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Concurrent HP metamorphism on both margins of Iapetus: Ordovician ages for eclogites and garnet pyroxenites from the Seve Nappe Complex, Swedish Caledonides

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Abstract: Eclogites and garnet pyroxenites from the Seve Nappe Complex in the Jämtland area of the Scandinavian Caledonides give Sm–Nd mineral ages (garnet–clinopyroxene–whole rock ± orthopyroxene ± amphibole) that are identical within error and give a weighted average age of 457.9 ± 4.5 Ma (95% confidence). The age is 50 Ma younger than ages determined from eclogites from the apparently similar Norrbotten terrane, roughly 200 km to the north. Both terranes are correlated with the western margin of Baltica, suggesting that at least two eclogite-facies metamorphic events affected this margin prior to the final closure of Iapetus during the 430–400 Ma Scandian Orogeny. The *c*. 458 Ma ages are nearly identical to ages determined from the eclogite-bearing Tromsø Nappe of the uppermost allochthon. The uppermost allochthon is generally considered part of the Laurentian margin, which, if true, requires that it evolved independently of Baltica until the Scandian Orogeny, when Laurentia and Baltica collided. Thus high-pressure eclogite-facies metamorphism and the introduction of mantle peridotite bodies into the crust appear to have occurred concurrently on opposite sides of Iapetus. We suggest that the HP collision recorded in the Jämtland area be called the 'Jämtlandian Orogeny' if further studies confirm its Early Ordovician age.

We present six Sm–Nd mineral isochrons from eclogites and garnet pyroxenites from a region of high-pressure (HP) rocks in the Seve Nappe Complex in the Jämtland area of the Swedish Caledonides that give very consistent ages of 448–464 Ma (average 457.9 ± 4.5 Ma or Early Ordovician, very close to the Llandeilo–Caradoc boundary). We interpret these ages as closely approximating the time of peak HP metamorphism. The ages are interesting for three reasons. First, if, as is generally believed, the Seve Nappe Complex is largely composed of the thinned margin of Baltica (Stephens & Gee 1985; Stephens 1988; Andréasson 1994; Andréasson *et al*. 1998), the ages indicate that an Early Ordovician HP collision affected this margin even though there is little current evidence for an HP event of this age anywhere else along the Baltic margin. Second, eclogites from the geologically similar Norrbotten HP terrane, which is on strike with the Jämtland area and which is also mapped as part of the Seve Nappe Complex, give ages of *c*. 500 Ma; that is, 50 Ma older than the ages from Jämtland (Dallmeyer & Gee 1986; Mørk *et al*. 1988; Dallmeyer & Stephens 1991; Essex *et al*. 1997). Third, metamorphic terranes that give Early Ordovician ages from other parts of the Scandinavian Caledonides (Andersen *et al*. 1998; Corfu *et al*. 2003) are generally believed to have been outboard of the Baltic margin and probably closer to Laurentia than Baltica (Roberts 2003). Among these units is a 452 Ma HP terrane within the Tromsø Nappe Complex (Krogh *et al*. 1990; Corfu *et al*. 2003). The Tromsø Nappe Complex is part of the uppermost allochthon of the Scandinavian Caledonides, which is generally regarded as a composite of Laurentia and terranes that accreted to Laurentia on the other (western) side of Iapetus. If the ages and the tectonostratigraphic assignments of the different terranes are correct, they imply that there were two simultaneous collisions on either side of a closing Iapetus that resulted in the formation of eclogite-facies assemblages.

We previously suggested a tectonic model that attempted to accommodate the many eclogite-forming events that occurred during the evolution of the Scandinavian Caledonides (Brueckner & Van Roermund 2004). In this model we noted that there may have been two HP events at the same time on opposite sides of Iapetus, but the evidence that the two terranes were on opposite sides was not developed in any detail. Here we present the data that lead us to believe the rocks of the Jämtland area underwent an HP metamorphic event at *c*. 458 Ma. We also address the issue of whether or not the rocks in the Jämtland area could have been part of the uppermost allochthon, which, if true, would imply that the HP terrane formed with the Tromsø Nappe along the Laurentian margin rather than along the Baltic margin. Finally, we present evidence that the Jämtland terrane and the Tromsø Nappe originated from Baltica and Laurentia, respectively. We suggest that the HP event that we believe affected Baltica, if verified by further studies, be called the 'Jämtlandian Orogeny'.

