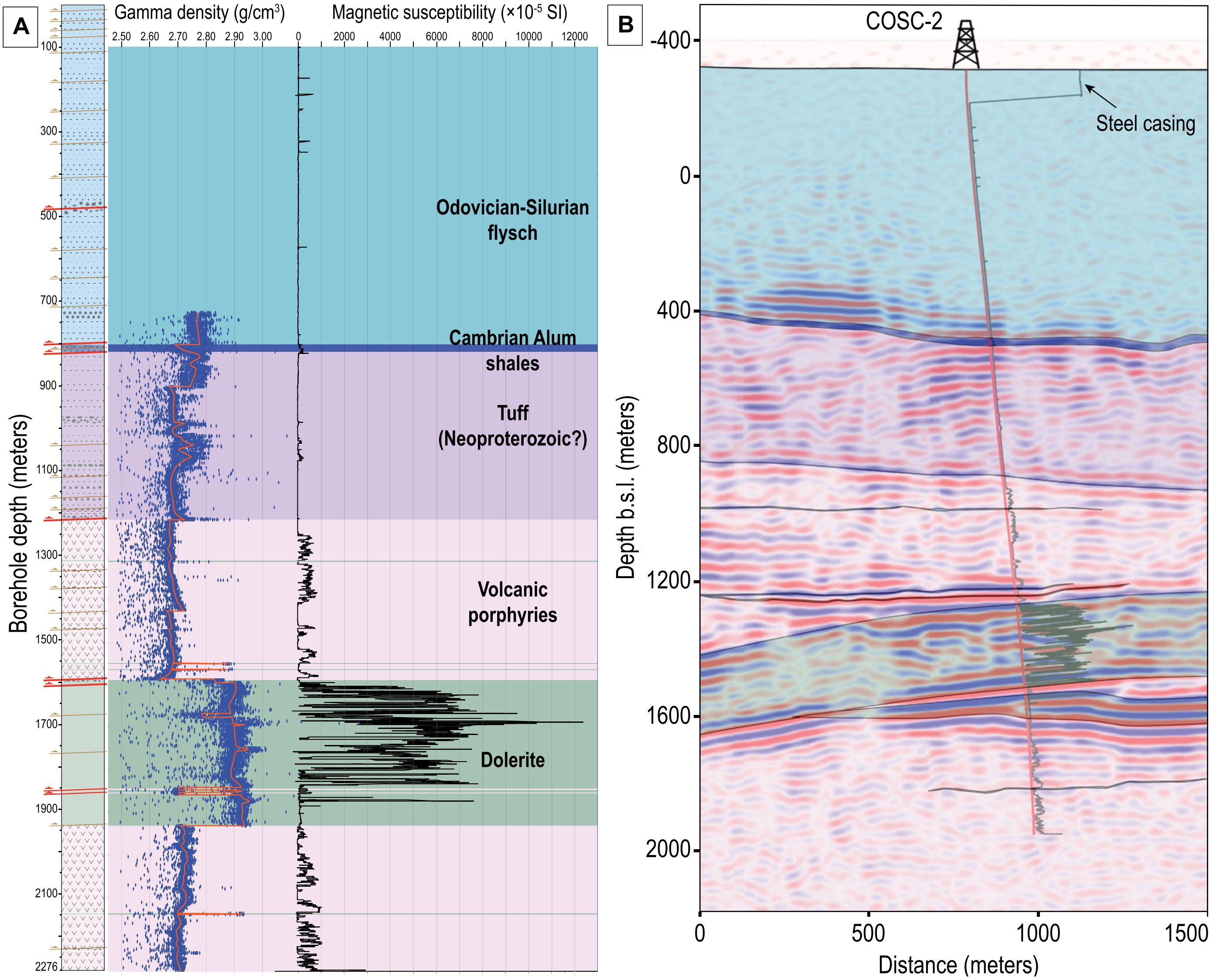


Figure 5. (A) Preliminary geologic log is based on the drill core description as well as related magnetic susceptibility and gamma density measured by downhole logging and on core samples, respectively. Note the high magnetic susceptibility and density associated with the dolerites. (B) Close-up view and first-order interpretation of the composite seismic profile (CSP) at the location of the Collisional Orogeny in the Scandinavian Caledonides (COSC)-2 project borehole. Structures are omitted for simplification. The true deviation of the borehole with the magnetic susceptibility log were projected onto the CSP. Note the very good correlation between the main seismic reflections and the lithological boundaries identified.

3.3. Gravity and Magnetic Anomalies and New Gravity Data Along the CSP

The aeromagnetic and gravity potential field data used to produce the maps presented in Figures 7B–7D are provided by the Swedish Geological Survey (SGU; https://www.sgu.se). The gravity measurements were acquired between 1975 and 2014 by different organizations and compiled by the Swedish Geological Survey. Based on these data, the Bouguer anomaly map (Fig. 7B) was calculated in the reference field RG82. The aeromagnetic data were acquired in several campaigns between 1969 and 2006 (Table S1[1]). The Definitive Geomagnetic Reference Field (DGRF 1965.0) was subtracted from the aeromagnetic data by the Swedish Geological Survey. The Oasis Montaj software (https://www.seequent.com/products-solutions/geosoft-oasis-montaj/) was used for processing. The magnetic data were gridded using a minimum curvature interpolation method with a node spacing of 200 m. A reduction to the pole was applied to the magnetic anomaly map to correct for the distortion of magnetic anomalies caused by the inclination and declination of the Earth's magnetic field. Subsequently, the 0.5 vertical derivative of the pole-reduced magnetic field was calculated (Fig. 7D). The fractional vertical derivative (i.e., 0.5) was used because first-

---

[1] Supplemental Material. Table S1: Acquisition parameters and spatial extent of various aeromagnetic surveys compiled by the SGU from the Jämtland, Västernorrland and Gävleborg counties (central Sweden); Table S2: Gravity measurements along the COSC Composite Seismic Profile (Jämtland county, Sweden). Please visit https://doi.org/10.1130/GSAB.S.19067159 to access the supplemental material, and contact editing@geosociety.org with any questions.

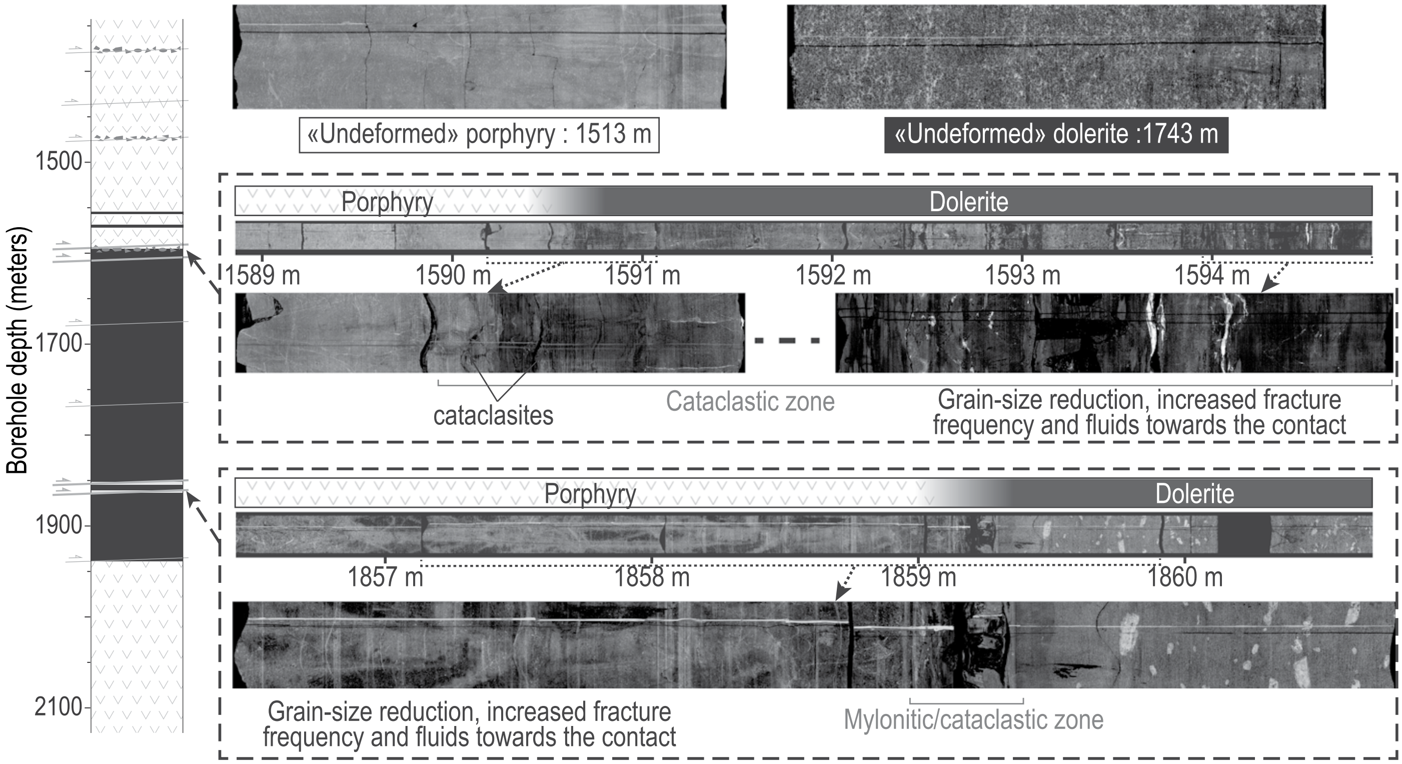


Figure 6. Core scan pictures from the Collisional Orogeny in the Scandinavian Caledonides (COSC)-2 project drilling show the deformation along the dolerite margins at ~1591 m and ~1859 m. Deformation (fractures, fluids, and grain-size-reduction) increases toward the contacts between the dolerites and the host rock (porphyries), and the contacts show mylonitic/cataclastic zones. Core scan pictures of "undeformed" dolerite and porphyry away from the contacts are shown for comparison.

and second-order derivatives led to significant noise on the resulting map. As with the first- or second-order derivatives, the fractional vertical derivative delineates high-frequency magnetic anomalies and highlights linear features such as faults or dikes (Dentith and Mudge, 2014; Brahimi et al., 2020).

The magnetic anomaly map (Fig. 7C) can be divided into two regions of contrasting magnetic intensity: a low-amplitude magnetic domain corresponding to the Svecofennian basement and the Revsund granite to the northeast and a high-amplitude magnetic domain corresponding to the rocks of the Transscandinavian Igneous Belt (e.g., Rätan granite) to the southwest. The gravity map (Fig. 7B) shows gravity lows west of the Caledonian front and in particular over the basement windows (e.g., Olden and Mullfjället). East of the Caledonian front, a major WNW–ESE-trending low gravity anomaly can be observed over the trace of the Hassela Shear Zone and Storsjön–Edsbyn Deformation Zone. This zone also corresponds to a magnetic low with locally elongated magnetic highs that trend parallel to the shear zone. Within the Rätan batholith, density and magnetic values can vary (see also Mattsson and Elming, 2001a). Local, round, very high magnetic and gravity anomalies (e.g., N1 in Figs. 7B and 7D) related to the monzodiorite and monzogabbroic rocks of the "Nordkölen belt" are observed to the north of the Rätan body (Gorbatschev, 1997; Högdahl et al., 2004). Anomalies showing similar size, shape, and magnetic and gravity amplitudes ($\sim$600 nT, $\sim$10 mGal) are recognized west of the Caledonian front (e.g., N2 and N3 in Fig. 7D). Within the Fennoscandian Shield, thin and elongated magnetic anomalies (e.g., D1) with amplitudes that vary from 100 nT to more than 400 nT are observed. These correspond to Central Scandinavian Dolerite Group dolerites that have been mapped at the surface (Figs. 7A and 7C–7D). West of the Caledonian front, elongated N–S to NE–SW magnetic anomalies can be observed as highlighted by the L anomalies (L1–L4) in Figure 7D. Although obscured to the north by very high magnetic anomalies (N3 and similar), the L3 and L4 lineament anomalies, and to a lesser degree the L2 anomaly, appear to form a gentle arc that bends toward the east. On the gravity map, the trace of the L2 magnetic lineament corresponds to the western boundary of a N–S-trending gravity low, which appears to terminate across the trace of the Persåsen fault to the south and along the western limb of the Olden antiform to the north (Figs. 7A–7B).

To investigate the shallow structure of the crust, new gravity measurements were acquired along the CSP (Figs. 8 and S2; see footnote 1). Measurements were conducted using a Scintrex CG5 relative gravimeter with a global navigation satellite system (GNSS) and real-time kinematic positioning. Recordings were subjected to a standard processing scheme using GravProcess (Cattin et al., 2015) and computed with a reduction density of 2670 kg/m^3. The data set's accuracy is mainly related to the vertical accuracy of the GNSS positioning system and does not exceed 0.2 mGal (Fig. S2; see footnote 1).

4. POTENTIAL FIELD MODELS

4.1. Pre-existing Models

The first magnetic models in central–western Sweden were presented by Dyrelius (1980), who attempted to model the large Jämtland anomaly based on a set of parallel, E–W-striking profiles. This study suggested that a thick ($>$10 km), asymmetric and highly magnetic ($\sim$0.075 SI) body needs to be introduced to account for the

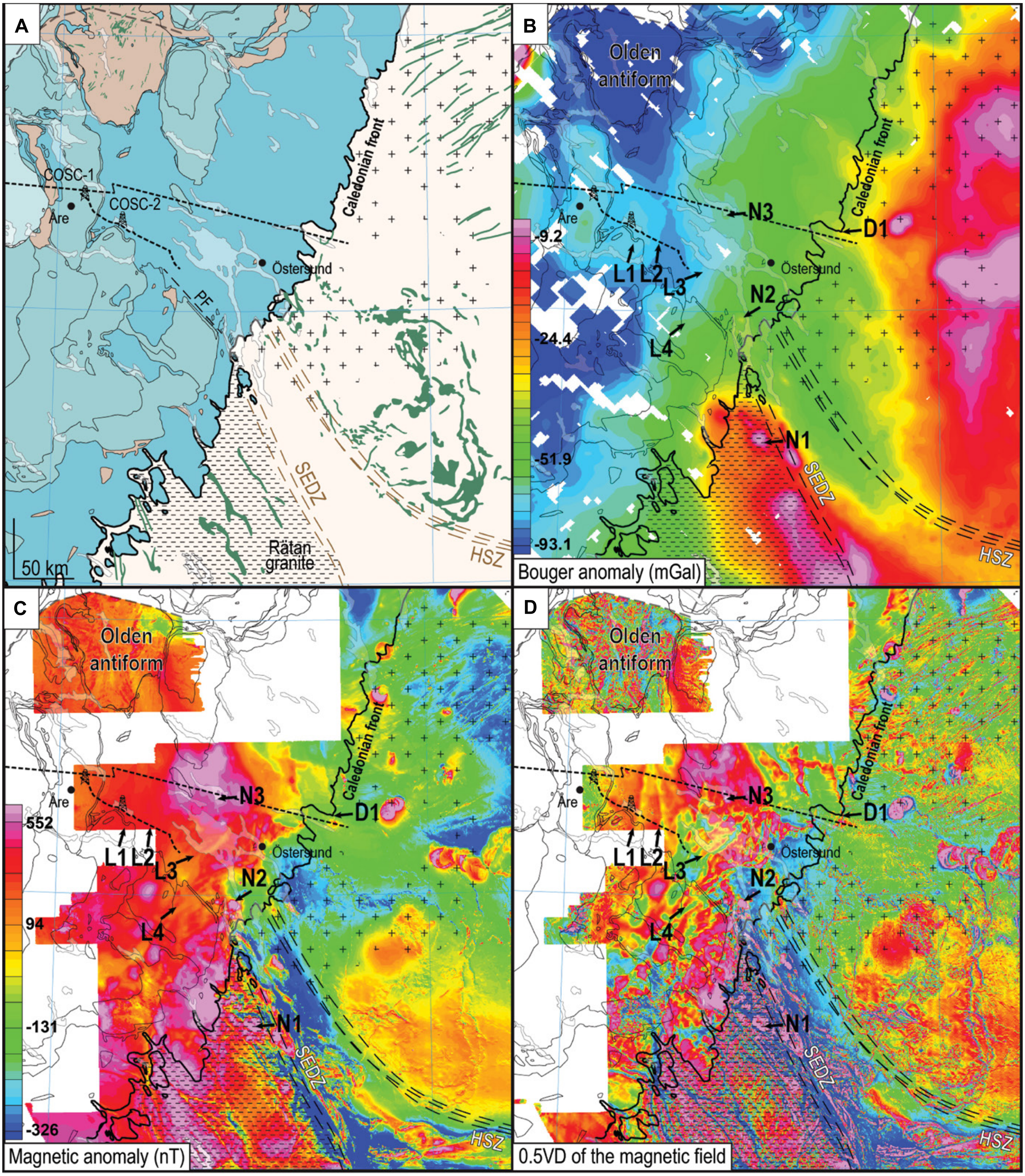


Figure 7. Maps of central Sweden are shown. (A) Geologic, (B) Bouguer gravity anomaly, (C) magnetic anomaly, and (D) 0.5 vertical derivative of the magnetic field. Note the change in the intensity of the magnetic and gravity anomalies across the Storsjön–Edsbyn Deformation Zone and the continuation of the Transscandinavian Igneous Belt-related positive magnetic anomaly (Jämtland anomaly) beneath the Caledonian nappes. East of the Caledonian front and north of the Hassela Shear Zone, the dolerites of the Central Scandinavian Dolerite Group mapped in Figure 7A (in green) are clearly apparent on the magnetic map in panel D. Magnetic and gravity anomalies L1, L2, L3, L4, N1, N2, N3, and D1 are discussed in the text. COSC—Collisional Orogeny in the Scandinavian Caledonides boreholes; SEDZ—Storsjön–Edsbyn Deformation Zone; HSZ—Hassela Shear Zone; PF—Persåsen fault.

