

Subduction along and within the Baltoscandian margin during closing of the Iapetus Ocean and Baltica-Laurentia collision

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ABSTRACT

The recent discovery of ultrahigh-pressure (UHP) mineral parageneses in the far-transported (greater than 400 km) Seve Nappe Complex of the Swedish Caledonides sheds new light on the subduction system that dominated the contracting Baltoscandian margin of continental Baltica during the Ordovician and culminated in collision with Laurentia in the Silurian to Early Devonian. High-grade metamorphism of this Neoproterozoic to Cambrian rifted, extended, dike-intruded outer-margin assemblage started in the Early Ordovician and may have continued, perhaps episodically, until collision of the continents at the end of this period. The recent discovery of UHP kyanite eclogite in northern Jämtland (west-central Sweden) yields evidence of metamorphism at depths of 100 km. Although UHP rocks are only locally preserved from retrogression during the long-distance transport onto the Baltoscandian platform, these high-pressure parageneses indicate that deep subduction played an important role in the tectonothermal history of the complex. Based on existing isotopic age data, this UHP metamorphism occurred in the Late Ordovician, shortly before, or during, the initial collision between the continents (Scandian orogeny). In some central parts of the complex, migmatization and hot extrusion occurred in the Early Silurian, giving way to thrust emplacement across the Baltoscandian foreland basin and platform that continued into the Early Devonian. Identification of HP/UHP metamorphism at different levels within the Scandian allochthons, definition of their pressure-temperature-time paths, and recognition of their vast transport distances are essential for an understanding of the deeper structural levels of the orogen in the hinterland (e.g., the Western Gneiss Region), where the attenuated units were reworked together during the Early Devonian.

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INTRODUCTION

There are few places in the world where it is possible to trace a hot allochthon for 200 km across a continental margin, demonstrate its lateral displacement to have been more than twice this distance, infer that it was generated in an outer-margin subduction system during the final stages of ocean closure, and show that emplacement onto the platform occurred during subsequent continent collision. As a result of good exposure in the Scandian mountain belt and erosion to middle-crustal levels, the Caledonides in Scandinavia provide one of the best opportunities on the planet to study these aspects of orogeny.

Ninety years ago, Eskola (1921) described the remarkable occurrence of eclogites in the deep hinterland of the Caledonides in southwestern Norway, the so-called Western Gneiss Region. Subsequently, compelling evidence was provided of their widespread formation by recrystallization of dolerites and gabbros in the Baltoscandian basement (Gjelsvik, 1952;

Bryhni et al., 1970; Krogh, 1977; Griffin and Carswell, 1985; Griffin et al., 1985), their Caledonian age (Krogh et al., 1974; Griffin and Brueckner, 1980; Gebauer et al., 1985), and local evidence of ultrahigh-pressure (UHP) metamorphism (Smith, 1984; Dobrzhinetskaya et al., 1995; Wain, 1997; Van Roermund and Drury, 1998; Wain et al., 2000; Terry et al., 2000; Van Roermund et al., 2002; Carswell et al., 2006; Vrijmoed et al., 2006; Scambelluri et al., 2008; Hacker et al., 2010). Forty years ago, Zwart (1974) reported eclogites in the long-transported Seve Nappe Complex in the Swedish Caledonides, thrust far onto the Baltoscandian foreland basin and platform. Emplacement of this continental outer-margin assemblage of amphibolite-, granulite-, and eclogite-facies gneisses, with abundant amphibolites, metagabbros, and, locally, ultramafites, was inferred to have occurred during Scandian (Early Silurian to Early Devonian) collision of Baltica with Laurentia and subsequent underthrusting of the latter by the former (Gee, 1975). Eclogites were later found to be relatively widespread in

the Seve complex in the Swedish Caledonides (summaries in Andréasson et al., 1985; Van Roermund, 1985), and many of these were inferred to have formed along the Baltoscandian outer margin during Ordovician subduction (Dallmeyer and Gee, 1986; Andréasson, 1994; Brueckner and van Roermund, 2004), prior to collision of the continents. This paper amplifies the first report (Majka and Janák, 2011) of UHP metamorphism occurring in the Seve Nappe Complex of northern Jämtland, and a detailed presentation of the petrology, mineralogy, mineral chemistry, and accompanying thermodynamic calculations used to constrain the pressure-temperature evolution of the eclogites (Janák et al., 2012a). In this paper, we emphasize the importance of defining the pressure-temperature-time (*P-T-t*) histories of these high-grade rocks at different tectonic levels within the mountain belt, from their well-preserved development in the type areas to their complex intercalation with underlying basement units in the deep hinterland (Western Gneiss Region) in western Norway. The evidence summarized

here of subduction along and within the Baltoscandian margin also supports the interpretation that the Caledonides provide an insightful analogue for the Himalaya-Tibet mountain belt, where orthogonal collision has dominated orogeny over the past 50 m.y., with many hundreds of kilometers of underthrusting of Asia by India.

GEOLOGICAL BACKGROUND

The eastern flank of the North Atlantic Caledonides is particularly well exposed in the mountains of western Scandinavia, the Scandes (Fig. 1). This mid-Paleozoic orogen was formed by closure of the Ediacaran-Cambrian Iapetus Ocean during the Ordovician and collision between the continents Laurentia and Baltica in the Silurian. Underthrusting of the former by the latter continued into the Devonian, with hinterland uplift, collapse of the mountain belt, and continued emplacement of the allochthons far onto the continental platforms (Gee et al., 2008). Along the western side of the orogen, presently exposed in eastern Greenland, the Caledonian nappes were derived from the Laurentian continental margin, with the highest units emplaced westward on the order of 200 km onto the Laurentian platform (Higgins and Leslie, 2000; Higgins et al., 2008). In the Scandinavian Caledonides, the nappes were thrust eastward and comprise a more comprehensive tectonostratigraphic succession (Gee et al., 1985), including both Baltica margin and outboard terranes, some of Laurentian affinities (Stephens and Gee, 1985). The Baltoscandian platform cover of the autochthonous Baltic Shield is separated by a regional décollement from Ediacaran to Cambrian passive-margin and subsequent foreland basin successions of the Lower Allochthon, which are in turn overthrust by the Middle Allochthon of Cryogenian to Ediacaran rift-related successions derived from the outer parts of the margin and continent-ocean transition zone (Seve Nappe Complex). The overlying Köli Nappes of the Upper Allochthon comprise Iapetus Ocean terranes, with extensive tracts of Cambrian to Ordovician rocks, including ophiolites, island-arc and forearc and backarc assemblages, some derived from locations proximal to Baltica, others to Laurentia. These are overthrust by fragments of the Laurentian continental margin (Uppermost Allochthon).