The Scandinavian Caledonides

The Caledonides of Scandinavia (Fig. 1a) is a deeply eroded, early to mid-Palaeozoic orogen that evolved during the closure of northern Iapetus although the early phase of closure may have involved a different ocean (the Ægir Sea of Hartz & Torsvik

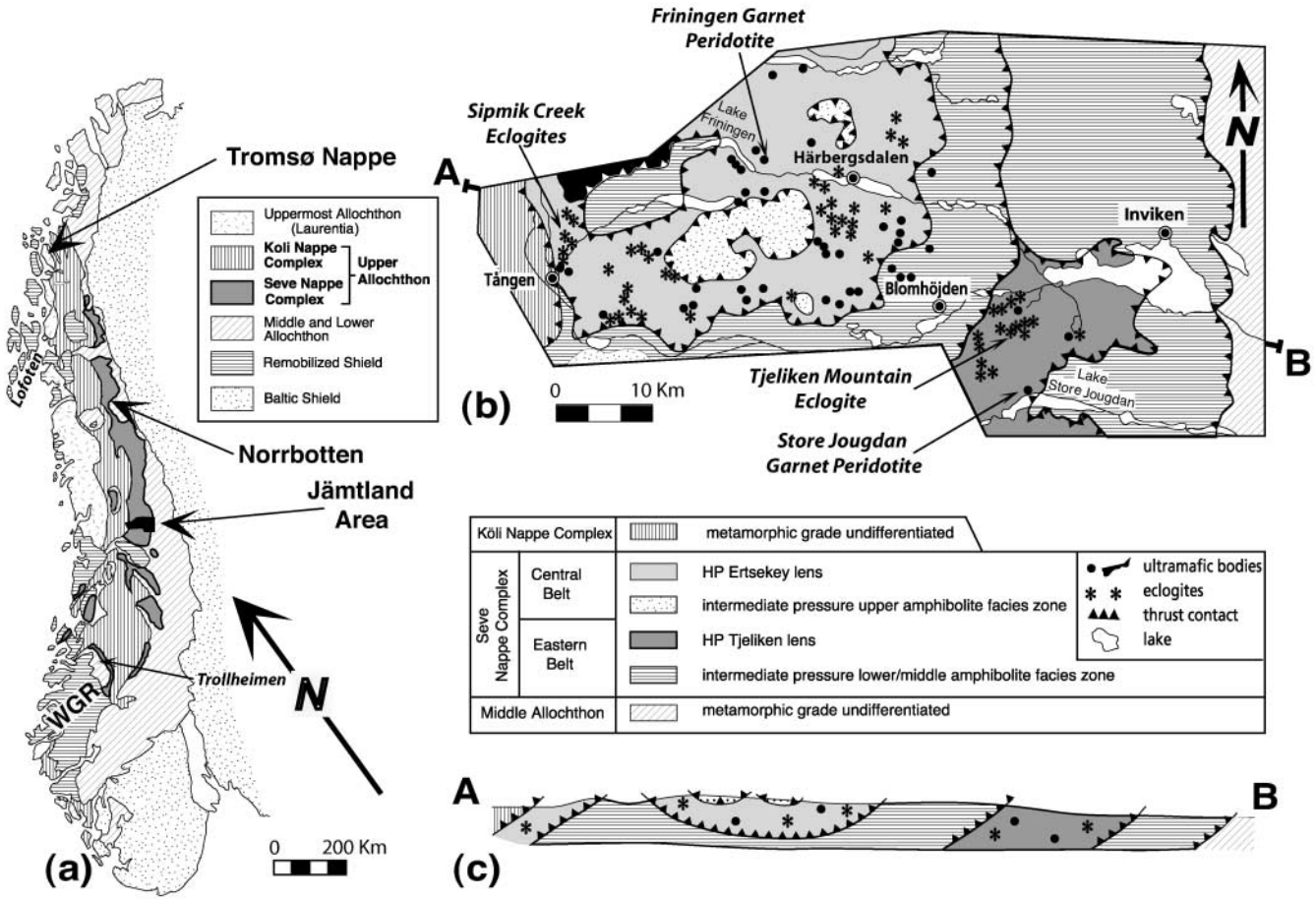

Fig. 1. (**a**) Simplified tectonic map of the Scandinavian Caledonides (modified from Gee & Sturt 1985) showing the location of the Jämtland area. WGR, Western Gneiss Region. (**b**) Generalized map of the Jämtland area (after Van Roermund 1985) showing the locations of the eclogites and and garnet pryoxenites analysed in this study. (**c**) Schematic cross-section illustrating the allochthons of the Jämtland area.

2002). The Caledonian cycle ended when Iapetus closed and an eastern continent, Baltica, collided with a western continent, Laurentia, during the Scandian Orogeny at 400–430 Ma (Roberts & Gee 1985). Baltica underthrust Laurentia, resulting in the thrusting or renewed thrusting of allochthons to the east over the Baltic Shield (Roberts & Gee 1985; Roberts & Stephens 2000; Brueckner & Van Roermund 2004). This shield is exposed in windows through the allochthons as basement complexes of high-grade gneisses and supracrustal rocks. These complexes generally give Precambrian crystallization ages, similar to those in the Baltic Shield to the east of the allochthons, but many, particularly those in the west, also give Caledonian recrystallization ages and hence represent Baltica remobilized ('Caledonized') to varying degrees by Caledonian metamorphic events (Bryhni & Grimstad 1970; Brueckner 1972; Tucker *et al*. 1992). One of these complexes, the Western Gneiss Region (WGR in Fig. 1a), contains eclogite-facies rocks (Griffin *et al*. 1985; Smith 1988; Cuthbert & Carswell 1990; Krogh & Carswell 1995) that locally contain coesite and microdiamonds, indicating ultrahigh-pressure (UHP) metamorphism (Cuthbert *et al*. 