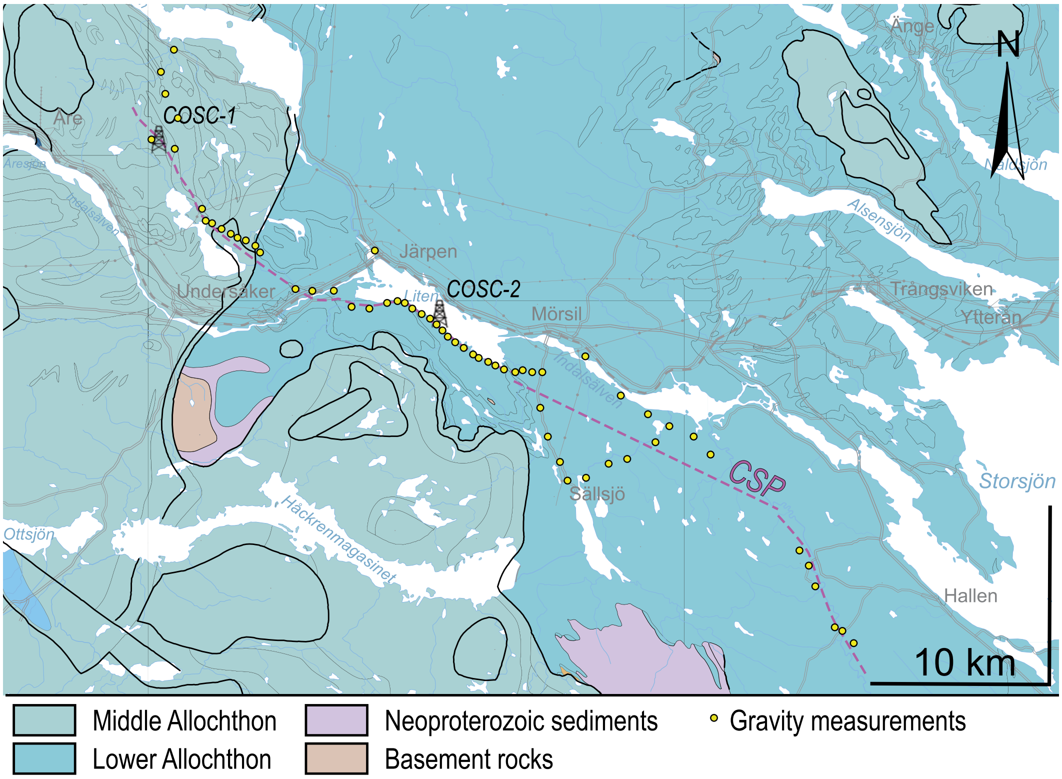


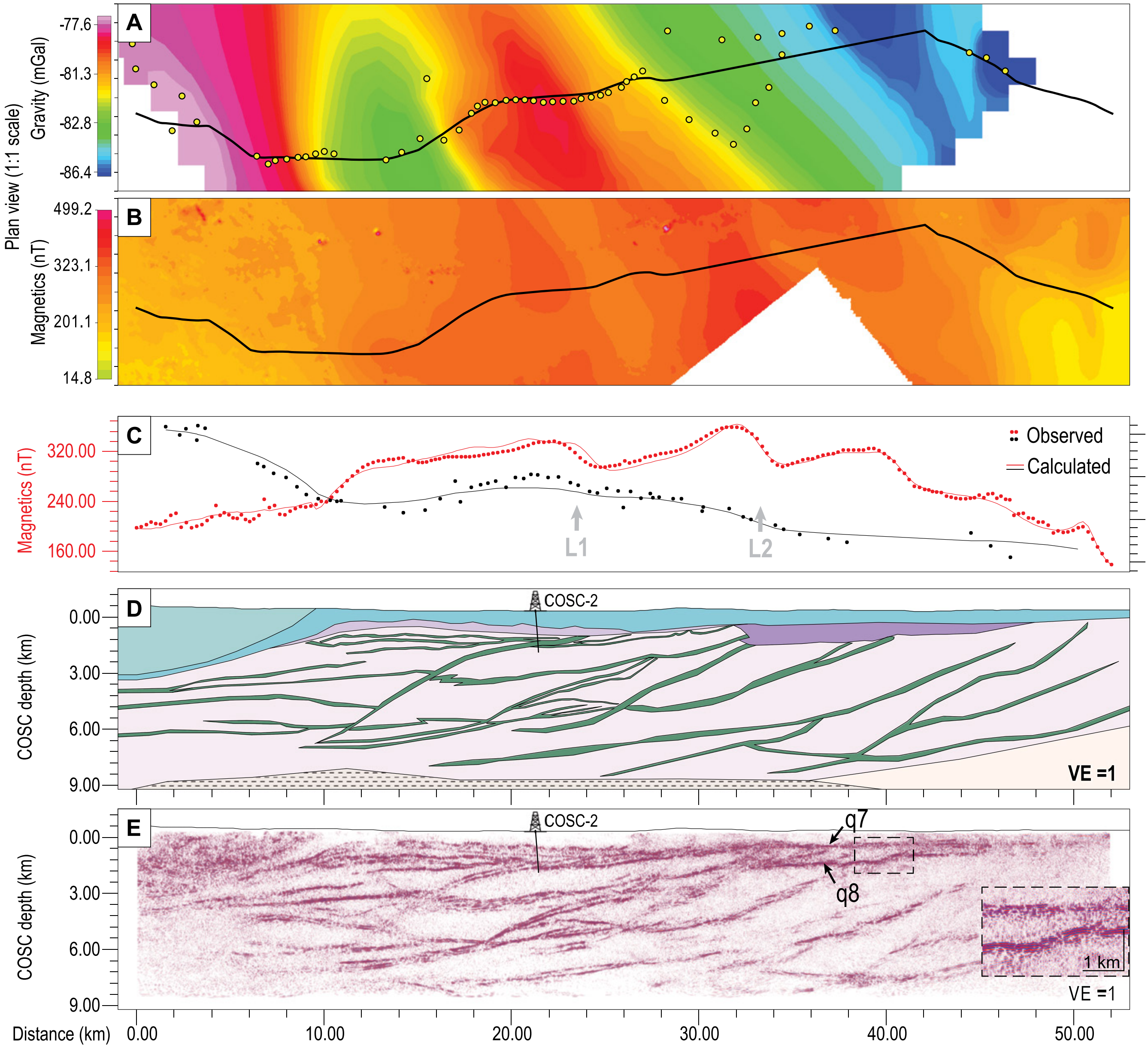
Figure 8. Locations of individual gravity measurements acquired along the composite seismic profile (CSP) are shown. Gravity values are plotted in Figure 9 and detailed in Figure S2 (see footnote 1). COSC—Collisional Orogeny in the Scandinavian Caledonides boreholes.

magnitude and shape of the Jämtland anomaly. It was assumed that variations of the magnetic field could be explained by highly magnetic top basement undulation, which is commonly ascribed to the Rätan granite. Subsequently, various potential field models of the Central Scandes were proposed based on new data sets such as sampled rock density and magnetic susceptibility values (Elming, 1980) or heat flow values (Pascal et al., 2007). The focus was on long wavelength anomalies related to the Caledonian nappes and the rocks of the Transscandinavian Igneous Belt (e.g., Dyrelius, 1986; Elming, 1988; Skilbrei et al., 2002; Ebbing et al., 2012). These models focused on the interpretation of the shape of the Caledonian nappes and the main lithological units that form the crust along an E–W section that roughly follows the trace of the Central Caledonian Transect profile and extends westward to the Norwegian coast. In a more local study, Hedin et al. (2014) modeled in 3-D the anomaly related to the Seve Nappe complex (Middle Allochthon) based on the geophysical data from the COSC-1 drilling project and the interpretation of the CSP.

Despite these different models, no study attempted to model second-order potential field anomalies based on the interpretation of the seismic reflection profiles to determine the architecture of the basement underneath the Caledonian nappes. Whereas the small-scale anomalies have usually been proposed to be related to highly magnetic basement undulation (e.g., Dyrelius, 1980; Hedin et al., 2014), basement rocks exposed in antiformal basement windows actually correspond to porphyries and granitoids that are only weakly magnetized (Elming, 1980, 1988). This observation is supported by the results from the COSC-2 drilling, which revealed that the underlying basement is composed of weakly magnetized volcanic porphyries and that only the dolerites show a considerably high magnetic susceptibility (Fig. 5A). As such, existing geologic models do not explain the magnetic and gravity anomalies observed in the study area (Figs. 7B and 7D).

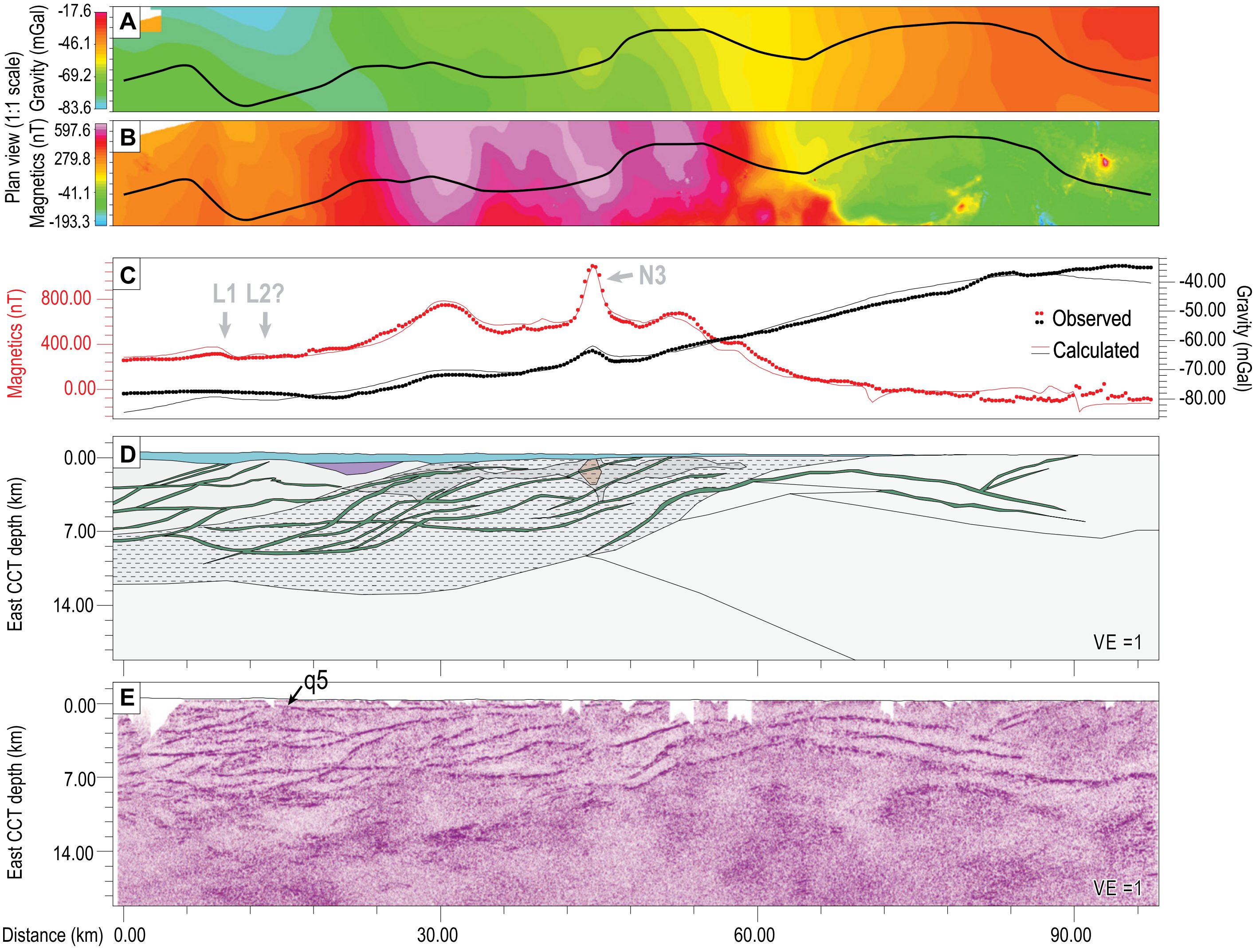
4.2. New Forward Gravity and Magnetic Models along the CSP and East–Central Caledonian Transect Profile

New forward magnetic and gravity modeling was done along the CSP (Fig. 9) and the eastern segment of the Central Caledonian Transect (Fig. 10) that incorporates new petrophysical and geophysical data from the COSC drilling and the new gravity surveying, as well as geometric constraints from the reflection seismic profiles. Modeling procedures were developed with the GM-SYS extension of the Oasis Montaj software (https://www.seequent.com/products-solutions/geosoft-oasis-montaj/gm-sys/). Only the eastern part of the Central Caledonian Transect (East Central Caledonian Transect) profile was modeled because of the lack of magnetic data in the western part. Our new gravity data follow the acquisition line of the CSP via Sällsjö (Fig. 8) and were projected onto the Common Depth Points (CDP) line of the CSP profile. The same was done with some offset measurements to the north of the CSP. A N–S projection was used, which roughly corresponds to the strike of the magnetic anomalies in map view. Density and magnetic susceptibility values used for the models are listed in Figures 9–10. They are mostly derived from the Gamma density (MSCL) and magnetic susceptibility (downhole logging) values acquired during the COSC-2 drilling (see Fig. 5A) and partly from the data set of Elming (1980). Because magnetic remanence of the rocks in the study area was shown to be negligible (Elming, 1980) and due to the lack of information about the magnetic properties of the rocks at depth, our models do not consider magnetic remanence. It is clear that magnetic susceptibility and density may change significantly within the same lithological unit and at the outcrop scale (Elming, 1980). For example, the magnetic susceptibility of the Rätan granite shows strong variation from the contacts to the center of the pluton, and the latter shows much higher susceptibility values (mean 0.030 ± 0.007 SI)



		Used magnetic susceptibility (SI)	Used density (kg/m³)
🟦	Middle Allochthon (Seve nappe)	0.0001	2760
🟦	Odovician-Silurian sedimentary cover	0.0001	2760
🟪	Neoproterozoic (?) basin	0.001; 0.001	2690; 2650
🟩	Dolerites	0.05	2910
☐	Volcanic porphyries (TIB)	0.002	2680
▨	Rätan granite (TIB)	0.04	2730
☐	Unknown basement rocks (e.g. Svecofennian, Revsund, mafics)	0.001	2720

Figure 9. Forward gravity and magnetic model of the composite seismic profile (CSP) is shown. Map view of the (A) gravity (minimum curvature gridding of the new gravity data presented in Figure S2; see footnote 1) and (B) magnetic anomalies along the CSP line, (C) profile view of the observed and calculated potential field anomalies, and (D) associated block model based on the interpretation of the (E) CSP. Note the magnetic and gravity anomaly L1, which correlates with the tip of the parallel west-dipping seismic reflections that were identified as the top and base of a ~240-m-thick dolerite by the Collisional Orogeny in the Scandinavian Caledonides (COSC-2) project drilling (Fig. 5). Also note the gravity low to the east of the L2 anomaly that we infer to be related to a ~1-km-thick basin between the sub-horizontal reflections q7 and q8. Inset shows the interpreted west-dipping normal fault at the base of the basin.



			Used magnetic susceptibility (SI)	Used density (kg/m^3)
🟦	Odovician-Silurian sedimentary cover		0.0001	2760
🟪	Neoproterozoic (?) basin		0.001	2650
🟩	Dolerites		0.05	2910
⬜	Volcanic porphyries	(TIB)	0.002	2680
▨	Rätan granite (3 types)	(TIB)	0.04; 0.06; 0.1	2730; 2730; 3000
⬜	Unknown basement rocks (e.g. Svecofennian, Revsund, mafics)		0.001 - 0.04	2710 - 2800

Figure 10. Forward gravity and magnetic model of the East Central Caledonian Transect profile is shown. Map view of the (A) gravity and (B) magnetic anomalies along the East Central Caledonian Transect line, (C) profile view of the observed and calculated potential field anomalies, and (D) associated block model based on the interpretation of the (E) Central Caledonian Transect seismic profile. The high and symmetric magnetic and gravity anomalies (e.g., N3) are attributed to isolated bodies within the Rätan batholith, whereas the asymmetric L1 anomaly is similar in amplitude, wavelength, and shape to the L1 anomaly on the Composite Seismic Profile (Fig. 9C), which is attributed to a thick, west-dipping dolerite.

than the western (0.007 ± 0.008 SI) and eastern (0.018 ± 0.012 SI) boundaries of the intrusion (Mattsson and Elming, 2001a). Similarly, the magnetic susceptibilities of individual dolerites east of the Caledonian front (Central Scandinavian Dolerite Group) vary considerably, from ~0.003 SI to ~0.06 SI and locally up to ~0.08 SI in the Ulvö area (Elming and Mattsson, 2001). The results of the COSC-2 drilling (Fig. 5A) also show that there is considerable variation within a single dolerite intrusion. However, for the sake of simplicity, our models do not include density or magnetic susceptibility gradients. Only the Rätan batholith is divided into three different bodies to account for the stronger magnetic and gravity anomalies east of the Caledonian front (see discussion below).