A factor of particular importance for the interpretation of the HP/UHP allochthons in the Scandinavian mountain belt has been an understanding of the stratigraphic relationships between the Baltoscandian platform to foreland basin assemblages of the Lower Allochthon, and the more metamorphosed and ductilely deformed overlying Neoproterozoic units of the

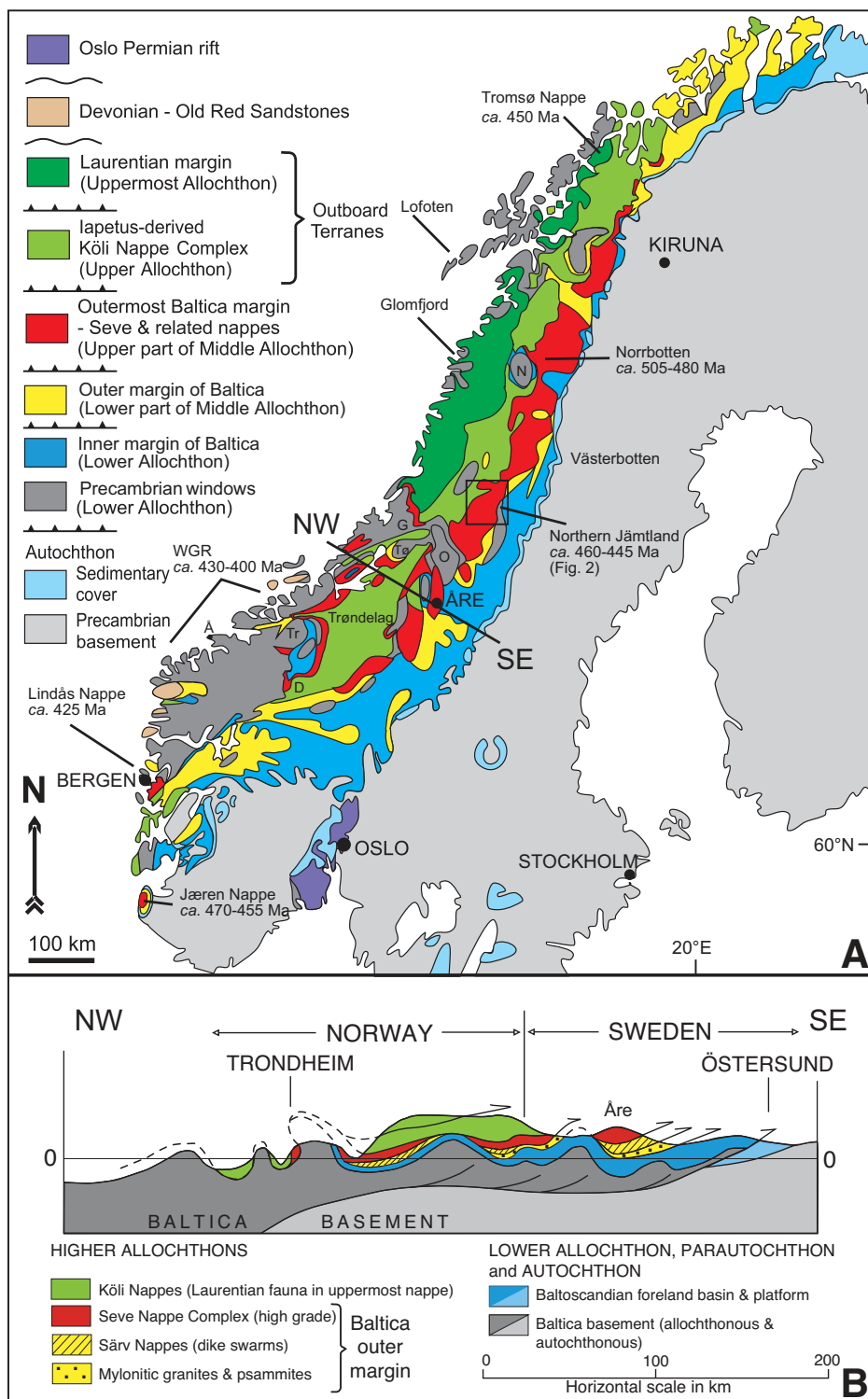


Figure 1. Tectonostratigraphic map (A) and section (B) of the Scandinavian Caledonides, from Gee et al. (2010), with minor revision; black line shows the location of the section (vertical exaggeration 5 \times). Note, on the latter, that attenuation of the major allochthons in the western hinterland, separating the Köli Nappes from the basement, prevents their display at this scale. Some of the places referred to in the text are abbreviated on this figure: D—Dombas, G—Grong, N—Nasafjäll, O—Olden, Tr—Trollheimen, Tø—Tømmerås, Å—Ålesund.

Middle Allochthon. The different tectonic units of the Lower Allochthon in the central Scandes, the Jämtlandian Nappes, are closely related and unambiguously coupled to the autochthonous platform black shales and carbonates of the Baltoscandian platform. The successions in these overlying nappes, which include Cambrian-Ediacaran sandstones (quartzites) and Middle and Late Cambrian black (alum) shales, are remarkable for their Ordovician and Silurian facies changes into deeper-water siliciclastic formations of the foreland basin. Hinterland-derived turbidites (Karis *in* Karis and Strömberg, 1998) occur in the Early to mid-Ordovician (ca. 475–460 Ma) and Early to mid-Silurian (ca. 433–423 Ma), apparently in response to early and late Caledonian nappe emplacement along the Baltoscandian margin. The shallow-marine deposition separating these turbidites may reflect an interval of tectonic quiescence along this margin. Late Neoproterozoic successions, including tillites, are preserved in the higher thrust sheets of the Lower Allochthon, allowing direct correlation with the stratigraphy of the overlying Middle Allochthon. The successions in the latter are several kilometers thick (Kumpulainen and Nystuen, 1985), and they are dominated by fluvial to shallow-marine sandstones that pass stratigraphically upward into carbonates and tillites and then late Ediacaran sandstones. Rift-related, ca. 600 Ma dolerite dike swarms (Solyom et al., 1979; Hollocher et al., 2007) intrude these formations of the Särvi Nappes in the upper part of the Middle Allochthon, and they are overthrust in turn by the Seve Nappe Complex. In many places, this contact is a major thrust zone, marked by a sharp jump in metamorphic grade. Locally, however, transitions from dike-intruded Särvi sandstones, via amphibolitized, ductilely deformed, mafic dikes in quartzites to eclogitized dikes in sheath-folded quartzites have been described (Van Roermund and Bakker, 1984; Andréasson et al., 1985; Andréasson and Albrecht, 1995). There can be little doubt that the Särvi and the Seve nappes are related, and the latter represent the outermost part of the rifted and highly extended Baltoscandian margin, including the continent-ocean transition zone (Andréasson and Gee, 2008).