2000; Van Roermund *et al*. 2002; Root *et al*. 2005; Carswell *et al*. 2006; Vrijmoed *et al*. 2006; Young *et al*. 2006), as well as mantle-derived orogenic peridotite bodies (Medaris & Carswell 1990; Van Roermund & Drury 1998; Spengler *et al*. 2006). Another Caledonized complex that contains local evidence of eclogite-facies metamorphism (i.e. along fractures and shear zones) is exposed in the islands of Lofoten (Boundy *et al*. 2003).

The allochthons are usually divided into the lower, middle, upper and uppermost allochthons (Fig. 1a). Slices of Baltica occur in the lower and middle allochthons as imbricated thrusts of Precambrian crystalline rocks and Upper Proterozoic and/or Lower Palaeozoic platform and miogeocline sediments that were deposited on top of the basement. The two overlying allochthons are more complicated and probably represent composite terranes that were assembled during the closure of Iapetus and prior to the Scandian Orogeny. The highest allochthon, the 'uppermost' allochthon is composed of units, including thick carbonate complexes and crystalline basement, that are generally interpreted as the eastern margin of Laurentia, as well as terranes that accreted to this margin during the closure of Iapetus (Krogh *et al*. 1990; Pedersen *et al*. 1992; Melezhik *et al*. 2000; Roberts *et al*. 2002; Yoshinobu *et al*. 2002; Roberts 2003). Most of these accretionary events occurred during the Taconic Orogeny, which here is taken *sensu stricto* to refer to Ordovician collisions that affected the Laurentian margin (Roberts 2003). Of particular interest within this allochthon is the Tromsø Nappe, which contains eclogites and garnet-bearing peridotites (Ravna *et al*. 2006) that underwent HP metamorphism at 452.1 ± 1.7 Ma (Corfu *et al*. 2003).