We used the results from the COSC-2 drilling and the seismic profiles as the initial framework to test our geologic interpretations. The majority of the flat-lying, prominent reflections discussed in section 3.1 are therefore assumed to be dolerites with high magnetic susceptibility and density that intrude, mainly, porphyries with rather low magnetic susceptibility and low-density.

The magnetic profile along the CSP model (Figs. 9B–9C) displays a large, long wavelength anomaly centered on the profile that decreases in intensity toward the edges of the profile. Such an anomaly requires the presence of a large and highly magnetic body (most likely of the Transscandinavian Igneous Belt, e.g., Rätan-type). In the western part of the profile, the increase in gravity and decrease in the magnetics can be associated with the occurrence of the dense Lower Seve Nappe (Middle Allochthon). At the center of the profile, at least three asymmetric magnetic anomalies can be recognized (L1, L2, and one at 40 km in Fig. 9C). The magnetic anomaly L1, which also fits with the eastern termination of a local gravity high, can be directly related to the highly magnetic and dense ~240-m-thick dolerite drilled by the COSC-2 well. Because the volcanic porphyries have a rather low magnetic susceptibility and similar west-dipping seismic reflections also terminate upward at the location of the other magnetic anomalies (e.g., L2), we interpret the highly magnetic dolerites to generate the short wavelength (<10 km) and low amplitude (~60 nT) magnetic anomalies (Figs. 9B–9D). On the eastern part of the profile, a gravity low is observed whose western limit corresponds to magnetic anomaly L2 (Figs. 9A and 9C). On the seismic profile, the location of the gravity low corresponds to the occurrence of two parallel sub-horizontal seismic reflections at 0 km (q7 in Fig. 9E) and ~1 km (q8 in Fig. 9E) depth (b.s.l.). In between them, a blurring of the reflectivity is observed. The lower reflection (q8) of this seismic unit displays a normal offset at 40 km along the profile that we interpret as a west-dipping normal fault (see insert in Fig. 9E). As such, this unit is interpreted as a sedimentary basin that lies beneath the main Caledonian décollement (q7 reflection).

The East Central Caledonian Transect model (Fig. 10) shows a long wavelength (50-km-wide) and high-amplitude positive magnetic anomaly at the center of the profile (Figs. 10B–10C). The magnetic intensity decreases toward the eastern and western edges of the profile, and the eastern part of the section shows in general a lower magnetic intensity (~0 nT) than the western part (~300 nT). The latter value (300 nT) is close to the "background," or average, magnetic intensity along the CSP section (Fig. 9C), which suggests that the basement is composed of rocks with similar physical properties. The gravity decreases westward from −40 mGal to −80 mGal and remains constant between 20 km and 0 km (Figs. 10A and 10C). These large-scale anomalies suggest that the density of the crust increases toward the east and that a highly magnetic body is located at shallow depth in the center of the profile and potentially extends westward beneath less magnetic rocks. As such, our interpretation involves a thick (~10 km), highly magnetic (>0.04 SI) Rätan body at shallow depth at the center of the section that deepens westward under the low density, low magnetic volcanic porphyries. Toward the east, this Rätan body progressively wedges out and is replaced by a very dense and weakly magnetic crust of Svecofennian origin, as observed at the surface of the Fennoscandian Shield (Fig. 7). Three nearly symmetric, high-amplitude magnetic anomalies (amplitude >300 nT), which are associated with gravity peaks, can be recognized at 34 km, 45 km (N3), and 53 km along the profile (Fig. 10C). These anomalies do not seem to relate to any of the west-dipping reflections on the seismic section (Fig. 10E). Instead, the N3 anomaly is clearly located above the ~3-km-wide, droplet-shaped zone q6 of blurred reflectivity seen in Figure 4B and described in section 3.1. In map view, these anomalies appear as isolated circular bodies and are similar in shape, size, and amplitude to the monzodiorite and monzogabbroic rocks of the "Nordkölen belt," which intrude the Rätan granite east of the Caledonian front (see section 2.2). In the western part of the section, we observe an asymmetric, positive magnetic anomaly of comparatively low amplitude (<100 nT; Figs. 10B–10C) above the upward termination of steeply west-dipping reflections on the seismic section (Fig. 10E). This anomaly shares the same magnetic (asymmetric shape and ~60 nT amplitude) and seismic characteristics as the interpreted dolerites on the CSP section (e.g., anomaly L1 and L2 in Fig. 9). A gravity low can be recognized at 20 km in the gravity profile (Fig. 10C) and gravity map (Fig. 10A). It occurs east of a large, undulated seismic reflection (q5 in Figs. 4B and 10E) and, in map view, in the northern continuation of the gravity low that dominates the eastern part of the CSP model (Figs. 9A and 7B). As such, we interpret this gravity low to be related to a ~1-km-thick sedimentary basin that underlies the flat-lying Lower Allochthon. The base of this basin corresponds to the top of the conductive layer identified on the resistivity profile (Fig. 4C; Korja et al., 2008).

5. DISCUSSION

5.1. Crustal Architecture and Northward Extension of the Transscandinavian Igneous Belt in Western-Central Sweden

Volcanic porphyries were observed in basement windows of central-western Sweden, and we report similar rocks down to at least 2.3 km depth in the parautochthonous basement (Fig. 5). Potential field models (Figs. 9–10) suggest the existence of a rather thick (~10 km) volcanic sequence underneath the Caledonian nappes that is potentially similar in composition, age, and mode of formation to the Dala porphyries (Beckholmen, 1978; Roberts, 1997; Lundqvist and Persson, 1999). Interestingly, the distribution of the volcanic porphyries from the Jämtland area occurs as an apparent right-stepping en-échelon continuation of the Dala porphyries (Fig. 11A), mirroring the geometry of the Jämtland anomaly on the magnetic map, which appears to be delimited by NW–SE-trending features (Fig. 11B; Olesen et al., 2010). These observations are in accordance with the model of Bergman et al. (2006), who proposed that the emplacement of the rocks of the Transscandinavian Igneous Belt and the Dala Porphyries is related to dextral transpression along WNW–ESE-trending shear zones such as the Storsjön–Edsbyn Deformation Zone. The strain pattern resulting from such dextral transpression potentially implies the formation of WNW–ESE pull-apart basins and, by analogy with the Dala porphyries, these rocks might have been deposited in a subsiding volcanotectonic graben (Bergman et al., 2006). It is still unclear, however, what kind of structures define the boundaries of these basins and how these volcanics were deposited with respect to the intrusive rocks of the Transscandinavian Igneous Belt and the Svecofennian basement.

5.2. Geometry, Distribution, and Origin of the Mafic Intrusions

Our potential field models and seismic interpretations suggest that the basement underneath the Caledonian nappes is intruded by mainly flat-lying, thin (~1 m) and thick (up to 240 m) dolerites, which mostly steepen toward the east (Figs. 9–10). On the magnetic anomaly map (Figs. 7C and 12), the arcuate N–S-trending anomalies (e.g., L3 and L4, see section 3.3) have the same order of amplitude (~100 nT) and wavelength (<10 km) as the magnetic anomalies that could be tied to the dolerites in the potential field models (e.g., L1 and L2; Figs. 7 and 9–10). As such, we propose that these anomalies

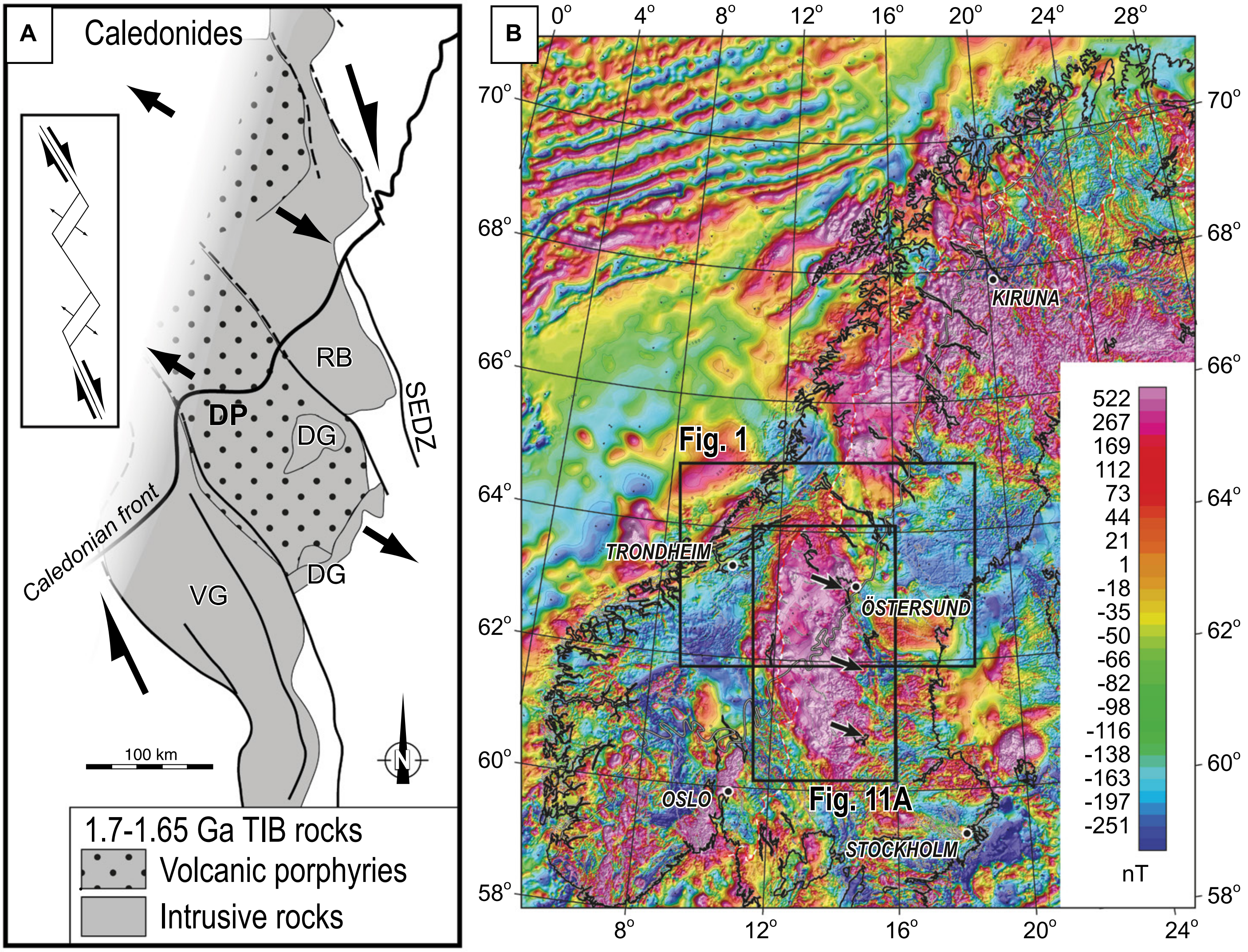


Figure 11. (A) Schematic tectonic map illustrates the proposed regional kinematics related to the formation of the 1.7–1.65 Ga Transscandinavian Igneous Belt rocks (modified after Bergman et al., 2006). Inset shows the main structures and kinematics related to the formation of right-stepping en-échelon pull-apart basins. (B) Magnetic anomaly map of Scandinavia shows the geometry of the Jämtland positive magnetic anomaly associated with the rocks of the Transscandinavian Igneous Belt (TIB; from Hedin et al., 2014, based on Olesen et al., 2010). Note the apparent right-stepping en-échelon geometry on the eastern edge of the Jämtland magnetic anomaly (black arrows). The Dala and Jämtland volcanic porphyries show a similar en-échelon distribution that is in accordance with the formation of pull-apart basins controlled by NW–SE shear zones. DP—Dala porphyries; RB—Rätan batholith; DG—Dala granitoids; VG—Värmland granitoids; SEDZ—Storsjön–Edsbyn Deformation Zone.

correspond to the surface expression of west-dipping dolerites in the basement beneath the Caledonian cover as interpreted on the East Central Caledonian Transect and CSP sections (Fig. 12). In this case, the geometry of these anomalies in map view suggests that the easternmost intrusions recognized on the CSP and Central Caledonian Transect profile form arcuate, inclined sheets in their eastward termination. The geometries, in section and in map view, of the mafic intrusions described above are commonly associated with the "saucer-shaped" type of intrusions, which are characterized in 3-D by a flat-lying inner sill that becomes steeper laterally (inclined sheets or "wings") and often flattens outward as an outer sill (Thomson and Hutton, 2004; Polteau et al., 2008b; Galland et al., 2009). At the surface, saucer-shapes (and also sill complexes) often form elliptic intrusions, as described in the Karoo Basin region in South Africa (Chevallier and Woodford, 1999; Polteau et al., 2008a; Galerne et al., 2011). Interestingly, thick and wide (~110 km) saucer-shaped intrusions attributed to the Central Scandinavian Dolerite Group were identified in the Bothnian Sea east of the study area (Buntin et al., 2019). Moreover, the elliptical shape of the Central Scandinavian Dolerite Group intrusions within the Fennoscandian Shield (east of the Caledonian front; Fig. 12C), which is pictured on the geologic map for ~100 km in the NW–SE direction (Fig. 1), agrees with the geometry of saucer-shaped intrusions in the sub-surface. In addition, elliptic Central Scandinavian Dolerite Group sills showing thicknesses ranging from ~50 cm to 300 m (similar to the dolerites drilled by COSC-2) were described in the Ulvö complex (Larson, 1980), which is north of the city of Sundsvall (Fig. 1). This reasoning suggests that the arcuate

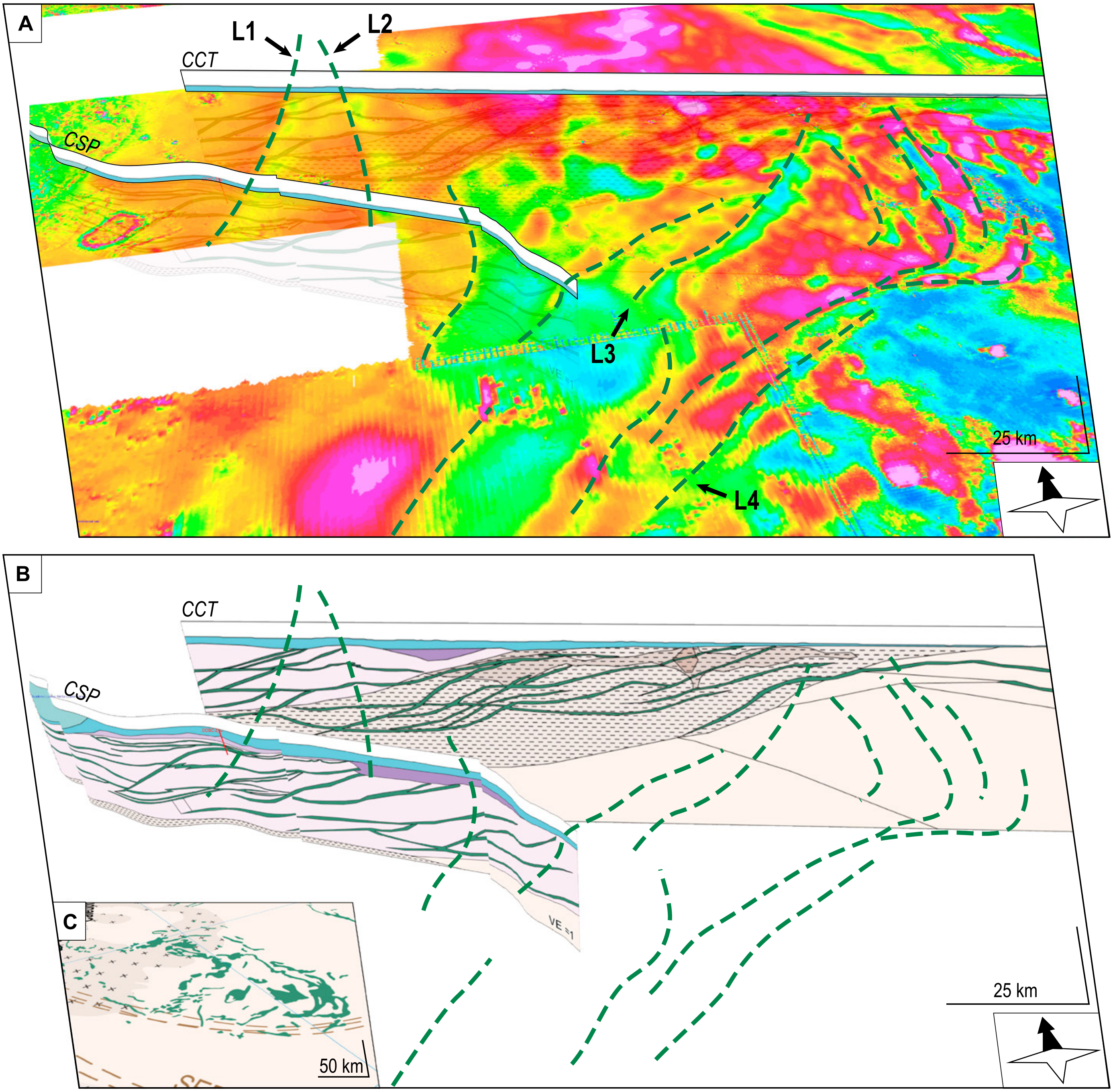


Figure 12. (A) Oblique 3-D view of the magnetic map (0.5 vertical derivative; see Fig. 7D) at the location of the composite seismic profile (CSP) and Central Caledonian Transect (CCT) profile highlight the geometry of the magnetic lineaments at the surface. (B) Same view as in panel A with transparent magnetic map to reveal the sections from the potential field models of Figures 9D–10D. The arcuate magnetic lineaments (green dashed lines) correspond to the surface termination of the west-dipping reflections that are interpreted as dolerites on the CSP and CCT section. (C) Oblique 3-D view of the geologic map east of the Caledonian front shows the elliptical shape of the Central Scandinavian Dolerite Group (Fig. 1). Note the striking similarities in size and shape in map view between the magnetic lineaments and the dolerites of the Central Scandinavian Dolerite Group.

shape of the magnetic anomalies in map view (Fig. 12A), which we relate to westward-dipping mafic intrusions at depth (Fig. 12B), corresponds to the eastern flank of large-scale sill complexes and saucer-shaped intrusions. By extrapolation, the gently eastward-dipping reflections on the western side of the Central Caledonian Transect profile (Fig. 4B) correspond to the western flank of ~110-km-wide, flat-lying intrusions beneath the Caledonian nappes.