The displacement distances of the various Caledonian allochthons in Scandinavia have been known to be considerable ever since the early work of Törnebohm (1888, 1896) and Högbom (1909). They demonstrated that the high-grade Seve nappes could be traced ~200 km across the central parts of the orogen from type areas in Sweden to Trondheimsfjord in western Norway (see profile in Fig. 1). Asklund (1938) reaffirmed this evidence, requiring that the so-called Great Seve Nappe was derived

from west of the Norwegian coast, and Holte-dahl (1953) and Strand and Kulling (1972) provided further support. Subsequently, various attempts were made to better quantify the displacement distances (Gee, 1975), taking more detailed account of the characteristics of the different thrust sheets of the Middle and Lower Allochthons, and to make palinspastic reconstructions of the extended, rifted, and drifted Baltoscandian passive margin (Hossack et al., 1985; Kumpulainen and Nystuen, 1985; Morley, 1986; Gayer et al., 1987; Rice, 2005; Greiling and Garfunkel, 2007; Nystuen et al., 2008).

The character and age of the older basement upon which the Neoproterozoic to Early Paleozoic successions were deposited are highly contested. Some favor Paleoproterozoic and older crystalline complexes (e.g., Li et al., 2008), while others are persuaded that the collapsed, extended and deeply eroded Sveconorwegian orogen comprised this basement, continuing northward from type areas in southern Scandinavia beneath the Baltoscandian Iapetus margin into what is now the Arctic (e.g., Zwart and Dornsiepen, 1978; Lorenz et al., 2012). The latter interpretation, built on evidence of Mesoproterozoic, including Sveconorwegian-age, source rocks for the overlying Neoproterozoic and Paleozoic sedimentary successions, eliminates the need for complex, exotic interpretations of the Scandian Middle Allochthon suggested by some authors mainly on the basis of geochronological and paleomagnetic data (e.g., Corfu et al., 2007; Kirkland et al., 2007; Torsvik, 1998).

Attenuation of the allochthons derived from the Baltoscandian margin, when traced from the foreland type areas in Sweden westward toward the hinterland (Zachrisson, 1969; Nicholson and Rutland, 1969; Trouw, 1973), and the general concordance of the thinned lenticular tectonic units in the deep hinterland have hindered precise estimates of the displacement distances (Gee, 1978). Nevertheless, simple lines of evidence, such as the absence of mafic dike swarms in the hinterland basement comparable to those in the Särvi and Seve nappes, place clear constraints on the minimum possible displacements. In the profile (Fig. 1), no attempt is made to show the complexity of the isoclinal folding and refolding of the attenuated Lower and Middle Allochthons and their relationship to the underlying basement in westernmost areas. Bryhni (1989) summarized the character and distribution of the various supracrustal units in the Western Gneiss Region and drew attention to similarities with some of the attenuated Scandian allochthons in areas farther north (Trøndelag). Various authors have described relationships along the northern margin of the region, from Dombas and Trollheimen (Krill, 1985) westward via Surnadal to

Molde and Ålesund (Robinson, 1995; Terry and Robinson, 2003), where eclogites and garnet peridotites occur at different structural levels and have yielded mainly Early Devonian ages, but range from the mid-Silurian, perhaps to the mid-Devonian (Carswell and Cuthbert, 2003; Spengler et al., 2009; Kylander-Clark et al., 2009; Krogh et al., 2011).

Seve Nappe Complex

The Seve Nappe Complex can be followed at least 1000 km along the length of the Scandinavian Caledonides (Andréasson, 1994), underlain by lower-grade units of the Middle and Lower Allochthons and overthrust by the outboard, Iapetus-related terranes of the Köli Nappes (Fig. 1). Seve metasediments include quartzites, feldspathic and calc-silicate-bearing psammities and subordinate marbles in the lower parts, giving way upward into more pelitic units. Amphibolitized dolerites and gabbros abound in the Seve Nappe Complex, and the latter are sometimes associated with ultramafites. Lenticularity, both along and across the mountain belt, characterizes the individual tectonic units, and strains vary greatly. Strong E-W linear structures, associated sheath folds and high ductile strains, accompanying amphibolites-facies retrogression, are widespread, but not ubiquitous. Remarkable preservation of primary relationships occurs locally, particularly where mafic dikes dominate over the metasedimentary host rocks.

Two main areas occur in Sweden where some of the thrust sheets of the Seve Nappe Complex are characterized by eclogite-facies metamorphism: southern Norrbotten (Thelander, 2009) and northern Jämtland counties (Strömberg et al., 1984). Isotope age data demonstrate that the former are significantly older than the latter. The structural relationships between these eclogite-bearing thrust sheets in the Seve Nappe Complex remain enigmatic, and the intervening areas in Västerbotten are less well exposed and investigated, but the apparent absence of high-pressure assemblages may be, at least in part, the result of superimposed retrogression.