Between the middle and uppermost allochthons is the upper

allochthon, a composite of tectonic units derived from both Iapetus and the outermost edge of Baltica. Its uppermost unit, called the Köli Nappe Complex in Sweden, is composed of ophiolites, volcanic arc terranes, marginal basins, etc. and records the closure history of Iapetus (Stephens & Gee 1985, 1989). Below it is the Seve Nappe Complex, which records the evolution of the Baltic margin and which is the focus of this study. This nappe complex is discussed in greater detail below.

HP terranes within the Seve Nappe Complex

The Seve Nappe Complex is classically interpreted as the continent–ocean transition between Baltica and the ocean that opened outboard of it (Andréasson 1986, 1994; Andréasson *et al*. 1998). This interpretation is primarily based on lithological association, as the rocks are generally metamorphosed and lack fossils (for a comprehensive review, see Gee & Sturt 1985). Furthermore, it is cut by numerous low-angle faults with abrupt changes in metamorphic grade across these faults. Faulting causes units to thin and disappear both along and perpendicular to strike (Stephens & Gee 1985). It exposes gneisses and, locally, anorthosites that appear similar to the Proterozoic crystalline rocks of the Baltic Shield. The gneisses are overlain by metasedmentary units including quartzites, psammitic schists, semipelitic schists and marbles, an association that is consistent with a shelf sequence on a passive margin. The quartzo-feldspathic units are locally thick and dominate the stratigraphy. The metasedimentary units also contain amphibolites and, locally, eclogites that probably originated as mafic dykes and sills and lava flows. Thus the rocks are interpreted as representing the western edge of Baltica, which was thinned into a passive margin during the rifting that led to the opening of Iapetus and covered with largely clastic shelf sediments. Mafic igneous activity associated with rifting led to the development of dykes and other intrusions as well as extrusive lavas.

The Seve Nappe Complex includes at least two HP metamorphic regions characterized by the presence of eclogites and orogenic peridotites (Fig. 1a). One area is in northern Jämtland, central Sweden (Van Roermund & Bakker 1984; Van Roermund 1985, 1989) and is the subject of this paper. Another occurs in the Norrbotten region, northern Sweden (Stephens & Van Roermund 1984; Andréasson *et al*. 1985; Van Roermund 1989; Andréasson & Albrecht 1995; Albrecht 2000). Eclogites have also been described from the Blåhø Nappe near Trollheimen, a unit considered equivalent to the Seve Nappe Complex (Roberts & Stephens 2000). It seems likely that other eclogite terranes occur within the Seve Nappe Complex but have not yet been recognized.

The Norrbotten terrane

The Seve Nappe Complex in the region around Norrbotten (Fig. 1) is divided into three nappe sequences (Zachrisson & Stephens 1984) called, from bottom to top, the Vaimok, Sarek and Tsäkkok 'lenses' (Andréasson & Albrecht 1995). HP eclogites occur within specific tectonic units of the Vaimok and Tsäkkok lenses. For example, the eclogites within the Vaimok lens occur within the Grapesvare and Maddåive Nappes, both of which are composed of quartzites (e.g., the very thick Juron quartzite), marbles, mica schists, calc-silicates and metavolcanic rocks (Albrecht 2000). The eclogites from the Grapesvare Nappe were originally dolerite dykes (Albrecht 2000). Thus the rocks are interpreted as the rift-related sediments, volcanic rocks and intrusions that formed on the thinned Baltic margin as discussed above. An eclogite within a thick quartzite unit in the Grapesvare Nappe (the Juron quartzite of Albrecht 2000) gives a Sm–Nd mineral isochron age of 503 ± 14 Ma (Mørk *et al*. 1988). The Tsäkkok lens is also dominated by psammitic and pelitic rocks, and is also interpreted as originating along the outermost part of the Baltic miogeocline (Kullerud *et al*. 1990). The eclogites in this lens formed from pillow lavas (Kullerud *et al*. 1990), one of which has given a Sm–Nd mineral isochron age of 505 ± 18 Ma (Mørk *et al*. 1988). Thus despite the different tectonic positions, the two nappe complexes were metamorphosed at the same time. These ages coincide with the Finnmarkian Orogeny, which is a major orogenic event believed to have affected much of the Northern Scandinavian Caledonides. The Sm–Nd mineral ages are corroborated by U–Pb ages from titanites in associated rocks (Essex *et al*. 1997) and Ar–Ar ages from hornblendes and micas (Dallmeyer & Gee 1986; Dallmeyer & Stephens 1991), which also indicate that the nappes were exhumed to temperature conditions of less than 500 °C by 490–460 Ma (Essex *et al*. 1997). The Norrbotten eclogites are associated with orogenic ultramafic lenses that locally contain garnet-bearing pyroxenites (Van Roermund 1989). These pyroxenites have not been dated, but show major element zoning patterns within minerals that are consistent with similar prograde patterns found in the associated eclogites (Van Roermund 1989; Albrecht & Andréasson 2000), suggesting that the garnet pyroxenites were metamorphosed at the same time as the eclogites at *c*. 500 Ma. If so, the peridotites are the 'prograde type subduction zone peridotites' as described by Brueckner & Medaris (2000).