We observe that the width of the proposed flat-lying intrusions on the Central Caledonian Transect profile (~110 km) is similar to those of the elliptical Central Scandinavian Dolerite Group on the geologic map and the saucers identified on the BABEL seismic reflection profiles below the Bothnian Sea by Buntin et al. (2019). In contrast to the BABEL section, we acknowledge the fact that it is hard to identify continuous, 100-km-wide, flat-lying reflections on the Central Caledonian Transect profile, especially because the prominent reflections seem disrupted or absent near the center of the section (40–70 km). Different explanations can account for such disruptions in this part of the section: (1) the reactivation of the sills as thrust faults/shear zones related to the Caledonian orogeny (see section 5.3), i.e., the sub-horizontal seismic reflections correspond to both deformation zones and mafic intrusions, and deformation (cataclasites and mylonites) at the contact between the dolerites (high seismic velocity) and the host rock (lower seismic velocity) could be responsible for a lower impedance contrast; or (2) the occurrence of a complex and dense set of dikes, sills, and related mafic magma percolation in the center of the saucers that are generally poorly imaged by reflection seismology (e.g., Eide et al., 2018; Rabbel et al., 2018; Buntin et al., 2019). The occurrence of mainly mafic rocks would increase the average seismic velocity in the center of the sill complex and thus attenuate the seismic impedance contrast between the dolerites and the host rock. An interpretation involving more dense material at the lower–middle crustal level in this part of the Central Caledonian Transect profile is partly supported by the existence of seismic velocity anomalies (Fig. 4C). Another striking observation is the apparent asymmetry of the intrusions on the Central Caledonian Transect section, i.e., the eastern flank shows steeper sheets than the sub-horizontal intrusions on the western flank. We suggest that this asymmetry could be related to the conditions of intrusion (e.g., direction of the magma flow, host-rock lithologies, regional stress field) and/or to subsequent basement deformation and tilting related to the Caledonian orogeny. Note, however, that it could also be a cut effect of a 2-D line through a 3-D intrusion (i.e., the western part of the section is oblique to the dolerite sheets).

Information on the age of the dolerites that intrude the basement beneath the nappes would help to constrain their origin. Because evidence for syn- to late Caledonian magmatism or volcanism is lacking in the Lower Allochthon, and because dolerites are affected by Caledonian deformation in the parautochthonous basement (Johansson, 1980; Stel, 1988), a Caledonian age for the intrusions can be discarded. As the dolerites intrude the equivalent of the Dala porphyries, they must be younger than 1.7 Ga. Different ages might actually exist (1.5 Ga, 1.2 Ga, or 1 Ga; see section 2.2 and Fig. 3), and it is unclear whether all of the intrusions observed on the CSP and Central Caledonian Transect profile have the same age. However, it is likely that most of the intrusions belong to the ca. 1.2 Ga Central Scandinavian Dolerite Group because of their widespread occurrence in central Sweden (Fig. 3) and a similar mode of emplacement, i.e., elliptical, flat-lying intrusions with thickness ranging from ∼1 m to ∼300 m (Larson, 1980). More precise age-dating is required to determine the exact timing of emplacement with respect to the different Central Scandinavian Dolerite Group sub-groups identified in the area (Söderlund et al., 2006).

Further evidence for ascribing these dolerites to the Central Scandinavian Dolerite Group is the apparent genetic link between the emplacement of the dolerites in the Jämtland region and the main shear zones. As postulated by Söderlund et al. (2006), older (Svecofennian or Transscandinavian Igneous Belt-related) shear zones could have functioned as pathways for magma, as was suggested for the Lower Cretaceous High Arctic Large Igneous Province in the Barents Sea by Minakov et al. (2018). The parallel orientation of the intrusions that form the southern margin of the 100-km-wide elliptical intrusions and the Hassela Shear Zone (Fig. 7) suggests at least a minor control of pre-existing structures on the distribution of the Central Scandinavian Dolerite Group magmatism. West of the Caledonian front, the complex network of flat-lying intrusions described in this study is located in the potential westward continuation of the Storsjön–Edsbyn Deformation Zone and Hassela Shear Zone. The spatial extension of these shear zones and of the Central Scandinavian Dolerite Group, which run from western-central Sweden eastward to the Bothnian Sea (Bergman et al., 2006), corresponds to the area characterized by a 10-km-thick, high-velocity lower crust (Fig. 4C; England and Ebbing, 2012). As such, in contrast to England and Ebbing (2012), who proposed that the very dense and thick lower crustal material is related to mafic underplating associated with the Transscandinavian Igneous Belt formation, we suggest that it is related to the ca. 1.2 Ga Central Scandinavian Dolerite Group magmatic event. Indeed, the wide extent of the high-velocity lower crustal body better corresponds to the spatial distribution of the Central Scandinavian Dolerite Group than to the rocks of the Transscandinavian Igneous Belt (see Fig. 3). Moreover, the velocity anomaly in the center of the Central Caledonian Transect profile seems to form a dome in the lower crust and propagate upward into the middle and upper crust (Fig. 4A), which corresponds to the center of the large, flat-lying intrusions. A very similar doming of the lower crust was reported by Buntin et al. (2019) below the saucer-shaped intrusions in the Bothnian Sea. Altogether, and in accordance with Söderlund et al. (2006), this suggests that shear zones such as the Hassela Shear Zone could have been used as pathways for magma migration at the base of the crust. That, in turn, favored the formation of dike and sill complexes in the overlying middle/upper crust. Finally, the major axis of elliptical, saucer-shaped sills was inferred to be parallel to the feeder dike below (Pollard and Johnson, 1973; Goulty and Schofield, 2008; Galerne et al., 2011). The striking parallelism between the Hassela Shear Zone and the major axis of the NW–SE elongated, elliptical intrusions west of the Caledonian front (Fig. 1) further supports a link between this shear zone and the feeder system of the Central Scandinavian Dolerite Group.

The documentation of flat-lying dolerite sheets (flat parts of the saucers/sills) in the shallow crystalline crust, as in the Transscandinavian Igneous Belt or in the metavolcanic and granitoid rocks of the Svecofennian crust (Figs. 3 and 10; Juhlin, 1990; Buntin et al., 2019), is an intriguing observation. Similar flat-lying intrusions in igneous middle/upper crust have been reported from different cratons (e.g., Howard, 1991; Ivanic et al., 2013; Brown and Kim, 2020), but models concerning their emplacement are still debated (Buntin et al., 2019). The mechanisms controlling their emplacement are not straightforward in light of the established models for sill emplacement, which state that either (1) far field compressional tectonic stresses control the formation of horizontal igneous sheets perpendicular to σ_3 (e.g., Walker et al., 2017; Stephens et al., 2018); (2) the host rock is mechanically layered (e.g., Kavanagh et al., 2006; Galland et al., 2009, 2018), as in numerous sedimentary basins worldwide (e.g., Svensen et al., 2009; Magee et al., 2016; Spacapan et al., 2018), in layered volcanic systems (e.g., Smittarello et al., 2019), and in anisotropic rocks such as foliated shale (Souche et al., 2019) or strongly sheared lower crustal rocks (Wrona et al., 2019); or (3) the magma reached at the so-called "level of neutral buoyancy" when the density of the mafic magma became higher than that of the host rock (e.g., Francis, 1982). However, the geologic observations poorly support these models. Firstly, the proposed tectonic scenarios for the formation of the Central Scandinavian Dolerite Group suggest back-arc extension or hotspot-related magmatism (Söderlund et al., 2006), which rules out a scenario for sill formation controlled by compressional stresses. Secondly, prominent layering, heterogeneities, or anisotropy of the host rock do not explain a mechanical control on the emplacement of the sills. The Jämtland volcanic porphyries may display structural heterogeneities between the succession of lava flows and the batholiths of the Transscandinavian Igneous Belt, and the Svecofennian domain may consist of amalgamated, flat-lying lenses of granite with both sub-horizontal contacts and magmatic foliations (e.g., Bartley et al., 2012; Cruden and Weinberg, 2018, and references therein). However, even if this characteristic batholith structure could exist (e.g., Mattsson and Elming, 2001a, for the easternmost part of the Rätan granite), it is very unlikely that the intrusive contacts and foliations extend over distances as large as 100 km, as suggested by the complex nature of the foliation in the Svecofennian basement (Skyttä et al., 2020). The presence of older, large-scale, flat-lying shear zones controlling sill emplacement is also unlikely considering the prominent vertical Storsjön–Edsbyn Deformation Zone and Hassela Shear Zone in the basement of central Sweden. Thirdly, the large volumes of the dolerite sills suggest significant magma influx and driving pressures, as opposed to the neutral buoyancy theory that implies low driving pressure and the likely halt of magma propagation (Hogan et al., 1998). Consequently, a reliable explanation for the formation of large, flat-lying mafic sheets in the Baltican crust is lacking at the moment. This poses the question of whether the established theories for sill emplacement have missed a fundamental aspect, in particular in crystalline bedrock.

Based on the results of the COSC-2 drilling, we interpret most of the prominent seismic reflections in the basement as mafic intrusions (Figs. 9D–10D). Such an interpretation is supported by forward magnetic and gravity modeling, which identifies the west-dipping seismic reflections as highly magnetic and dense sheets (Figs. 9–10) as responsible for N–S-trending magnetic lineaments (Fig. 12). The results from the COSC-2 drilling also confirm that the double, parallel seismic reflections with opposite impedance contrast correspond to the top and bottom of thick intrusions ($\sim$240 m) across which the seismic velocity is increasing (Fig. 5). Accordingly, we interpret similar double reflections on the CSP and Central Caledonian Transect profile as thick mafic intrusions. Besides, many of the reflection intersections do not exhibit offset, which precludes their interpretation as faults or shear zones younger than 1.2 Ga. Nevertheless, basement deformation related to the Caledonian orogeny is clearly observed at the surface, and we can infer that some of these reflections correspond to deformation zones or lithological boundaries.

5.3. Implications for Basement Deformation During Caledonian Orogeny

We assume that interpreted basement deformation on the CSP and Central Caledonian Transect profile is related to the Caledonian orogeny. While we cannot rule out basement deformation related to the Sveconorwegian orogeny (1.1–0.9 Ga), different observations from the sub-surface support the Caledonian orogeny (ca. 430 Ma) as being the main tectonic event in the study area. East–SE-directed Caledonian deformation (i.e., shortening in the orientation of the seismic profiles) dominates the geologic map, as indicated by the N–S to NNW–SSE orientation of basement windows and the strike of major thrusts (Fig. 1). The low-angle deformation zones described in the pre-Cambrian tuffs can be observed in the Ordovician flysch and in the volcanic porphyries, which suggests that they all deformed during the same post-Ordovician contractional event. In contrast, as far as we know, the nearest area affected by the Sveconorwegian deformation is the Dala Province to the south, where orogenic structures and late orogenic 0.98–0.95 Ga dikes strike in the WNW–ESE orientation, i.e., parallel to the seismic profiles (Fig. 3; Lundqvist and Persson, 1996; Magnor et al., 1996; Stephens and Wahlgren, 2020).

Seismic reflections attributed to Proterozoic intrusions represent reliable markers for investigating basement deformation during the Caledonian orogeny. On the Central Caledonian Transect profile, we recognize some reflections that are interrupted against a $\sim$60-km-long interface that is determined by aligned, discontinuous, and gently west-dipping, flat-lying reflections (dashed line in Fig. 13A). Using the Move software (https://www.petex.com/products/move-suite/), which allows kinematic restoration of geologic and seismic sections, we attempt to match the pairs of reflections by applying the same amount of top-to-the-west displacement ($\sim$6 km). The restored profile shows a very good fit between pairs of reflections across the proposed structure (Fig. 13B). It is striking that the upward termination of this interface lies, along-strike, to the east of the eastern limb of the Olden antiform, which corresponds to the easternmost major Caledonian deformation involving the basement in the area (Fig. 1). Considering this, note that the dome-shaped seismic reflections recognized on the Central Caledonian Transect profile (q5 in Fig. 4B) are located in the hanging wall of the proposed contractional structure and probably represent the basement antiform of the Olden window toward the south. As such, based on our results and the geology of the area, we propose that the interface along which seismic reflections are offset represents a good candidate for the location of the Caledonian sole thrust in this section. Similar gently west-dipping reflections in the hanging wall may represent deformation zones as well. As part of this study, we present a seismic interpretation of the North-Central Caledonian Transect-1 and Central Caledonian Transect profiles (Fig. 13C) that includes the deformation related to the Caledonian orogeny. Our interpretation mostly involves gently west-dipping shear zones or thrust faults, with the Mullfjället antiform as an antiformal stack related to basement duplexes that were subsequently tilted toward the foreland due to underthrusting and the formation of a triangle zone, a geometry described by, e.g., Couzens-Schultz et al. (2003). At the front of this triangle zone, low-angle thrusts propagate and allow for the juxtaposition of basement slices such as observed in the Olden window (Gee, 1975b; Rice and Anderson, 2016). Interestingly, in the hanging wall of these subhorizontal thrusts, the dome-shaped (or undulated) top basement, between 60 km and 80 km along the Central Caledonian Transect profile (Fig. 13C), appears to be the southward continuation of the Olden antiform in map view (Fig. 1). The occurrence of a gravity low in our potential field model (Fig. 10E) suggests that the eastern antiform (78 km) is overlain to the east by a sedimentary basin. Potential candidates for these sedimentary rocks are the Tonian to Cambrian conglomerates, sandstones, and shales of the Risbäck and Sjoutälven Groups (Gee, 1975a). These sediments were mapped in the northern part of Jämtland County, where they are affected by several thrust faults (e.g., Greiling et al., 2018). Finally, we interpret most of the west-dipping reflections beneath the Skardöra antiform (Fig. 4B) as contractional structures that propagate eastward across the flat-lying to gently east-dipping mafic intrusions. They are responsible for the small horizontal offset and kinked geometry of the reflections in this part of the profile (Figs. 13A and 13C).

The interpretation of the CSP based on the results from the COSC-2 drilling suggests that the upper crust of the Fennoscandian basement is intruded by a complex network of west-dipping and saucer-shaped dolerites (Fig. 14). Flat-lying reflections appear to be offset across the thick dolerite drilled (Figs. 14A–14C). This vertical offset of $\sim$700 m can be observed along the entire intrusion and is in accordance with the structural observations of the drill core, which show deformation zones along the margins of the thick dolerite (Figs. 5A and 6). Note, in particular, the clear duplication and offset of the reflections in Figure 14A that rule out the interpretation of the reflection offsets as related to intrusion opening. In addition, the dilation due to intrusion opening will be much smaller than the offset shown by the reflectors. Also, other west-dipping dolerites seem to offset sub-horizontal reflections (Figs. 14D–14E) and thus localize contractional deformation. Our