In Norrbotten, two major composite thrust sheets have been identified, mainly consisting of eclogitized dolerites in psammities, separated by a remarkable dolerite dike swarm-dominated unit, the Sarektjåkkö Nappe (Svenningsen, 2001), which apparently did not experience the high-pressure metamorphism. The underlying so-called Vaimok Lens, consisting of the Lower Seve Nappe and overlying, eclogite-bearing Grapesvare and Maddäive nappes (Albrecht, 2000), shows the “transition” down into the Särvi Nappes referred to earlier, while, by contrast, the upper Tsäkökk Lens includes, in its

upper part, glaucophane-bearing, eclogitized pillow basalts (Kullerud et al., 1990). Temperatures of 690–730 °C and minimum pressures of 1.9 GPa (Santallier, 1988), perhaps up to 2.7 GPa (Albrecht, 2000), have been reported from the Vaimok Lens and 610 °C and 1.5 GPa for the Tsäkkok unit (Stephens and van Roermund, 1984). Various attempts to date the timing of high-pressure metamorphism of the Seve Nappe Complex in Norrbotten include application of the U/Pb titanite (Essex et al., 1997) and zircon (Root and Corfu, 2012) methods and Ar/Ar on hornblende (Dallmeyer and Gee, 1986); they have yielded Early Ordovician ages of 490–475 Ma. Somewhat older Sm/Nd ages of ca. 505 Ma (Mørk et al., 1988) have also been obtained, suggesting that this subduction-related deformation and metamorphism started before the Ordovician. However, these mid- to Late Cambrian ages are about 20 m.y. older than zircon ages from the Vaimok and Tsäkkok lenses (both 482 Ma) and may result from isotopic disequilibrium (Root and Corfu, 2012); the precise timing of this Early Ordovician subduction remains uncertain. Regionally, it is related in time to the obduction of some of the Late Cambrian to earliest Ordovician ophiolites, located farther south in the orogen (Furnes et al., 1985, 2012) and the development of volcanic arcs proximal to Baltica, as recorded in the overlying lower Köli nappes (Claesson et al., 1983; Dallmeyer and Gee, 1986).

Some 300 km farther south, in southern Västerbotten and northern Jämtland (Zachrisson, 1969), high-pressure metamorphism occurs at middle and lower levels of the Seve Nappe Complex (Van Roermund and Bakker, 1984; Van Roermund, 1985, 1989), and the occurrence of both eclogites and garnet peridotites has been investigated in some detail. The Seve Nappe Complex has been described by Zachrisson and Sjöstrand (1990) to consist of three units, the Lower, Middle, and Upper Seve nappes (previously referred to as the Eastern, Central, and Western belts by Williams and Zwart, 1977), with the high-grade rocks preserved in the lower two, and the Upper Seve wedging out southward from Västerbotten into Jämtland (Fig. 2). The Lower Seve Nappe is similar to the Vaimokk unit in Norrbotten, being dominated by quartzites, feldspathic psammites, and some marbles. The more pelitic Middle Seve Nappe provides widespread evidence of migmatization. Van Roermund and Bakker (1984) and Van Roermund (1985) reported temperatures and pressure of 550 ± 70 °C and 1.4 ± 0.15 GPa for the Lower Seve Nappe and 780 ± 50 °C and 1.8 ± 0.1 GPa (updated to 2.4 GPa by Van Roermund, 1989) for the Middle Seve Nappe. Ages of high-pressure metamorphism have been investigated by

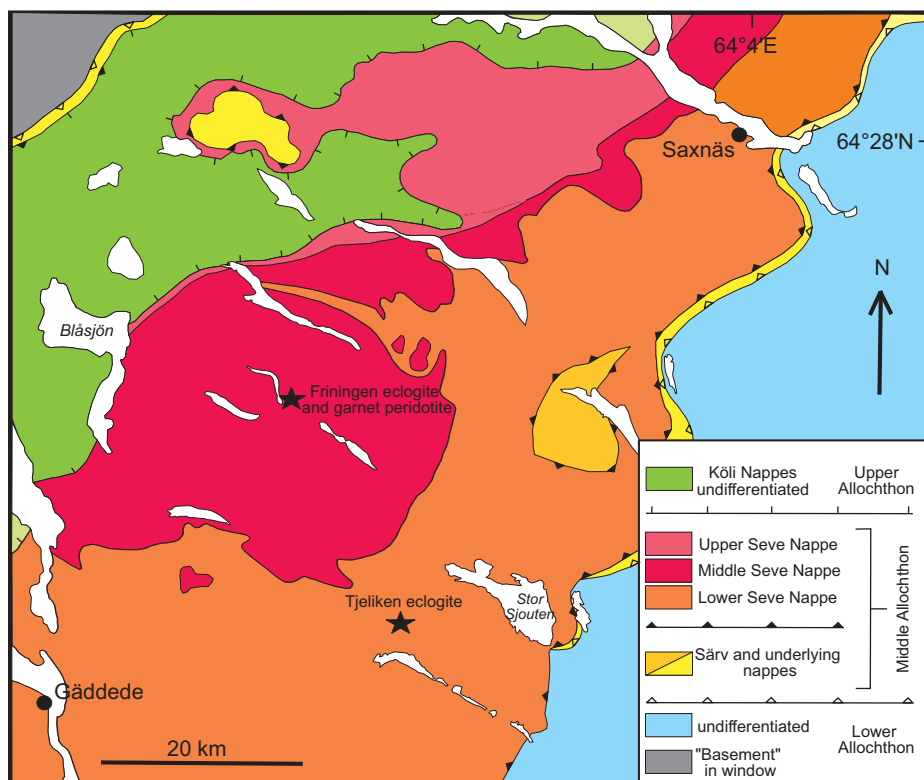


Figure 2. Tectonostratigraphic map of southern Västerbotten and northern Jämtland (see Fig. 1 for location) with sample locality marked. Figure is modified from Strömberg et al. (1984), Van Roermund (1985), and Zachrisson and Sjöstrand (1990).

the Sm/Nd mineral-whole-rock method on both eclogites and garnet peridotites (Brueckner et al., 2004; Brueckner and van Roermund, 2007) in the Middle and Lower Seve Nappes, and by the U/Pb method on an eclogite (Root and Corfu, 2012). All ages are Middle to Late Ordovician, consistently younger than in Norrbotten.