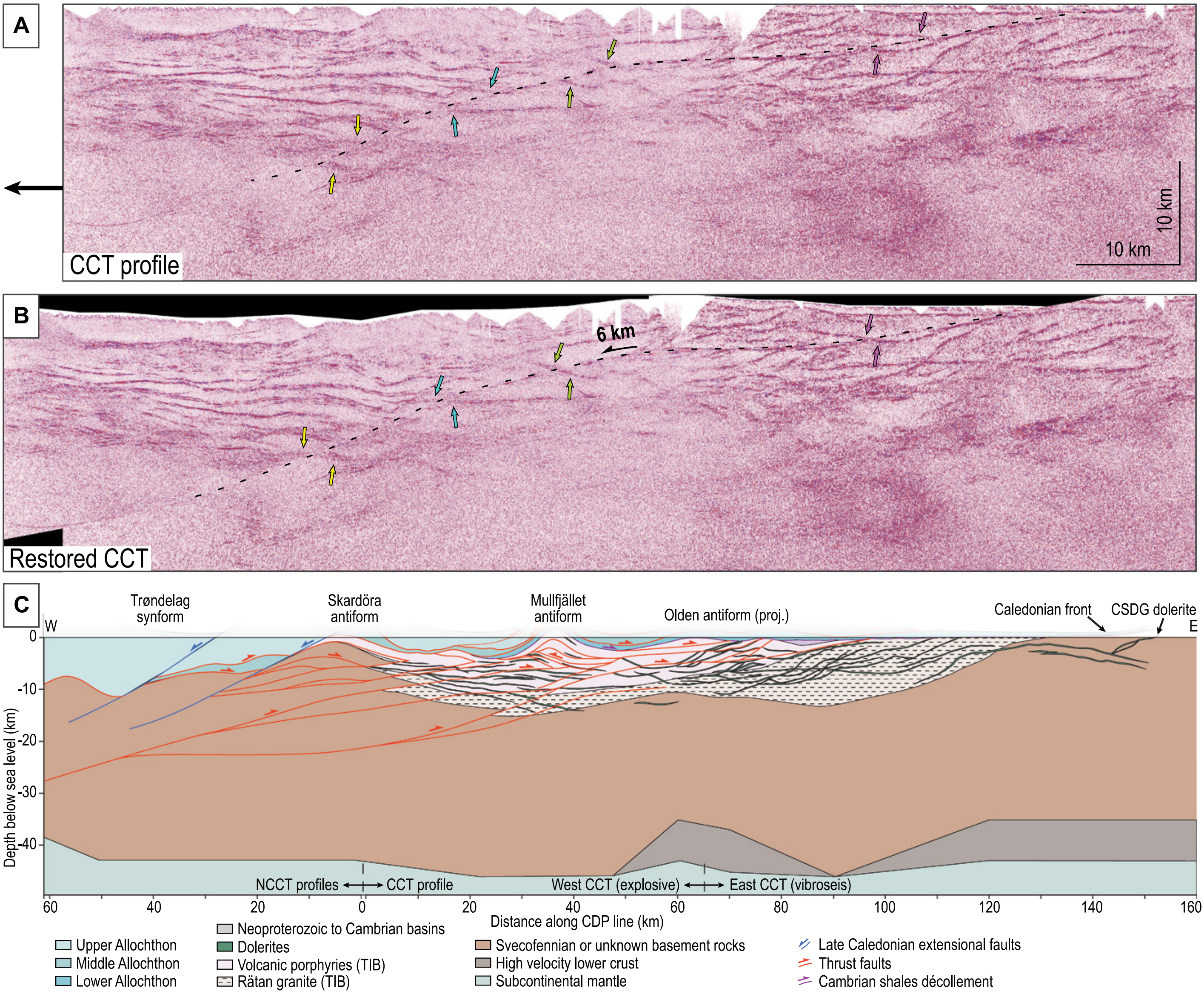


Figure 13. (A) Central Caledonian Transect (CCT) is shown. (B) Attempt to partially restore the CCT seismic profile using offset seismic reflections. Pairs of yellow, blue, green and pink arrows point towards seismic reflections that can be used as markers for restoration. About 6 km of displacement along the dashed line is required to align pairs of reflections. (C) Seismic interpretation of the North Central Caledonian Transect (NCCT) and CCT profiles. Note the flat-lying geometry of the mafic intrusions and the flat-ramp geometry of the proposed thrusts at the center of the CCT profile. CSDG—Central Scandinavian Dolerite Group; CDP—Common Depth Points line.

interpretation suggests basement duplication in the hanging wall of mafic intrusions at the western margin of the pre-Cambrian basin (34 km in Fig. 14). This contractional deformation was potentially transferred within and detached at the base of the basin, as is suggested by the occurrence of several west-dipping reflections that are interpreted as thrusts within this unit (Fig. 14F). We propose that part of the basement deformation was localized and accommodated along the mafic intrusions' margins in this section. Although the amount of displacement seems rather low along a single intrusion (i.e., a few hundreds of meters), a significant amount of shortening could have been accommodated, considering the numerous dolerites interpreted on this profile (and possibly those that are too small to be resolved). Such strain localization along dike margins has already been described in the Olden window (Johansson, 1980; Troëng, 1982), in various nappes of the Caledonides (e.g., Gayer et al., 1978; Krill, 1986; Rice, 1986; Hudleston, 1989), as well as in other tectonic systems (e.g., Fossen and Cavalcante, 2017; Scott, 2019; Wilson et al., 2020). The dolerites potentially acted as rheological heterogeneities along which strain can localize, facilitated by strain-softening and fluid circulation (e.g., MacDonald et al., 2017). The occurrence of the pre-orogenic, continuous (no offset), and thick drilled dolerite that extends from 1.5 km to 7.5 km depth between 10 km and 25 km precludes the existence of a sole thrust (or any low-angle thrust) at shallow crustal depth (<8 km) on the western part of the section as formerly proposed by Hedin et al. (2012). Indeed, if any shallow dipping fault were present at shallow depth on the western part of the section, the parallel double

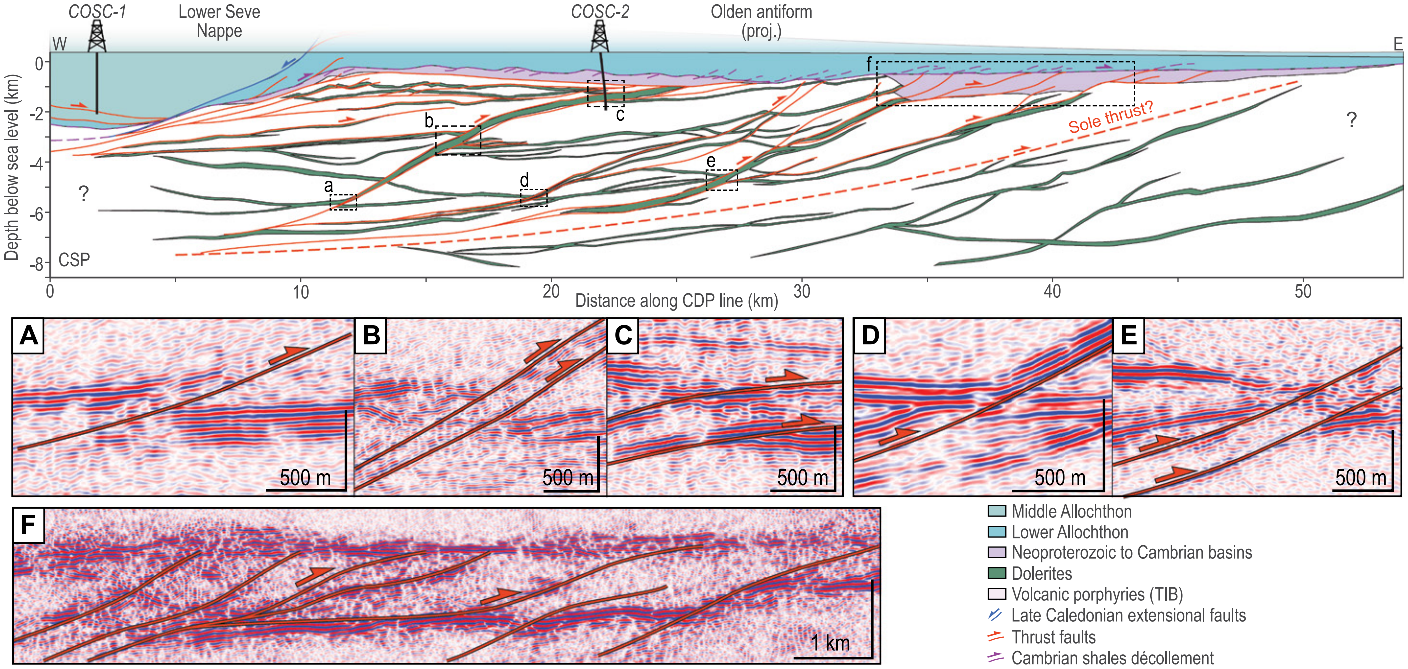


Figure 14. The Composite Seismic Profile (CSP) is interpreted and close-ups are shown of locations where reflections are offset (insets A, B, C, D, and E). Note the upward extension of the thrust identified in Figure 14E into the pre-Cambrian basin (Fig. 14F). Note also the gently west-dipping and saucer geometries of the dolerite intrusions. COSC—Collisional Orogeny in the Scandinavian Caledonides project; CDP—Common Depth Points line.

reflections (reflection q1 in Fig. 4A) corresponding to the drilled west-dipping dolerite would likely be offset horizontally. However, a potential candidate for the location of the sole thrust on the section can be found in a west dipping zone across which no cross-cutting reflection can be recognized and along which reflections appear to become parallel (Fig. 14). Assuming that this zone corresponds to a deformation zone, the sole thrust would be located at 8 km depth on the western part of the section and would reach the surface near the eastern end of the profile (Fig. 14).

The determination of contractional structures on the CSP and Central Caledonian Transect profile provides the basis for discussing the mode of deformation of the Baltica basement during the Caledonian orogeny. While some of the contractional structures appear to cross-cut dolerites (Central Caledonian Transect profile, Fig. 13), other faults localized along some of these intrusions, most likely along the dolerites that were favorably oriented with respect to the direction of shortening (CSP, Fig. 14). East of the Lower Seve Nappe, our seismic interpretation of the Central Caledonian Transect profile suggests the existence of about three décollement levels in the upper 8 km of the basement (60 km in Fig. 13). In contrast, maximum two potential décollement levels at ~3 km and ~8 km depth can be identified on the CSP (10 km in Fig. 14). This along-strike structural variation can reasonably be attributed to basement structural/compositional inheritance and suggests an important control of pre-existing mafic intrusions on basement deformation during the Caledonian orogeny. As observed in Figure 3, the Fennoscandian Shield in central Sweden is characterized by numerous mafic intrusions of various geometries, and our study confirms the existence of a dense network of flat-lying intrusions west of the Caledonian front (Fig. 15). It is also the area across which the architecture of the Caledonian orogeny appears to be segmented along-strike by the Grong-Olden basement window and the Persåsen fault, as discussed above (Fig. 1). However, this area is also characterized by the Hassela Shear Zone and the Storsjön–Edsbyn Deformation Zone, and we cannot rule out that these structures played a role during the orogenic evolution. As such, one can question whether the non-cylindrical orogenic architecture in central Sweden was primarily controlled by (1) the Hassela Shear Zone and Storsjön–Edsbyn Deformation Zone or (2) by the occurrence of a dense network of thick mafic intrusions within the basement. In the first case, older structures would be expected to have reactivated (structural inheritance), as is supported by the occurrence of fluid circulation along the Storsjön–Edsbyn Deformation Zone during the Middle Devonian (Högdahl et al., 2001). However, clear evidence for deformation along this structure that is younger than 1.2 Ga is lacking (Bergman et al., 2006). In the case of the mafic intrusions (compositional inheritance), we know that dolerite margins partly accommodated deformation. However, it is unclear how much this contributes to crustal shortening and how deformation was distributed in a basement intruded by a dense network of dolerites. It is possible that the west-dipping segments of these intrusions functioned as local ramps, whereas their sub-horizontal parts acted as flats. Since these dolerites intruded at different levels where they formed a sub-horizontal/saucer-shaped stacked layering (Fig. 15), they may function as flat-ramp trajectories at different levels. This would render displacement along individual intrusions relatively small (e.g., Fig. 14). We suggest that the geometry and length of the sub-horizontal thrusts interpreted from the Central Caledonian Transect profile were (at least partly) governed by pre-existing sills in the basement (Figs. 13 and 15). Further field investigations, guided by analogue/numerical models, would be useful for addressing the respective roles of inherited structures and pre-existing intrusions during Caledonian deformation.

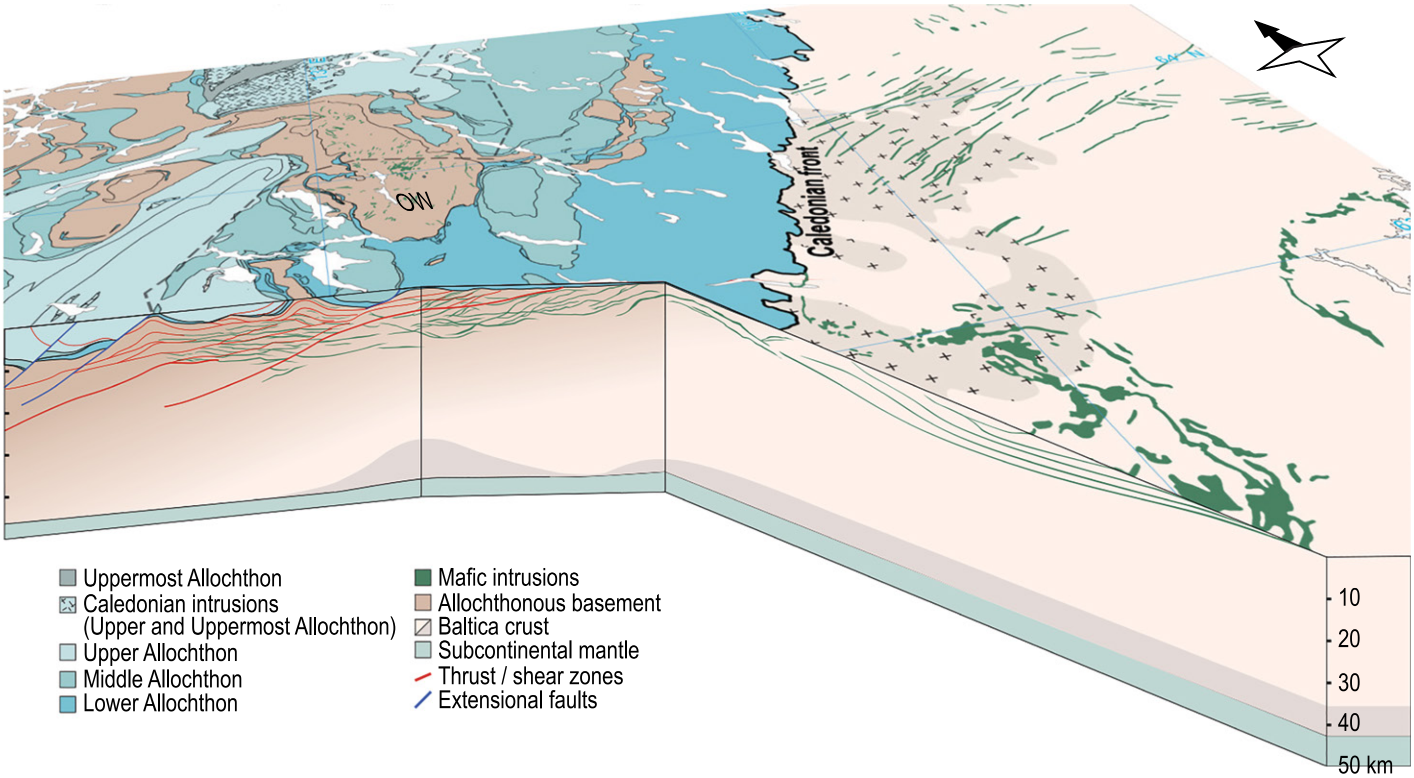


Figure 15. Three-dimensional block diagram of central Sweden shows the geometry of mafic intrusions within the crust of Baltica and the Caledonian deformation (1:1 scale). The basement antiforms in the hanging wall of gently west-dipping thrusts coincide with the southward continuation of the Grong-Olden window (OW).

5.4. Nature of the Seismic Reflections in the Basement

Results from COSC-2 and our forward gravity and magnetic models show that most of the prominent seismic reflections at shallow depth correspond to mafic intrusions. The positive magnetic (observed as ~60 nT linear features on the magnetic map in Figs. 7D and 12A) and gravity anomalies related to the gently dipping reflections (e.g., anomaly L1 in Figs. 9 and 12) can only be explained by a sharp lithological contrast between high density/magnetic bodies and their host rocks. This is supported by the presence of a mapped dolerite (Central Scandinavian Dolerite Group) to the east of the Caledonian front, which propagates northwestward below the Caledonian nappes. The magnetic anomaly of this outcropping dolerite (anomaly D1 in Figs. 7A and 7D) has an amplitude and geometric characteristics similar to those of the magnetic anomalies associated with the prominent west-dipping reflections in the CSP and Central Caledonian Transect profile (e.g., anomalies L1, L2, and L3 in Figs. 7D and 9–10). The characteristics of these anomalies are incompatible with shear zones, which are generally not characterized by high density nor high magnetic susceptibility, and whose boundaries are often gradual across the protolith. This assumption is supported by the complex and low magnetic and gravity anomalies associated with the Storsjön–Edsbyn Deformation Zone and the Hassela Shear Zone in the Fennoscandian Shield (Figs. 7A and 7C).

The question that poses itself is whether some of the reflections at depth could represent alternative features such as shear zones. Seismic profiling of the crystalline continental crust showed early in the 1980s that it could be highly reflective, and several hypotheses were put forward concerning the source of the reflectivity, including mylonite zones (Fountain et al., 1984), overpressured fracture zones (Jones and Nur, 1984), and large-scale lithological boundaries (Brewer et al., 1981). Normally pressured fracture zones in the upper crust and mafic sills were alternative options discussed (e.g., Juhlin and Pedersen, 1987). Since those early studies, a number of studies have identified sources of seismic reflections by either drilling or projecting reflecting zones to the surface and correlating them with mapped geologic features. Fracture zones that are at hydrostatic or near hydrostatic pressure have been identified in both Canada and Sweden as reflectors in conjunction with surveying to site repositories for the storage of spent nuclear fuel (Mair and Green, 1981; Juhlin and Stephens, 2006). In addition, strong reflections originating from dolerites and weaker ones from felsic sills were identified in the Siljan area of central Sweden via drilling into the crystalline crust to ~6.6 km (Juhlin, 1990). Mylonite zones have also been interpreted as the source of reflections in a number of areas in North America (Hurich et al., 1985; Johnson and Smithson, 1985; Ratcliffe et al., 1986). Recently, Brown and Kim (2020) reviewed seismic profiling data from 16 locations in Europe and North America and concluded that most of the reflectivity observed at these sites could be attributed to mafic sills that have intruded into more felsic bedrock. Where reflections have been interpreted or proven to originate from dolerites, they generally have a distinct signature with usually a simple waveform representing the reflection. Often the reflections from the top and bottom interfere with one another constructively to amplify the reflected signal. This is due to the dolerites being laterally continuous over large areas and having a thickness that is relatively constant. In contrast, reflections from mylonite or shear zones generally have a complex pattern of reflectivity with no sharp reflections and significant variation in signature laterally (e.g., Rey et al., 1994; Wrona et al., 2020) and occur over a longer time interval. This can be attributed to the complex and variable nature of the physical properties of these zones (Burlini et al., 2005; Almqvist et al., 2013; Adam et al., 2020). Most of the reflections between 1 km and 9 km on the CSP and Central Caledonian Transect profiles east of COSC-1 have clear, distinct onset and are likely dolerites, while the few others could indeed represent shear zones, or sheared dolerites, of unknown age.

It is possible that some of the mafic intrusions were emplaced during shear zone formation, for example, during the 1.2 Ga event (Central Scandinavian Dolerite Group), or followed the path of pre-existing shear zones. This hypothesis can be postulated because some of the reflections display a lozenge-shaped geometry at depth on the Central Caledonian Transect profile (e.g., below reflection q1 in Fig. 4B), while a few others show a sigmoid shape (q2 in Fig. 4B). With the available data, it is not possible to exclude this hypothesis. However, observations from the Olden window suggest rather that dolerites are deformed by Caledonian shear zones (see, e.g., fig. 8 in Stel, 1988) and that Caledonian deformation is localized along mafic intrusions (Johansson, 1980; Stel, 1988). Besides, there is no evidence from field observations that these intrusions follow pre-existing or active shear zones. In addition, it is hard to explain the geometry (saucer-shapes and sills) and length (>100 km) of the intrusions as corresponding to shear zones that were subsequently intruded by magma (see section 5.2). As such, our primary interpretation involving dense and thick dolerites can largely account for most of the prominent reflections in the basement of central-western Sweden.

6. CONCLUSION

Based on the results from the COSC-2 drilling, new gravity data, and forward potential models, we show that the basement west of the Caledonian front is mostly composed of volcanic porphyries and granites from the Transscandinavian Igneous Belt. In accordance with the tectonic scenario involving dextral en-échelon pull-apart basins for the emplacement of the Transscandinavian Igneous Belt rocks, we propose that these porphyries correspond to the northwestward extension of the Dala porphyries underneath the Caledonian nappes. In addition, we show that the basement is intruded by thick (∼240 m), highly magnetic and dense dolerite sheets that are responsible for arcuate-shaped, asymmetric, and short wavelength anomalies on aeromagnetic maps. Further interpretation of the CSP and Central Caledonian Transect seismic profile indicates the existence of ∼100-km-wide sill complexes and saucer-shaped mafic intrusions in the upper crust. The spatial extent, geometry, and petrology of these flat-lying mafic intrusions compare well with the dolerites of the Central Scandinavian Dolerite Group recognized further east in the Fennoscandian Shield and in the Bothnian Sea. These results suggest a genetic link between the Central Scandinavian Dolerite Group and the pre-existing Hassela Shear Zone and Storsjön–Edsbyn Deformation Zone and reveal a discrepancy between the proposed tectonic setting for the emplacement of the Central Scandinavian Dolerite Group involving extension and the pre-existing models for the emplacement of sills in crystalline upper crust that imply compressional stresses or mechanical layering.

Structural observations from the COSC-2 drilling and seismic interpretations show that Caledonian deformation localized along dolerite margins, which likely represent rheological heterogeneities. Our interpretation of the Central Caledonian Transect profile further indicates the existence of a sole thrust whose length and flat-lying geometry suggest that part of the deformation was controlled by pre-existing sills in the basement. In the hanging-wall of this sole thrust, similar low-angle thrusts and the stacking of basement slices could explain the kilometer-wide basement antiforms observed in the Central Caledonian Transect profile and described further north in the Grong-Olden basement window. On a broad scale, the existence of such a dense network of thick mafic intrusions that controlled basement deformation may partly account for the non-cylindrical architecture of the orogen in central-western Sweden.

ACKNOWLEDGMENTS

This study benefited from the support of the Swedish Research Council (VR project 2018-03414) and the International Continental Scientific Drilling Program (ICDP). COSC-2 used the *Riksriggen* national research infrastructure for scientific drilling (Sweden) and was supported by the ICDP, the Swedish Research Council, the German Science Foundation, and the National Science Centre Poland. The authors thank Petroleum Experts Limited for providing us with the Move software academic license. We thank all who participated in the COSC-2 drilling project. R. Lescoutre thanks David Gee for the interesting discussions about the geology of the Jämtland region, as well as Mohsen Bazargan and George Westmeijer for their company at the drill site. We thank Craig Magee and an anonymous reviewer for thoughtful comments that helped to improve the clarity of the manuscript.

REFERENCES CITED

Adam, L., Frehner, M., Sauer, K., Toy, V., and Guerin-Marthe, S., 2020, Seismic anisotropy and its impact on imaging the shallow Alpine fault: An experimental and modeling perspective: Journal of Geophysical Research: Solid Earth, v. 125, https://doi.org/10.1029/2019JB019029.

Ahl, M., Sundblad, K., and Schöberg, H., 1999, Geology, geochemistry, age and geotectonic evolution of the Dala granitoids, central Sweden: Precambrian Research, v. 95, p. 147–166, https://doi.org/10.1016/S0301-9268(98)00131-4.

Almqvist, B.S.G., Hirt, A.M., Herwegh, M., Ebert, A., Walter, J.M., Leiss, B., and Burlini, L., 2013, Seismic anisotropy in the Morcles nappe shear zone: Implications for seismic imaging of crustal scale shear zones: Tectonophysics, v. 603, p. 162–178, https://doi.org/10.1016/j.tecto.2013.05.025.

Andersson, A., Dahlman, B., Gee, D., and Snall, S., 1985, The Scandinavian alum shales: Sveriges geologiska undersökning. Serie Ca. Avhandlingar och uppsatser I A4, v. 56, p. 1–50.

Bartley, J.M., Glazner, A.F., and Mahan, K.H., 2012, Formation of pluton roofs, floors, and walls by crack opening at Split Mountain, Sierra Nevada, California: Geosphere, v. 8, p. 1086–1103, https://doi.org/10.1130/GES00722.1.

Beckholmen, M., 1978, Geology of the Nordhallen—Duved—Greningen area in Jämtland, central Swedish Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 100, p. 335–347, https://doi.org/10.1080/11035897809454471.

Bender, H., Ring, U., Almqvist, B.S.G., Grasemann, B., and Stephens, M.B., 2018, Metamorphic zonation by out-of-sequence thrusting at back-stepping subduction zones: Sequential accretion of the Caledonian Internides, Central Sweden: Tectonics, v. 37, p. 3545–3576, https://doi.org/10.1029/2018TC005088.

Bender, H., Glodny, J., and Ring, U., 2019, Absolute timing of Caledonian orogenic wedge assembly, Central Sweden, constrained by Rb–Sr multi-mineral isochron data: Lithos, v. 344–345, p. 339–359, https://doi.org/10.1016/j.lithos.2019.06.033.

Bergman, S., and Sjöström, H., 1994, The Storsjön–Edsbyn Deformation Zone, central Sweden, research report: Uppsala, Sveriges Geologiska Undersökning, 46 p.

Bergman, S., Sjöström, H., and Högdahl, K., 2006, Transpressive shear related to arc magmatism: The Paleoproterozoic Storsjön–Edsbyn Deformation Zone, central Sweden: Tectonics, v. 25, https://doi.org/10.1029/2005TC001815.

Bingen, B., Andersson, J., Soderlun, U., and Moller, C., 2008, The Mesoproterozoic in the Nordic countries: Episodes, v. 31, p. 29, https://doi.org/10.18814/epiiugs/2008/v31i1/005.

Brahimi, S., Le Maire, P., Ghienne, J.F., and Munschy, M., 2020, Deciphering channel networks from aeromagnetic potential field data: The case of the North Sea Quaternary tunnel valleys: Geophysical Journal International, v. 220, p. 1447–1462, https://doi.org/10.1093/gji/ggz494.

Brander, L., 2011, The Mesoproterozoic Hallandian event—A region-scale orogenic event in the Fennoscandian Shield [Ph.D. thesis]: Göteborg, Sweden, Faculty of Science, University of Gothenburg, 24 p., http://hdl.handle.net/2077/25445.

Brander, L., and Söderlund, U., 2009, Mesoproterozoic (1.47–1.44 Ga) orogenic magmatism in Fennoscandia; Baddeleyite U–Pb dating of a suite of massif-type anorthosite in S. Sweden: International Journal of Earth Sciences, v. 98, p. 499–516, https://doi.org/10.1007/s00531-007-0281-0.

Brander, L., Söderlund, U., and Bingen, B., 2011, Tracing the 1271–1246 Ma Central Scandinavian Dolerite Group mafic magmatism in Fennoscandia: U–Pb baddeleyite and Hf isotope data on the Moslätt and Børgefjell dolerites: Geological Magazine, v. 148, p. 632–643, https://doi.org/10.1017/S0016756811000033.

Brewer, J.A., Brown, L.D., Steiner, D., Oliver, J.E., Kaufman, S., and Denison, R.E., 1981, Proterozoic basin in the southern Midcontinent of the United States revealed by COCORP deep seismic reflection profiling: Geology, v. 9, p. 569–575, https://doi.org/10.1130/0091-7613(1981)9<569:PBITSM>2.0.CO;2.

Brown, L.D., and Kim, D., 2020, Extensive sills in the continental basement from deep seismic reflection profiling: Geosciences, v. 10, p. 449, https://doi.org/10.3390/geosciences10110449.

Buntin, S., Malehmir, A., Koyi, H., Högdahl, K., Malinowski, M., Larsson, S.Å., Thybo, H., Juhlin, C., Korja, A., and Górszczyk, A., 2019, Emplacement and 3-D geometry of crustal-scale saucer-shaped intrusions in the Fennoscandian Shield: Scientific Reports, v. 9, 10498, https://doi.org/10.1038/s41598-019-46837-x.

Burlini, L., Arbaret, L., Zeilinger, G., and Burg, J.-P., 2005, High-temperature and pressure seismic properties of a lower crustal prograde shear zone from the Kohistan Arc, Pakistan, *in* Bruhn, D., and Burlini, L., eds., High-Strain Zones: Structure and Physical Properties: Geological Society, London, Special Publication 245, p. 187–202, https://doi.org/10.1144/GSL.SP.2005.245.01.09.

Bylund, G., and Elming, S.-Å., 1992, The Dala dolerites, central Sweden, and their palaeomagnetic signature: Geologiska Föreningens i Stockholm Förhandlingar, v. 114, p. 143–153, https://doi.org/10.1080/11035899209453467.

Cattin, R., Mazzotti, S., and Baratin, L.-M., 2015, GravProcess: An easy-to-use MATLAB software to process campaign gravity data and evaluate the associated uncertainties: Computers & Geosciences, v. 81, p. 20–27, https://doi.org/10.1016/j.cageo.2015.04.005.

Chevallier, L., and Woodford, A., 1999, Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo, South Africa: South African Journal of Geology, v. 102, p. 43–54.

Claesson, S., and Lundqvist, T., 1995, Origins and ages of Proterozoic granitoids in the Bothnian Basin, central Sweden; isotopic and geochemical constraints: Lithos, v. 36, p. 115–140, https://doi.org/10.1016/0024-4937(95)00010-D.

Cocks, L.R.M., and Torsvik, T.H., 2002, Earth geography from 500 to 400 million years ago: A faunal and palaeomagnetic review: Journal of the Geological Society, v. 159, p. 631–644, https://doi.org/10.1144/0016-764901-118.

Corfu, F., Torsvik, T.H., Andersen, T.B., Ashwal, L.D., Ramsay, D.M., and Roberts, R.J., 2006, Early Silurian mafic–ultramafic and granitic plutonism in contemporaneous flysch, Magerøy, northern Norway: U–Pb ages and regional significance: Journal of the Geological Society, v. 163, p. 291–301, https://doi.org/10.1144/0016-764905-014.

Corfu, F., Andersen, T.B., and Gasser, D., 2014, The Scandinavian Caledonides: Main features, conceptual advances and critical questions, *in* Corfu, F., Gasser, D., and Chew, D.M., eds., New Perspectives on the Caledonides of Scandinavia and Related Areas: Geological Society, London, Special Publication 390, p. 9–43, https://doi.org/10.1144/SP390.25.

Couzens-Schultz, B.A., Vendeville, B.C., and Wiltschko, D.V., 2003, Duplex style and triangle zone formation: Insights from physical modeling: Journal of Structural Geology, v. 25, p. 1623–1644, https://doi.org/10.1016/S0191-8141(03)00004-X.

Cruden, A.R., and Weinberg, R.F., 2018, Mechanisms of magma transport and storage in the lower and middle crust—magma segregation, ascent and emplacement, *in* Burchardt, S., ed., Volcanic and Igneous Plumbing Systems: Amsterdam, The Netherlands, Elsevier, p. 13–53, https://doi.org/10.1016/B978-0-12-809749-6.00002-9.

Delin, H., 1993, The radiometric age of the Ljusdal granodiorite of central Sweden: Sveriges geologiska undersökning. Series C: forskningsrapporter, p. 13–16.

Delin, H., 1996, U–Pb zircon ages of granitoids in the Kårböle region, central Sweden, *in* Lundvqist, V., ed., Radiometric Dating Results: Sveriges Geologiska Undersökning, v. C828, p. 6–14.

Dentith, M., and Mudge, S.T., 2014, Geophysics for the Mineral Exploration Geoscientist: Cambridge, UK, Cambridge University Press, 438 p., https://doi.org/10.1017/CBO9781139024358.

Dewey, J.F., 1969, Evolution of the Appalachian/Caledonian Orogen: Nature, v. 222, p. 124–129, https://doi.org/10.1038/222124a0.

Dyrelius, D., 1980, Aeromagnetic interpretation in a geotraverse area across the central Scandinavian Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 421–438, https://doi.org/10.1080/11035898009454498.

Dyrelius, D., 1986, Gravity and magnetics in the central Scandes: Geologiska Föreningens i Stockholm Förhandlingar, v. 108, p. 278–280, https://doi.org/10.1080/11035898609454705.

Ebbing, J., England, R.W., Korja, T., Lauritsen, T., Olesen, O., Stratford, W., and Weidle, C., 2012, Structure of the Scandes lithosphere from surface to depth: Tectonophysics, v. 536–537, p. 1–24, https://doi.org/10.1016/j.tecto.2012.02.016.

Eide, C.H., Schofield, N., Lecomte, I., Buckley, S.J., and Howell, J.A., 2018, Seismic interpretation of sill complexes in sedimentary basins: Implications for the sub-sill imaging problem: Journal of the Geological Society, v. 175, p. 193–209, https://doi.org/10.1144/jgs2017-096.

Elming, S.-Å., 1980, Density and magnetic properties of rocks in the Caledonides of Jämtland, Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 439–453, https://doi.org/10.1080/11035898009454499.

Elming, S.-Å., 1988, Geological modelling based on gravity data from the central part of the Swedish Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 110, p. 317–327, https://doi.org/10.1080/11035898809452666.

Elming, S.-Å., and Mattsson, H.J., 2001, Post Jotnian basic intrusions in the Fennoscandian Shield, and the break up of Baltica from Laurentia: A palaeomagnetic and AMS study: Precambrian Research, v. 108, p. 215–236, https://doi.org/10.1016/S0301-9268(01)00131-0.

England, R.W., and Ebbing, J., 2012, Crustal structure of central Norway and Sweden from integrated modelling of teleseismic receiver functions and the gravity anomaly: Crustal structure of central Norway and Sweden: Geophysical Journal International, v. 191, p. 1–11, https://doi.org/10.1111/j.1365-246X.2012.05607.x.

Fossen, H., and Cavalcante, G.C.G., 2017, Shear zones—A review: Earth-Science Reviews, v. 171, p. 434–455, https://doi.org/10.1016/j.earscirev.2017.05.002.

Fossen, H., and Rykkelid, E., 1992, Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance: Geology, v. 20, p. 737–740, https://doi.org/10.1130/0091-7613(1992)020<0737:PEOTCO>2.3.CO;2.

Fountain, D.M., Hurich, C.A., and Smithson, S.B., 1984, Seismic reflectivity of mylonite zones in the crust: Geology, v. 12, p. 195–198, https://doi.org/10.1130/0091-7613(1984)12<195:SROMZI>2.0.CO;2.

Francis, E.H., 1982, Magma and sediment-I Emplacement mechanism of Late Carboniferous tholeiite sills in northern Britain: President's anniversary address 1981: Journal of the Geological Society, v. 139, p. 1–20, https://doi.org/10.1144/gsjgs.139.1.0001.

Galerne, C.Y., Galland, O., Neumann, E.-R., and Planke, S., 2011, 3-D relationships between sills and their feeders: Evidence from the Golden Valley Sill Complex (Karoo Basin) and experimental modelling: Journal of Volcanology and Geothermal Research, v. 202, p. 189–199, https://doi.org/10.1016/j.jvolgeores.2011.02.006.

Galland, O., Planke, S., Neumann, E.-R., and Malthe-Sørenssen, A., 2009, Experimental modelling of shallow magma emplacement: Application to saucer-shaped intrusions: Earth and Planetary Science Letters, v. 277, p. 373–383, https://doi.org/10.1016/j.epsl.2008.11.003.

Galland, O., et al., 2018, Storage and transport of magma in the layered crust—Formation of sills and related flat-lying intrusions, *in* Burchardt, S., ed., Volcanic and Igneous Plumbing Systems: Amsterdam, The Netherlands, Elsevier, p. 113–138, https://doi.org/10.1016/B978-0-12-809749-6.00005-4.