The UHP metamorphism that has recently been identified in the Middle Seve Nappe in northern Jämtland (Fig. 2) is recorded by a kyanite-bearing eclogite, associated with garnet pyroxenite in a dike (Fig. 3) cutting an isolated garnet peridotite near Lake Friningen (Van Roermund, 1989). The thermobarometric results (Janák et al., 2012a) constrain peak pressure conditions of ~3 GPa and 800 °C within the stability field of coesite. Together with the petrographic observations of parallel-oriented needle-like inclusions of pure SiO₂ and amphibole in omphacite (Fig. 4), as probable exsolutions from supersilicic Ca-Eskola clinopyroxene (e.g., Smith, 1984; Katayama et al., 2000; Terry and Robinson, 2001; Terry et al., 2003), these indicate exhumation from depths of over 100 km. Sm-Nd mineral ages of $453\text{--}452 \pm 7.5$ Ma have been reported for the eclogitic dike in which UHP mineralogy has been found (Brueckner and van Roermund, 2007). Some

20 km to the southeast, on Mount Tjeliken, eclogites in a klippe (Strömberg et al., 1994) of the Middle Seve Nappe, or within the upper part of the Lower Seve Nappe (Zachrisson and Sjöstrand, 1990) have yielded a zircon age of 446 Ma (Root and Corfu, 2012). Fifteen kilometers west of the Friningen garnet peridotite, near Blåsjön, also in the Middle Seve Nappe, migmatitic paragneisses hosting eclogites have provided mid-Silurian ion-microprobe U/Pb zircon ages (Williams and Claesson, 1987), and 100 km farther south in central Jämtland (Åreskutan), recent work on Middle Seve granulite-facies migmatites has provided strong evidence of decompressional melting (Klonowska, 2012) at 442–436 Ma (Ladenberger et al., 2012; Majka et al., 2012). This evidence suggests that late(st) Ordovician UHP metamorphism of the Seve Nappe Complex in Jämtland was followed by extrusion during the Early Silurian. The record in the underlying Lower Allochthon implies continued thrust emplacement toward and then across the foreland basin through the mid- and Late Silurian, probably into the Early Devonian.

Farther south in the mountain belt, in the Trollheimen area, eclogites were reported in the Blåhö Nappe, and, in southern Norway, two other (U)HP localities are also apparently in the

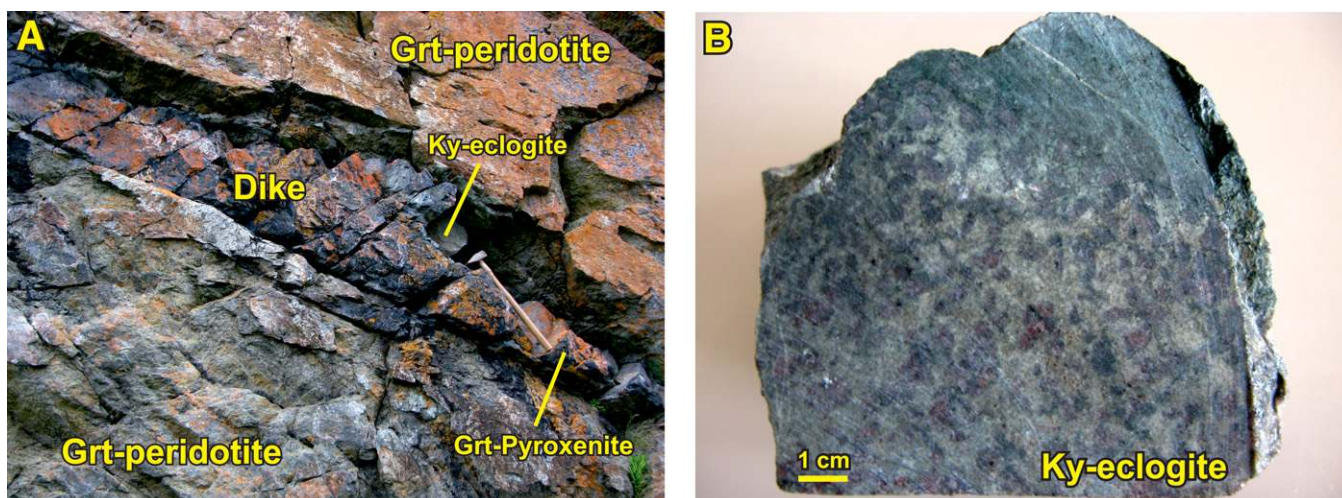


Figure 3. Field relationships, showing (A) the Friningen garnet (Grt) peridotite outcrop and crosscutting dike composed of garnet pyroxenite and kyanite (ky) eclogite, and (B) the texture of ultrahigh-pressure kyanite eclogite.