Gayer, R.A., Powell, D.B., and Rhodes, S., 1978, Deformation against metadolerite dykes in the caledonides of Finnmark, Norway: Tectonophysics, v. 46, p. 99–115, https://doi.org/10.1016/0040-1951(78)90108-7.

Gee, D.G., 1975a, A geotraverse through the Scandinavian Caledonides-Ostersund to Trondheim: Sveriges Geologiska Undersökning Serie C, v. 417, 198 p.

Gee, D., 1975b, A tectonic model for the central part of the Scandinavian Caledonides: American Journal of Science, v. 275, p. 468–515.

Gee, D.G., 1978, Nappe displacement in the Scandinavian Caledonides: Tectonophysics, v. 47, p. 393–419, https://doi.org/10.1016/0040-1951(78)90040-9.

Gee, D.G., 1980, Basement-cover relationships in the central Scandinavian Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 455–474, https://doi.org/10.1080/11035898009454500.

Gee, D.G., Karis, L., Kumpulainen, R., and Thelander, T., 1974, A summary of Caledonian front stratigraphy, northern Jämtland/southern Västerbotten, central Swedish Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 96, p. 389–397, https://doi.org/10.1080/11035897409454292.

Gee, D.G., Kumpulainen, R., Roberts, D., Stephens, M., Thon, A., and Zachrisson, E., 1985, Tectonostratigraphic map of the Caledonide Orogen—Scandinavia and related areas, *in* Gee, D.G., and Sturt, B.A., eds., The Caledonide Orogen—Scandinavia and related areas: Chichester, Wiley, scale 1:2,000,000.

Gee, D.G., Lobkowicz, M., and Singh, S., 1994, Late Caledonian extension in the Scandinavian Caledonides—the Røragen Detachment revisited: Tectonophysics, v. 231, p. 139–155, https://doi.org/10.1016/0040-1951(94)90126-0.

Gee, D.G., Fossen, H., Henriksen, N., and Higgins, A.K., 2008, From the early Paleozoic platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland: Episodes, v. 31, p. 44–51, https://doi.org/10.18814/epiiugs/2008/v31i1/007.

Gee, D.G., Juhlin, C., Pascal, C., and Robinson, P., 2010, Collisional Orogeny in the Scandinavian Caledonides (COSC): GFF, v. 132, p. 29–44, https://doi.org/10.1080/11035891003759188.

Gee, D.G., Janák, M., Majka, J., Robinson, P., and van Roermund, H., 2013, Subduction along and within the Baltoscandian margin during closing of the Iapetus Ocean and Baltica-Laurentia collision: Lithosphere, v. 5, p. 169–178, https://doi.org/10.1130/L220.1.

Gee, D.G., and Stephens, M.B., 2020a, Chapter 19: Regional context and tectonostratigraphic framework of the early–middle Paleozoic Caledonide orogen, northwestern Sweden, *in* Stephens, M.B., and Bergman Weihed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoir 50, p. 481–494, https://doi.org/10.1144/M50-2017-21.

Gee, D.G., and Stephens, M.B., 2020b, Chapter 20: Lower thrust sheets in the Caledonide orogen, Sweden: Cryogenian–Silurian sedimentary successions and underlying, imbricated, crystalline basement, *in* Stephens, M.B., and Bergman Weihed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoir 50, p. 495–515, https://doi.org/10.1144/M50-2018-7.

Gorbatschev, R., 1997, Den prekambriska berggrunden i Jämtlands län—Bergartsbeskrivningar—Översikter och sammanfattningar—Summary: An outline of Precambrian geology in the County of Jämtland: Uppsala, Sveriges geologiska undersökning, p. 18–174.

Gorbatschev, R., and Bogdanova, S., 1993, Frontiers in the Baltic Shield: Precambrian Research, v. 64, p. 3–21, https://doi.org/10.1016/0301-9268(93)90066-B.

Gorbatschev, R., Solyom, Z., and Johansson, I., 1979, The Central Scandinavian Dolerite Group in Jämtland, central Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 101, p. 177–190, https://doi.org/10.1080/11035897909448572.

Gorbatschev, R., Lindh, A., Solyom, Z., Laitakari, I., Aro, K., Lobach-Zhuchenko, S., Markov, M., Ivliev, A., and Bryhni, I., 1987, Mafic dyke swarms of the Baltic Shield, *in* Halls, H.C., and Fahrig, W.F., eds., Mafic Dyke Swarms: Geological Association of Canada, Special Paper 34, p. 361–372.

Goulty, N.R., and Schofield, N., 2008, Implications of simple flexure theory for the formation of saucer-shaped sills: Journal of Structural Geology, v. 30, p. 812–817, https://doi.org/10.1016/j.jsg.2008.04.002.

Greiling, R.O., Grimmer, J.C., De Wall, H., and Björk, L., 2007, Mesoproterozoic dyke swarms in foreland and nappes of the central Scandinavian Caledonides: Structure, magnetic fabric, and geochemistry: Geological Magazine, v. 144, p. 525–546, https://doi.org/10.1017/S0016756807003299.

Greiling, R.O., Kathol, B., and Kumpulainen, R.A., 2018, Nappe units along the Caledonian margin in central

Scandinavia (Grong–Olden to Nasafjället): Definition, distinction criteria and tectonic evolution: GFF, v. 140, p. 66–89, https://doi.org/10.1080/11035897.2018.1453864.

Hauser, E.C., Hurich, C., Palm, H., Dyrelius, D., and Kristoffersen, Y., 1990, Comment and Reply on "Deformation of the Baltic continental crust during Caledonide intracontinental subduction: Views from seismic reflection data": Geology, v. 18, p. 578–580, https://doi.org/10.1130/0091-7613(1990)018<0578:CARODO>2.3.CO;2.

Hedin, P., Juhlin, C., and Gee, D.G., 2012, Seismic imaging of the Scandinavian Caledonides to define ICDP drilling sites: Tectonophysics, v. 554–557, p. 30–41, https://doi.org/10.1016/j.tecto.2012.05.026.

Hedin, P., Malehmir, A., Gee, D.G., Juhlin, C., and Dyrelius, D., 2014, 3-D interpretation by integrating seismic and potential field data in the vicinity of the proposed COSC-1 drill site, central Swedish Caledonides, *in* Corfu, F., Gasser, D., and Chew, D.M., eds., New Perspectives on the Caledonides of Scandinavia and Related Areas: Geological Society, London, Special Publication 390, p. 301–319, https://doi.org/10.1144/SP390.15.

Hogan, J.P., Price, J.D., and Gilbert, M.C., 1998, Magma traps and driving pressure: Consequences for pluton shape and emplacement in an extensional regime: Journal of Structural Geology, v. 20, p. 1155–1168, https://doi.org/10.1016/S0191-8141(98)00063-7.

Högdahl, K., 2000, 1.86–1.85 Ga intrusive ages of K-feldspar megacryst-bearing granites in the type area of the Revsund granites in Jämtland County, central Sweden: GFF, v. 122, p. 359–366, https://doi.org/10.1080/11035890001224359.

Högdahl, K., and Sjöström, H., 2001, Evidence for 1.82 Ga transpressive shearing in a 1.85 Ga granitoid in central Sweden: Implications for the regional evolution: Precambrian Research, v. 105, p. 37–56, https://doi.org/10.1016/S0301-9268(00)00102-9.

Högdahl, K., Gromet, L.P., and Broman, C., 2001, Low P-T Caledonian resetting of U-rich Paleoproterozoic zircons, central Sweden: The American Mineralogist, v. 86, p. 534–546, https://doi.org/10.2138/am-2001-0416.

Högdahl, K., Andersson, U.B., and Eklund, O., eds., 2004, The Transscandinavian Igneous Belt (TIB) in Sweden: A Review of its Character and Evolution: Geological Survey of Finland, Special Paper 37, 125 p.

Hogmalm, K.J., Söderlund, U., Larson, S.Å., Meurer, W.P., Hellström, F.A., and Claeson, D.T., 2006, The Ulvö Gabbro Complex of the 1.27–1.25 Ga Central Scandinavian Dolerite Group (CSDG): Intrusive age, magmatic setting and metamorphic history: GFF, v. 128, p. 1–6, https://doi.org/10.1080/11035890601281001.

Howard, K.A., 1991, Intrusion of horizontal dikes: Tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States: Journal of Geophysical Research: Solid Earth, v. 96, p. 12461–12478, https://doi.org/10.1029/91JB00112.

Hudleston, P.J., 1989, The association of folds and veins in shear zones: Journal of Structural Geology, v. 11, p. 949–957, https://doi.org/10.1016/0191-8141(89)90046-1.

Hurich, C.A., 1996, Kinematic evolution of the lower plate during intracontinental subduction: An example from the Scandinavian Caledonides: Tectonics, v. 15, p. 1248–1263, https://doi.org/10.1029/96TC00828.

Hurich, C.A., and Roberts, D., 1997, A seismic reflection profile from Størdalen to Outer Fosen, central Norway: A note on the principal results: Norges Geologiske Undersøkelse Bulletin, v. 433, p. 18–19.

Hurich, C.A., Smithson, S.B., Fountain, D.M., and Humphreys, M.C., 1985, Seismic evidence of mylonite reflectivity and deep structure in the Kettle dome metamorphic core complex, Washington: Geology, v. 13, p. 577–580, https://doi.org/10.1130/0091-7613(1985)13<577:SEOMRA>2.0.CO;2.

Hurich, C.A., Palm, H., Dyrelius, D., and Kristoffersen, Y., 1989, Deformation of the Baltic continental crust during Caledonide intracontinental subduction: Views from seismic reflection data: Geology, v. 17, p. 423–425, https://doi.org/10.1130/0091-7613(1989)017<0423:DOTBCC>2.3.CO;2.

Ivanic, T., Korsch, R., Wyche, S., Jones, L., Zibra, I., Blewett, R., Jones, T., Milligan, P., Costelloe, R., and Van Kranendonk, M., 2013, Preliminary interpretation of the 2010 Youanmi deep seismic reflection lines and magnetotelluric data for the Windimurra Igneous Complex, *in* Youanmi and Southern Carnarvon seismic and magnetotelluric (MT) workshop, Geological Survey of Western Australia, Record 2013/6 v. 6, p. 93–107.

Jakob, J., Andersen, T.B., and Kjøll, H.J., 2019, A review and reinterpretation of the architecture of the South and South-Central Scandinavian Caledonides—A magma-poor to magma-rich transition and the significance of the reactivation of rift inherited structures: Earth-Science Reviews, v. 192, p. 513–528, https://doi.org/10.1016/j.earscirev.2019.01.004.

Janák, M., van Roermund, H., Majka, J., and Gee, D., 2013, UHP metamorphism recorded by kyanite-bearing eclogite in the Seve Nappe Complex of northern Jämtland, Swedish Caledonides: Gondwana Research, v. 23, no. 3, p. 865–879.

Johansson, L., 1980, Petrochemistry and regional tectonic significance of metabasites in basement windows of the central Scandinavian Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 102, p. 499–514, https://doi.org/10.1080/11035898009454503.

Johansson, L., and Johansson, Å., 1990, Isotope geochemistry and age relationships of mafic intrusions along the Protogine Zone, southern Sweden: Precambrian Research, v. 48, p. 395–414, https://doi.org/10.1016/0301-9268(90)90050-Z.

Johnson, R.A., and Smithson, S.B., 1985, Thrust faulting in the Laramie Mountains, Wyoming, from reanalysis of COCORP data: Geology, v. 13, p. 534–537, https://doi.org/10.1130/0091-7613(1985)13<534:TFITLM>2.0.CO;2.

Jones, T.D., and Nur, A., 1984, The nature of seismic reflections from deep crustal fault zones: Journal of Geophysical Research: Solid Earth, v. 89, p. 3153–3171, https://doi.org/10.1029/JB089iB05p03153.

Juhlin, C., 1990, Interpretation of the reflections in the Siljan Ring area based on results from the Gravberg-1 borehole: Tectonophysics, v. 173, p. 345–360, https://doi.org/10.1016/0040-1951(90)90229-2.

Juhlin, C., and Pedersen, L.B., 1987, Reflection Seismic Investigations of the Siljan Impact Structure, Sweden: Journal of Geophysical Research: Solid Earth, v. 92, p. 14113–14122, https://doi.org/10.1029/JB092iB13p14113.

Juhlin, C., and Stephens, M.B., 2006, Gently dipping fracture zones in Paleoproterozoic metagranite, Sweden: Evidence from reflection seismic and cored borehole data and implications for the disposal of nuclear waste: Journal of Geophysical Research: Solid Earth, v. 111, B09302, https://doi.org/10.1029/2005JB003887.

Juhlin, C., Hedin, P., Gee, D.G., Lorenz, H., Kalscheuer, T., and Yan, P., 2016, Seismic imaging in the eastern Scandinavian Caledonides: Siting the 2.5 km deep COSC-2 borehole, central Sweden: Solid Earth, v. 7, p. 769–787, https://doi.org/10.5194/se-7-769-2016.

Juhlin, C., et al., 2021, Collisional Orogeny in the Scandinavian Caledonides (COSC): Some preliminary results from drilling of the 2.276 km deep COSC-2 borehole, central Sweden: European Geophysical Union General Assembly 2021, online, 19–30 April 2021, EGU21-538, https://doi.org/10.5194/egusphere-egu21-538.

Juhojuntti, N., Juhlin, C., and Dyrelius, D., 2001, Crustal reflectivity underneath the Central Scandinavian Caledonides: Tectonophysics, v. 334, p. 191–210, https://doi.org/10.1016/S0040-1951(00)00292-4.

Karis, L., Strömberg, A.G., and Gorbatschev, R., 1998, Jämtlands Östliga Fjällberggrund: Beskrivning till Berggrundskartan över Jämtlands län: Del 2. Fjälldelen: Sveriges Geologiska Undersökning, Serie C, v. 53, no. 2, p. 1–363.

Kavanagh, J.L., Menand, T., and Sparks, R.S.J., 2006, An experimental investigation of sill formation and propagation in layered elastic media: Earth and Planetary Science Letters, v. 245, p. 799–813, https://doi.org/10.1016/j.epsl.2006.03.025.

Kisch, H.J., 1980, Incipient metamorphism of Cambro-Silurian clastic rocks from the Jåmtland Supergroup, Central Scandinavian Caledonides, Western Sweden: Illite crystallinity and "vitrinite" reflectance: Journal of the Geological Society, v. 137, p. 271–288, https://doi.org/10.1144/gsjgs.137.3.0271.

Koistinen, T., Stephens, M., Bogatchev, V., Nordgulen, Ø., Wennerström, M., and Korhonen, J., 2001, Geological map of the Fennoscandian Shield: Geological Survey of Finland, Norway and Sweden and the North-West Department of Nat. Resources of Russia, scale 1:2,000,000.

Korja, A., Heikkinen, P., and Aaro, S., 2001, Crustal structure of the northern Baltic Sea palaeorift: Tectonophysics, v. 331, p. 341–358, https://doi.org/10.1016/S0040-1951(00)00290-0.

Korja, T., Smirnov, M., Pedersen, L.B., and Gharibi, M., 2008, Structure of the Central Scandinavian Caledonides and the underlying Precambrian basement, new constraints from magnetotellurics: Geophysical Journal International, v. 175, p. 55–69, https://doi.org/10.1111/j.1365-246X.2008.03913.x.

Krill, A., 1986, Eidsvoll quarry, Oppdal, South Norway: A one-outcrop model for some aspects of Trollheimen-Dovrefjell tectonics: Norges Geologiske Undersøkelse Bulletin, v. 404, p. 21–30.

Larson, S.Å., 1980, Layered intrusions of the Ulvö dolerite complex, Ångermanland, Sweden [Ph.D. thesis]: Gothenburg University, Institution Geology Publ., v. A, 213 p.

Lindqvist, J.E., 1990, Thrust-related metamorphism in basement windows of the central Scandinavian Caledonides: Journal of the Geological Society, v. 147, p. 69–80, https://doi.org/10.1144/gsjgs.147.1.0069.

Lindström, M., Sturkell, E.F., Törnberg, R., and Ormouml, J., 1996, The marine impact crater at Lockne, central Sweden: GFF, v. 118, p. 193–206, https://doi.org/10.1080/11035899609546255.

Lorenz, H., et al., 2015, COSC-1—drilling of a subduction-related allochthon in the Palaeozoic Caledonide orogen of Scandinavia: Scientific Drilling, v. 19, p. 1–11, https://doi.org/10.5194/sd-19-1-2015.

Lorenz, H., Juhlin, C., Rosberg, J.-E., Bazargan, M., Klonowska, I., Kück, J., Lescoutre, R., Rejkjær, S., Westmeijer, G., and Ziemniak, G., 2021, COSC-2 operational report— Operational data sets: GFZ Data Services, https://doi.org/10.5880/ICDP.5054.003.

Lundmark, A.M., and Lamminen, J., 2016, The provenance and setting of the Mesoproterozoic Dala Sandstone, western Sweden, and paleogeographic implications for southwestern Fennoscandia: Precambrian Research, v. 275, p. 197–208, https://doi.org/10.1016/j.precamres.2016.01.003.

Lundqvist, T., and Persson, P.-O., 1996, U-Pb ages of porphyries and related rocks in northern Dalarna, south-central Sweden: GFF, v. 118, p. 17–18, https://doi.org/10.1080/11035899609546280.

Lundqvist, T., and Persson, P.-O., 1999, Geochronology of porphyries and related rocks in northern and western Dalarna, south-central Sweden: GFF, v. 121, p. 307–322, https://doi.org/10.1080/11035899901214307.