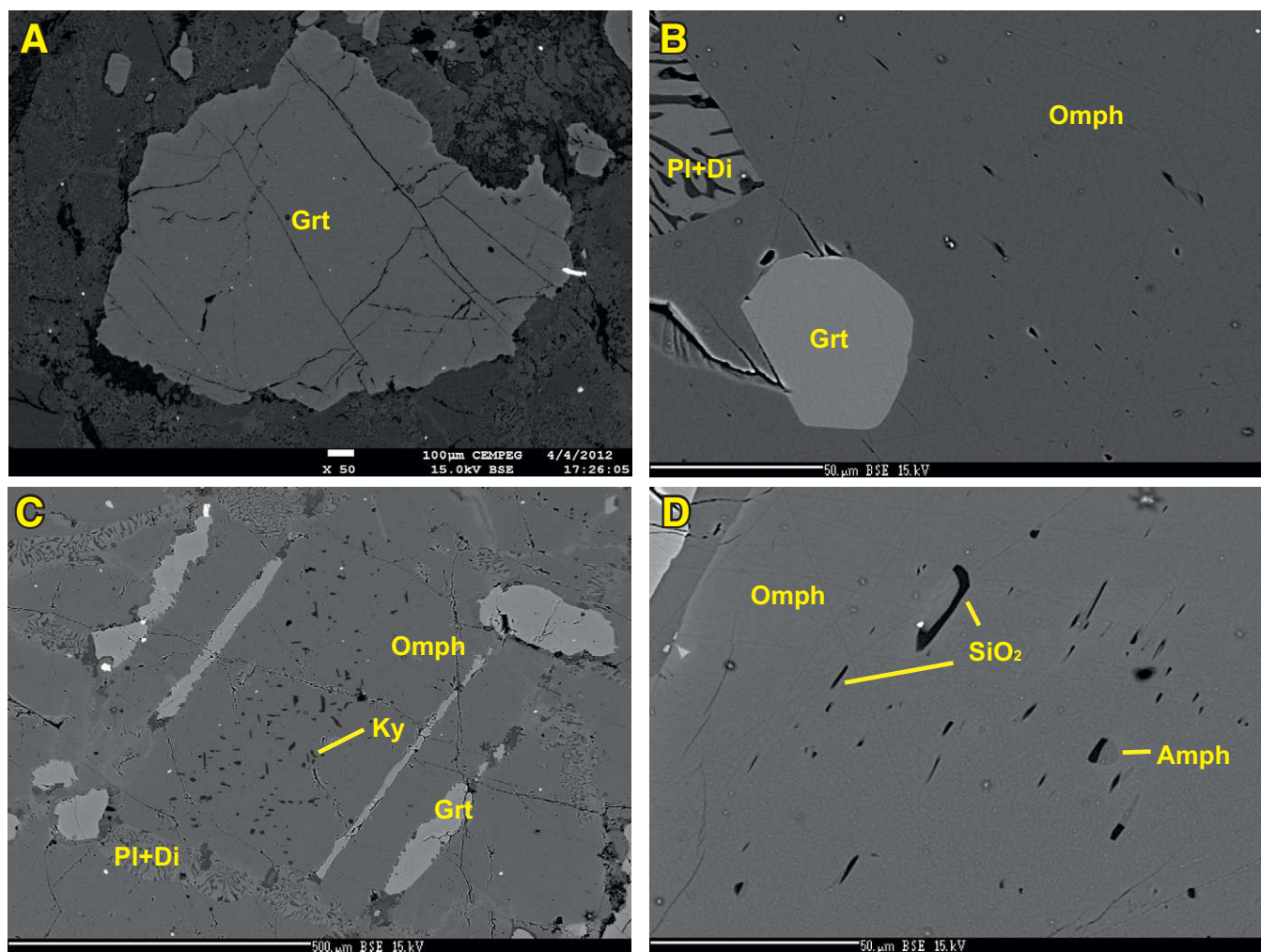


Figure 4. Backscattered-electron (BSE) images of microtextures of the ultrahigh-pressure (UHP) kyanite eclogite from the dike in the Friningen garnet (Grt) peridotite. (A) Large garnet (Grt I) in the matrix. (B) Small euhedral garnet (Grt IIa) in omphacite (Omph). (C) Garnet lamellae (Grt IIb) and kyanite (Ky) needles in omphacite. (D) Needles composed of silica (SiO_2) in omphacite. Other abbreviations used: PI—plagioclase, Di—diopside, Amph—amphibole.

Middle Allochthon and may be correlatives of the Seve Nappe Complex. Near Bergen, eclogitization of charnockitic protoliths in the Lindås Nappe (Austrheim, 1987, 1991) yielded ca. 456 Ma ages (Bingen et al., 2001), subsequently revised to ca. 423 Ma (Bingen et al., 2004) on the basis of zircon rim analyses. Farther south near Stavanger, the Jæren Nappe has yielded mid-Ordovician ages of 470–455 Ma (Smit et al., 2010). Also of interest in this context is the recognition of UHP metamorphism in the Tønsvika and Tromsdalstind eclogite bodies of the Tromsø Nappe, in northern Norway (Ravna and Roux, 2006; Janák et al., 2012b), an allochthon consisting of continental-margin psammites, marbles, metadolerites, and other mafic rocks, located in the Uppermost Allochthon in northern Norway. The P - T - t path of Tromsdalstind eclogite (Janák et al., 2012b) and its Late Ordovician age (452 Ma; Corfu et al., 2003) are remarkably similar to the P - T - t evolution of the Seve Nappe Complex near Friningen, in northern Jämtland. It was suggested by Janák et al. (2012b) that these nappes may be correlatives, the Tromsø Nappe being emplaced at a higher tectonostratigraphic level by out-of-sequence, late-orogenic thrusting. However, Ordovician eclogites are also known in several locations in the Taconian orogen (Jamieson, 1990) and the Caledonides of eastern Greenland (Brueckner et al., 1998; Gilotti et al., 2008), which could be consistent with the proposed Laurentian setting of the Uppermost Allochthon.

DISCUSSION

The new evidence of UHP metamorphism of the Seve Nappe Complex in the Jämtland Caledonides provides compelling support for an active Baltoscandian margin, with deep subduction during closing of the Iapetus Ocean. Much further work will now be needed both on the high-pressure mineralogy of the complex and the control of timing of subduction and emplacement onto the Baltoscandian platform in order to better define the structural evolution of this extended continental margin during Ordovician contraction, culminating in Baltica-Laurentia collision and Scandian orogeny.

A framework for understanding the evolution of the Iapetus Ocean has been provided by a combination of faunal evidence for oceanic separation of Baltica and Laurentia in the Cambrian and at least the Early to mid-Ordovician (Cocks and Fortey, 1982; Fortey and Cocks, 1992; Cocks and Torsvik, 2005), paleomagnetic evidence of latitudinal separation of Baltica and Laurentia (Torsvik et al., 1996), and the occurrence of fragmented oceanic crust (ophiolites) within the higher allochthons (Furnes et al.,

1985). Along the Baltoscandian outer margin, the evidence within the Seve Nappe Complex of high-pressure metamorphism, coinciding in time in the Early Ordovician with the obduction of ophiolites in the overlying Upper Allochthon, supports the interpretation that this so-called Finnmarkian subduction was related to early Iapetus contraction. Within the Scandinavian Caledonides, ophiolites occur in the Upper Allochthon, both at the base, immediately above the Middle Allochthon, and also at the top, in the Støren Nappe, locally underlain by blueschists (Eide and Lardeaux, 2002), and perhaps also in the Uppermost Allochthon. Faunas in shallow-marine successions of the Støren Nappe, directly overlying the obducted Løkken ophiolite, have unambiguous North American (Laurentian) affinities (Bruton et al., 1985), implying that both flanks of the Iapetus Ocean are represented within the Scandian allochthons. The youngest fragments of ocean floor in the orogen, inferred to be of backarc basin origin, the Solund-Stavfjord ophiolite (Andersen et al., 1990; Furnes et al., 2012), are of latest Ordovician to earliest Silurian age (443 Ma). Thus, the precise timing of initial collision between the outer margins of Laurentia and Baltica remains uncertain. Nevertheless, the record of deposition in the foreland basin requires that Scandian collisional orogeny between Baltica and Laurentia was under way early in the Silurian.

Within the Seve Nappe Complex, relationships between Early and Late Ordovician subduction events remain enigmatic. They may represent independent episodes, separated by intervals of quiescence (Brueckner and van Roermund, 2004), or they may be parts of a continuous process of contraction and partial subduction. Likewise the late(st) Ordovician episode may be related to, or independent of, the start of collision between Baltica and Laurentia. However, there can be little doubt that subduction occurred both along and within the outer Baltoscandian margin during closure of the Iapetus Ocean. The thrust sheets carrying eclogites of Finnmarkian age in Norrbotten may well be at a higher structural level within the complex and thin southward, perhaps wedging out, or being represented in the Upper Seve Nappe in southern Västerbotten and northern Jämtland. Evidence of Ordovician metamorphism in correlatives of the Seve Nappe Complex in Norway would favor this interpretation, as does the record of Ordovician turbidite deposition in the foreland basin (Karis *in* Karis and Strömberg, 1998). In this context, it is relevant to note that the width of the Caledonide orogen decreases northward in the Scandes from ~300 km in southern and central parts of the mountain belt to ~100 km in the far north. Much of the Caledonian foreland of

the southern part of the mountain belt, and particularly the Lower and Middle Allochthons, has been removed by erosion during Cenozoic uplift.

Contraction of the Baltoscandian margin continued through the Silurian and into the Devonian, but evidence of high-pressure metamorphism is confined to the hinterland, where eclogites abound in the Western Gneiss Region and also occur farther north along the Norwegian coast in the Lofoten Islands. Just to the south, in the Glomfjord area (Sørensen, 1955), garnet peridotites have been reported. In the Western Gneiss Region, along its northern edge in southern Trøndelag, eclogites occur in the Lower Allochthon. Whereas in the Caledonian front the Precambrian crystalline basement is essentially passive and separated from the Lower Allochthon by a major décollement (e.g., Gee et al., 1978), toward the hinterland basement imbrication increases, as seen in the antiformal windows along the border between Sweden and Norway, for example, in the Grong-Olden culmination (Gee, 1980) and Nasafjäll (Essex and Gromet, 2000; Thelander, 2009), and in the seismic-reflection profiling across the orogen (Palm et al., 1991; Juhojuntti et al., 2001). Greenschist-facies metamorphism characterizes the granitic gneisses in these basement-derived allochthons in Sweden and increases to amphibolite facies in central Trøndelag, for example, in the Tømmerås antiform (Andréasson and Lagerblad, 1980). In the northern parts of the Western Gneiss Region, in the western limb of the Trollheimen antiform (Krill 1985), these highly strained Precambrian crystalline rocks contain corona gabbros, with eclogite crystallization in shear zones (Tørudbakken, 1981); small metamorphic zircons yielded a “preliminary” mid-Silurian age of ca. 425 Ma (Möller et al., 2001). Footwall Cambrian and Ediacaran successions, unconformably overlying ca. 1.7 Ga granitic basement, are comparable to relationships in the Tømmerås antiform and Grong-Olden culmination (Gee, 1980, 2000) and have been referred to as “parautochthonous.” Displacement distances are estimated to a minimum of 80 km (Robinson et al., 2012). This eclogite-bearing, basement-derived allochthon, the Storli thrust sheet, has been traced southwestward into coastal parts of the Western Gneiss Region (Robinson, 1995), where similar structural relationships have been defined in the Reksdalshesten antiform (Robinson, 1997). In adjacent areas (Terry et al., 2000; Terry and Robinson, 2003), eclogites have been found in most tectonic units except the lowermost basement and metasedimentary cover. Farther south in the Western Gneiss Region (e.g., in the Sognefjord transect; Milnes et al., 1997), eclogites are widespread, and an underlying eclogite-free parautochthonous basement

has not been recognized. In the Lofoten Islands (Markl and Bucher, 1997; Steltenpohl et al., 2003), the eclogites occur in Precambrian crystalline rocks and are confined to southernmost parts (Flakstadøy); the relationships to the adjacent, probably underlying basement remain uncertain, as does the Caledonian, possibly mid-Ordovician age (Steltenpohl et al., 2011). Although some authors have speculated that these high-pressure units may be a part of the Uppermost Allochthon and derived from Laurentia, the unambiguous evidence that the Lofoten basement and quartzite cover, in northern parts, underlie the main Scandian allochthons (Björklund, 1987) favors affinity to the Baltoscandian margin (Steltenpohl et al., 2011) and suggests that the relationships may be comparable to those in the Western Gneiss Region.

Understanding the complex *P-T-t* data from the Western Gneiss Region, with the variety of evidence not only of pre-Caledonian protoliths, but also Caledonian (Ordovician and Silurian) events (e.g., Spengler et al., 2009; Cuthbert and van Roermund, 2011), prior to the late Scandian overprint, requires control of the tectonostratigraphy across the orogen into the hinterland. Correlation westward from the better preserved allochthons in western Sweden and eastern Norway is crucial for understanding the final episode of contraction and subduction of the Baltoscandian margin, with (U)HP metamorphism in the Early Devonian; “double-dunking” (Brueckner, 2011) may well have been widespread. Likewise, pre-orogenic, paleogeographic reconstructions are essential for understanding relationships between the rifted, attenuated Baltoscandian margin and the Baltica crust of more normal thickness, composition, and structure that entered the subduction zone in the Emsian (Fig. 5).

Underthrusting of Laurentia by Baltica during Scandian orogeny compares well with the modern analogue of India underthrusting Asia (Searle and Treloar, 1993; O’Brien et al., 2001; Gee et al., 2010; Teysier, 2011). It involved shortening of the Lower Allochthon by at least a couple of hundred kilometers and the overlying Middle Allochthon by substantially more. The Seve Nappe Complex originated from far to the west of the present hinterland of the orogen, as it is exposed along the Norwegian coast. Emplacement of the subduction-generated Seve allochthons to their present locations above the Baltoscandian foreland basin in Sweden took in the order of about 50 m.y. (ca. 440–390 Ma), with the hot, ductile transport occurring during the Early Silurian, and giving way to low amphibolite- to greenschist-facies thrusting onto the Baltoscandian platform during the Late Silurian and into the Early Devonian. The latter occurred while the deep hinterland of the Western Gneiss Region