Lundqvist, T., Bøe, R., Kousa, J., Lukkarinen, H., Lutro, O., Roberts, D., Solli, A., Stephens, M., and Weihed, P., 1996, Bedrock map of Central Fennoscandia: Geological Surveys of Finland, Norway (Trondheim), and Sweden (Uppsala), scale 1:1,000,000.

MacDonald, J.M., Magee, C., and Goodenough, K.M., 2017, Dykes as physical buffers to metamorphic overprinting: An example from the Archaean–Palaeoproterozoic Lewisian Gneiss Complex of NW Scotland: Scottish Journal of Geology, v. 53, p. 41–52, https://doi.org/10.1144/sjg2017-004.

Magee, C., et al., 2016, Lateral magma flow in mafic sill complexes: Geosphere, v. 12, p. 809–841, https://doi.org/10.1130/GES01256.1.

Magnor, B., Stigh, J., and Larson, S.Å., 1996, Mesoproterozoic deformation of the Lower Dala Group and the Jotnian sedimentary rocks: GFF, v. 118, p. 18, https://doi.org/10.1080/11035899609546281.

Mair, J.A., and Green, A.G., 1981, High-resolution seismic reflection profiles reveal fracture zones within a 'homogeneous' granite batholith: Nature, v. 294, p. 439–442, https://doi.org/10.1038/294439a0.

Mattsson, H.J., and Elming, S.-Å., 2001a, A paleomagnetic and AMS study of the Rätan granite of the Transscandinavian Igneous Belt, central Sweden: GFF, v. 123, p. 205–215, https://doi.org/10.1080/11035890101234205.

Mattsson, H.J., and Elming, S.-Å., 2001b, Magnetic fabrics and paleomagnetism of the Storsjön–Edsbyn deformation zone, central Sweden: Precambrian Research, v. 107, p. 265–281, https://doi.org/10.1016/S0301-9268(00)00145-5.

Minakov, A., Yarushina, V., Faleide, J.I., Krupnova, N., Sakoulina, T., Dergunov, N., and Glebovsky, V., 2018, Dyke emplacement and crustal structure within a continental large igneous province, northern Barents Sea, *in* Pease, V., and Coakley, B., eds., Circum-Arctic Lithosphere Evolution: Geological Society, London, Special Publication 460, p. 371–395, https://doi.org/10.1144/SP460.4.

Olesen, O., Gellein, J., Gernigon, L., Kihle, O., Koziel, J., Lauritsen, T., Mogaard, J.O., Myklebust, R., Skilbrei, J.R., and Usov, S., 2010, Magnetisk anomalikart, Norge og tilgrensende områder [Magnetic anomaly map, Norway and adjacent areas]: Geological Survey of Norway, scale 1:3 million, https://www.ngu.no/en/publikasjon/magnetic-anomaly-map-norway-and-adjacent-areas-scale-13-mill.

Palm, H., Gee, D., Dyrelius, D., and Björklund, L., 1991, A reflection seismic image of Caledonian structure in central Sweden: Sveriges geologiska undersökning, Serie Ca. 75, 36 p.

Pascal, C., Ebbing, J., and Skilbrei, J.R., 2007, Interplay between the Scandes and the Trans-Scandinavian Igneous Belt: Integrated thermo-rheological and potential field modelling of the Central Scandes profile: Norwegian Journal of Geology, v. 87, p. 3–12.

Patchett, P.J., Todt, W., and Gorbatschev, R., 1987, Origin of continental crust of 1.9–1.7 ga age: nd isotopes in the svecofennian orogenic terrains of Sweden: Precambrian Research, v. 35, p. 145–160, https://doi.org/10.1016/0301-9268(87)90050-7.

Patchett, P.J., Lehnert, K., Rehk Mper, M., and Sieber, G., 1994, Mantle and crustal effects on the geochemistry of Proterozoic dikes and sills in Sweden: Journal of Petrology, v. 35, p. 1095–1125, https://doi.org/10.1093/petrology/35.4.1095.

Pollard, D.D., and Johnson, A.M., 1973, Mechanics of growth of some laccolithic intrusions in the Henry mountains, Utah, II: Tectonophysics, v. 18, p. 311–354, https://doi.org/10.1016/0040-1951(73)90051-6.

Polteau, S., Ferré, E.C., Planke, S., Neumann, E.-R., and Chevallier, L., 2008a, How are saucer-shaped sills emplaced? Constraints from the Golden Valley Sill, South Africa: Journal of Geophysical Research: Solid Earth, v. 113, https://doi.org/10.1029/2008JB005620.

Polteau, S., Mazzini, A., Galland, O., Planke, S., and Malthe-Sørenssen, A., 2008b, Saucer-shaped intrusions: Occurrences, emplacement and implications: Earth and Planetary Science Letters, v. 266, p. 195–204, https://doi.org/10.1016/j.epsl.2007.11.015.

Rabbel, O., Galland, O., Mair, K., Lecomte, I., Senger, K., Spacapan, J.B., and Manceda, R., 2018, From field analogues to realistic seismic modelling: A case study of an oil-producing andesitic sill complex in the Neuquén Basin, Argentina: Journal of the Geological Society, v. 175, p. 580–593, https://doi.org/10.1144/jgs2017-116.

Ratcliffe, N.M., Burton, W.C., D'Angelo, R.M., and Costair, J.K., 1986, Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania: Geology, v. 14, p. 766–770, https://doi.org/10.1130/0091-7613(1986)14<766:LEFRMA>2.0.CO;2.

Rey, P.F., Fountain, D.M., and Clement, W.P., 1994, P wave velocity across a noncoaxial ductile shear zone and its associated strain gradient: Consequences for upper crustal reflectivity: Journal of Geophysical Research: Solid Earth, v. 99, p. 4533–4548, https://doi.org/10.1029/93JB03105.

Rice, A.H.N., 1986, Structures associated with superimposed inhomogenous shearing of basic dykes from Finnmark, Norway: Tectonophysics, v. 128, p. 61–75, https://doi.org/10.1016/0040-1951(86)90308-2.

Rice, A.H.N., and Anderson, M.W., 2016, Restoration of the external Scandinavian Caledonides: Geological Magazine, v. 153, p. 1136–1165, https://doi.org/10.1017/S0016756816000340.

Ripa, M., and Stephens, M.B., 2020a, Chapter 12 Dolerites (1.27–1.25 Ga) and alkaline ultrabasic dykes (c. 1.14 Ga) related to intracratonic rifting, *in* Stephens, M.B., and Bergman Welhed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoir 50, p. 315–323, https://doi.org/10.1144/M50-2017-5.

Ripa, M., and Stephens, M.B., 2020b, Chapter 13 Siliciclastic sedimentation in a foreland basin to the Sveconorwegian orogen and dolerites (0.98–0.95 Ga) related to intracratonic rifting, *in* Stephens, M.B., and Bergman Welhed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoirs 50, p. 325–333, https://doi.org/10.1144/M50-2017-6.

Roberts, D., 1997, Geochemistry of Palaeoproterozoic porphyritic felsic volcanites from the olden and T∅mmerås windows, central Norway: GFF, v. 119, p. 141–148, https://doi.org/10.1080/11035899709546470.

Roberts, D., and Gee, D.G., 1985, An introduction to the structure of the Scandinavian Caledonides, *in* Roberts, D., and Gee, D.G., 1985, An Introduction to the Structure of the Scandinavian Caledonides: The Caledonide Orogen—Scandinavia and Related Areas: Chichester, UK, Wiley, p. 55–68.

Roberts, D., Nissen, A.L., and Walker, N., 1999, U-Pb zircon age and geochemistry of the Bl fjellhatten granite, Grong-Olden Culmination, Central Norway: Norsk Geologisk Tidsskrift, v. 79, p. 161–168, https://doi.org/10.1080/002919699433799.

Robinson, P., Roberts, D., Gee, D.G., and Solli, A., 2014, A major synmetamorphic Early Devonian thrust and extensional fault system in the Mid Norway Caledonides: Relevance to exhumation of HP and UHP rocks: Geological Society, London, Special Publication 390, p. 241–270, https://doi.org/10.1144/SP390.24.

Scott, L., 2019, Dyke reactivation across the frictional-viscous transition: Precambrian deformation of Scourie dyke margins in NW Scotland, *in* Sjöström, H., and Talbot, C.J., 1987, Caledonian and Post-Caledonian Structure of the Olden Window, Scandinavian Caledonides: Geologiska Föreningens i Stockholm Förhandlingar, v. 109, p. 359–361, https://doi.org/10.1080/11035898709453109.

Sjöström, H., and Talbot, C.J., 1987, Caledonian and post-Caledonian structure of the Olden Window, Scandinavian Caledonides: Geologiska Föreningen i Stockholm Förhandlingar, v. 109, no. 4, p. 359–361, https://doi.org/10.1080/11035898709453109.

Sjöström, H., Talbot, C., and Bergman, S., 1996, The development of antiformal windows in the central Scandinavian Caledonides: Antiformal stacks modified by extensional detachments: GFF, v. 118, p. 40, https://doi.org/10.1080/11035899609546313.

Skilbrei, J.R., Olesen, O., Osmundsen, P.T., Kihle, O., Aaro, S., and Fjellanger, E., 2002, A study of basement structures and onshore-offshore correlations in Central Norway: Norwegian Journal of Geology, v. 82, p. 263–279.

Skyttä, P., Weihed, P., Högdahl, K., Bergman, S., and Stephens, M.B., 2020, Chapter 4 Paleoproterozoic (2.0–1.8 Ga) syn-orogenic sedimentation, magmatism and mineralization in the Bothnia–Skellefteå lithotectonic unit, Svecokarelian orogen, *in* Stephens, M.B., and Bergman Welhed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoir 50, p. 83–130, https://doi.org/10.1144/M50-2017-10.

Smittarello, D., Cayol, V., Pinel, V., Peltier, A., Froger, J., and Ferrazzini, V., 2019, Magma propagation at Piton de la Fournaise from joint inversion of InSAR and GNSS: Journal of Geophysical Research: Solid Earth, v. 124, p. 1361–1387, https://doi.org/10.1029/2018JB016856.

Söderlund, U., Isachsen, C.E., Bylund, G., Heaman, L.M., Jonathan Patchett, P., Vervoort, J.D., and Andersson, U.B., 2005, U–Pb baddeleyite ages and Hf, Nd isotope chemistry constraining repeated mafic magmatism in the Fennoscandian Shield from 1.6 to 0.9 Ga: Contributions to Mineralogy and Petrology, v. 150, p. 174–194, https://doi.org/10.1007/s00410-005-0011-1.

Söderlund, P., Söderlund, U., Möller, C., Gorbatschev, R., and Rodhe, A., 2004, Petrology and ion microprobe U-Pb chronology applied to a metabasic intrusion in southern Sweden: A study on zircon formation during metamorphism and deformation: Tectonics, v. 23, https://doi.org/10.1029/2003TC001498.

Söderlund, U., Elming, S.-Å., Ernst, R.E., and Schissel, D., 2006, The Central Scandinavian Dolerite Group—Protracted hotspot activity or back-arc magmatism?: Precambrian Research, v. 150, p. 136–152, https://doi.org/10.1016/j.precamres.2006.07.004.

Solyom, Z., Lindqvist, J.-E., and Johansson, I., 1992, The geochemistry, genesis, and geotectonic setting of Proterozoic mafic dyke swarms in southern and central Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 114, p. 47–65, https://doi.org/10.1080/11035899209453461.

Souche, A., Galland, O., Haug, Ø.T., and Dabrowski, M., 2019, Impact of host rock heterogeneity on failure around pressurized conduits: Implications for finger-shaped magmatic intrusions: Tectonophysics, v. 765, p. 52–63, https://doi.org/10.1016/j.tecto.2019.05.016.

Spacapan, J.B., Palma, J.O., Galland, O., Manceda, R., Rocha, E., D'Odorico, A., and Leanza, H.A., 2018, Thermal impact of igneous sill-complexes on organic-rich formations and implications for petroleum systems: A case study in the northern Neuquén Basin, Argentina: Marine and Petroleum Geology, v. 91, p. 519–531, https://doi.org/10.1016/j.marpetgeo.2018.01.018.

Stel, H., 1988, Basement-cover relations at the Grong-Olden culmination, Central Norway: Norsk Geologisk Tidsskrift, v. 68, p. 135–147.

Stephens, M.B., 1988, The Scandinavian Caledonides: A complexity of collisions: Geology Today, v. 4, p. 20–26, https://doi.org/10.1111/j.1365-2451.1988.tb00537.x.

Stephens, M.B., and Wahlgren, C.-H., 2020, Chapter 15 Polyphase (1.9–1.8, 1.5–1.4 and 1.0–0.9 Ga) deformation and metamorphism of Proterozoic (1.9–1.2 Ga) continental crust, Eastern Segment, Sveconorwegian orogen, *in* Stephens, M.B., and Bergman Welhed, J., eds., Sweden: Lithotectonic Framework, Tectonic Evolution and Mineral Resources: Geological Society, London, Memoir 50, p. 351–396, https://doi.org/10.1144/M50-2018-57.

Stephens, T.L., Walker, R.J., Healy, D., Bubeck, A., and England, R.W., 2018, Mechanical models to estimate the paleostress state from igneous intrusions: Solid Earth, v. 9, p. 847–858, https://doi.org/10.5194/se-9-847-2018.

Svensen, H., Planke, S., Polozov, A.G., Schmidbauer, N., Corfu, F., Podladchikov, Y.Y., and Jamtveit, B., 2009, Siberian gas venting and the end-Permian environmental crisis: Earth and Planetary Science Letters, v. 277, p. 490–500, https://doi.org/10.1016/j.epsl.2008.11.015.

Thomson, K., and Hutton, D., 2004, Geometry and growth of sill complexes: Insights using 3-D seismic from the North Rockall Trough: Bulletin of Volcanology, v. 66, p. 364–375, https://doi.org/10.1007/s00445-003-0320-z.

Troëng, B., 1982, Uranium-rich granites in the Olden Window, Sweden: Mineralogical Magazine, v. 46, p. 217–226, https://doi.org/10.1180/minmag.1982.046.339.08.

Ulmius, J., Andersson, J., and Möller, C., 2015, Hallandian 1.45 Ga high-temperature metamorphism in Baltica: P–T evolution and SIMS U–Pb zircon ages of aluminous gneisses, SW Sweden: Precambrian Research, v. 265, p. 10–39, https://doi.org/10.1016/j.precamres.2015.04.004.

Walker, R., Healy, D., Kawanzaruwa, T., Wright, K., England, R., McCaffrey, K., Bubeck, A., Stephens, T., Farrell, N., and Blenkinsop, T., 2017, Igneous sills as a record of horizontal shortening: The San Rafael subvolcanic field, Utah: Geological Society of America Bulletin, v. 129, p. 1052–1070, https://doi.org/10.1130/B31671.1.

Welin, E., Christansson, K., and Kähr, A.-M., 1993, Isotopic investigations of metasedimentary and igneous rocks in the Palaeoproterozoic Bothnian Basin, central Sweden: Geologiska Föreningens i Stockholm Förhandlingar, v. 115, p. 285–296, https://doi.org/10.1080/11035899309453915.

Wilson, C.J.L., Vassallo, J.J., and Hoek, J.D., 2020, Rheological behaviour of mafic dykes deformed in a granite host, Wanna, Eyre Peninsula, South Australia: Journal of Structural Geology, v. 140, https://doi.org/10.1016/j.jsg.2020.104164.

Wilson, M., Hamilton, P., Fallick, A., Aftalion, M., and Michard, A., 1985, Granites and early Proterozoic crustal evolution in Sweden: Evidence from SmNd, UPb and O isotope systematics: Earth and Planetary Science Letters, v. 72, p. 376–388, https://doi.org/10.1016/0012-821X(85)90059-7.

Wrona, T., Magee, C., Fossen, H., Gawthorpe, R.L., Bell, R.E., Jackson, C.A.-L., and Faleide, J.I., 2019, 3-D seismic images of an extensive igneous sill in the lower crust: Geology, v. 47, p. 729–733, https://doi.org/10.1130/G46150.1.

Wrona, T., Fossen, H., Lecomte, I., Eide, C.H., and Gawthorpe, R.L., 2020, Seismic expression of shear zones: Insights from 2-D point-spread-function based convolution modelling: Journal of Structural Geology, v. 140, https://doi.org/10.1016/j.jsg.2020.104121.

Yan, P., Garcia Juanatey, M.A., Kalscheuer, T., Juhlin, C., Hedin, P., Savvaidis, A., Lorenz, H., and Kück, J., 2017a, A magnetotelluric investigation of the Scandinavian Caledonides in western Jämtland, Sweden, using the COSC borehole logs as prior information: Geophysical Journal International, v. 208, p. 1465–1489, https://doi.org/10.1093/gji/ggw457.

Yan, P., Kalscheuer, T., Hedin, P., and Garcia Juanatey, M.A., 2017b, Two-dimensional magnetotelluric inversion using reflection seismic data as constraints and application in the COSC project: Two-dimensional MT inversion using seismic constraints: Geophysical Research Letters, v. 44, p. 3554–3563, https://doi.org/10.1002/2017GL072953.

Young, D.J., 2017, Structure of the (ultra)high-pressure Western Gneiss Region, Norway: Imbrication during Caledonian continental margin subduction: Geological Society of America Bulletin, v. 130, p. 926–940, https://doi.org/10.1130/B31764.1.

Science Editor: Rob Strachan
Associate Editor: Stefano Mazzoli

Manuscript Received 28 May 2021
Revised Manuscript Received 4 November 2021
Manuscript Accepted 27 December 2021

Printed in the USA