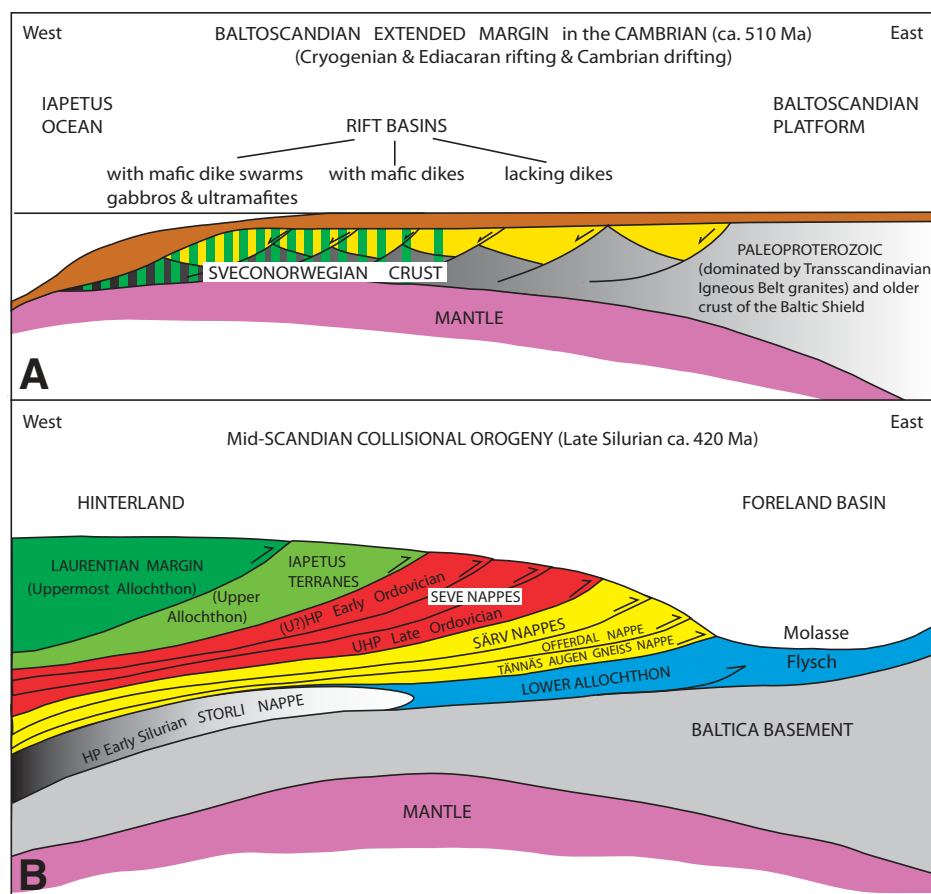


Figure 5. Diagrammatic presentation of the Baltoscandian margin (A) prior to and (B) during Caledonian orogenesis. (A) Outermost parts include the continent-ocean transition zone (COT) of highly extended crust (cf. Lundin and Doré, 2011), with sheeted dikes, gabbros, and mantle diapirs; central parts intruded by mafic dike swarms; and inner parts without mafic dikes, all underlain by Sveconorwegian (ca. 900–1600 Ma) continental crust and mantle. (B) Margin of the Scandinavian Caledonides (central parts) during mid-Scandian (Late Silurian) orogeny, prior to late Scandian (Early Devonian) deep subduction in the hinterland, as exposed in the Western Gneiss Region.

was undergoing UHP metamorphism, upper-crustal extension (Tucker et al., 2004; Krogh et al., 2011; Robinson et al., 2012), and superposed orogen-parallel, sinistral, ductile shear (Krabendam and Dewey, 1988; Terry and Robinson, 2003). As in Himalaya-Tibet, transpression (and transtension) apparently played a subordinate role in Caledonian orogeny, being prominent only in the deep hinterland of the Baltoscandian margin and on the Laurentian side of the orogen, from Svalbard via eastern Greenland and Scotland, perhaps as the result of the orthogonal collision, leading to indentation and lateral escape (Gee, 1987). Much of the evidence concerning the processes involved in the long-distance underthrusting of one continent by another that are exposed in the Scandinavian Caledonides today is difficult, perhaps impossible, to reconstruct for the Himalaya-Tibet orogen. Nevertheless, the Caledonides may provide insight into

the mechanisms operating in the lower to middle crust beneath this Cenozoic orogen today.

CONCLUSIONS

(1) Recently discovered eclogite-facies mineral parageneses in the Seve Nappe Complex of northern Jämtland record an UHP metamorphic episode that reflects deep subduction of the Baltoscandian margin during closure of the Iapetus Ocean.

(2) Palinspastic reconstructions of the Baltoscandian margin in the Neoproterozoic and early Paleozoic, reviewed here, indicate that the rifted and extended part of the margin restores to a position west of the present Norwegian coast. Termination of subduction near the end of the Early Devonian would have been influenced, perhaps controlled, by Baltica crust of normal thickness entering the subduction zone.

(3) On the basis of previous isotope age studies of the (U)HP metamorphism and the stratigraphic record of Baltoscandian foreland basin deposition, subduction occurred along the Baltoscandian margin in Early and Late Ordovician time and may have been separated by an interval of tectonic quiescence.

(4) Early Ordovician subduction was located along the outermost (western) part of the Baltoscandian margin and involved the obduction of Iapetus-derived ophiolites, preserved locally in the lower part of the Köli nappes in the Upper Allochthon.

(5) Late Ordovician UHP metamorphism occurred during contraction of the Baltoscandian margin in the earliest stages of, or just prior to, Scandian collision between the continents of Baltica and Laurentia.

(6) Decompressional melting, inferred in the Central Seve Nappe in Jämtland to follow the (U)HP metamorphism, led to Early Silurian extrusion of the Seve Nappe Complex onto the Baltoscandian outer margin. As the Seve Nappe Complex cooled, ductile flow gave way to thrusting across the Silurian successions of the Lower Allochthon. This movement probably continued into the Early Devonian.

(7) Recognition of Ordovician and Silurian HP/UHP metamorphism at different structural levels in the Scandinavian Caledonides, and the attenuation of these tectonic units toward the west highlight the importance of defining the tectonostratigraphy in the deep hinterland of the Western Gneiss Region and the Lofoten Islands in order to decipher the tectonothermal evolution during the final stages of Baltica-Laurentia collision in the Early Devonian.

(8) Emplacement distances of the Seve Nappe Complex, in excess of 400 km, may well be of the same order of magnitude as those estimated for the ongoing underthrusting of Asia by India in the Himalaya-Tibet orogen. The overall geometry of these two orogens, their subduction histories, and the dominance of orthogonal collision over a period of ~50 m.y. coupled with emplacement of hot allochthons suggest that their orogenic evolution may be closely comparable.

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