The Finnmarkian Orogeny was interpreted as an arc–continent collision (Stephens & Gee 1985, 1989; Dallmeyer & Gee 1986; Dallmeyer 1988; Andréasson 1994) in which the arc, called the Virisen Arc (Dallmeyer & Gee 1986), overrode the thinned western edge of Baltica. We have proposed (i.e. Brueckner & Van Roermund 2004) that the Virisen Arc collided with a microcontinent or peninsula that had previously rifted away from Baltica instead of with Baltica itself. We adopted this view in part because of the evidence we present below for a subsequent arc–continent collision that did involve the Baltic margin at *c*. 458 Ma (i.e. the proposed Jämtlandian Orogeny).

The Jämtland terrane

The field relationships in the Jämtland region (Fig. 1b) seem remarkably similar to those at Norrbotten and the two areas were sometimes considered together (i.e. Van Roermund 1985, 1989). The Seve Nappe Complex in the Jämtland region is divided traditionally from top to bottom into a western, central and eastern Belt (Zwart 1974); however, towards the south in northern Jämtland the western belt is missing. Here Van Roermund & Bakker (1984) and Van Roermund (1985, 1989) recognized eclogite-bearing tectonic 'lenses' similar to those at Norrbotten: the Ertsekey lens within the Central Belt and the Tjeliken lens within the Eastern Belt (Fig. 1b). The Tjeliken eclogites are largely metamorphosed dykes and intrusive rocks associated with quartzo-feldpathic rocks that appear very similar to the Juron Quartzite of the eclogite-bearing Grapesvare Nappe in Norrbotten (Albrecht 2000). Now the eclogites are tectonites with a well-developed foliation and clear LS fabrics (Van Roermund 1983; Godard & Van Roermund 1995). The Ertsekey eclogites are associated with migmatitic kyanite–sillimanite K-feldspar gneiss associated with minor quartzite, garnet–mica schist and marble. The Ertsekey lens has some similarities to the eclogite-rich Maddåive Nappe of Norrbotten but they are not as pronounced as those between the Tjeliken lens and the Grapesvare Nappe.

The similarities between the Norrbotten and Jämtland areas go beyond similarities in rock lithologies. HP rocks in both terranes are internally extremely deformed with abundant isoclinal folds, sheath folds and mylonites. Low-angle faults bound tectonic units in both areas. These faults are classically assumed to be thrust faults but some of the Norrbotten faults show earlier normal fault motion (Albrecht 2000) and it is probable that a modern kinematic study of Jämtland would reveal similar structures there. The faults that bound the Seve Nappe Complex in Jämtland separate rocks of amphibolite facies or higher from the greenschist-facies rocks of the Köli nappe above and the Sarv nappe below. The imbrications within the Seve Nappe Complex also separate slices that are at different metamorphic grades, in some cases with intermediate-pressure rocks above and below HP rocks (Fig. 1c). The HP units are often strikingly thin relative to their areal extent, suggesting extreme thinning during shearing. Most of these features are similar or identical to features in Norrbotten (Albrecht 2000). A final telling similarity is that both HP terranes are associated with peridotite lenses that locally contain garnet-bearing assemblages.

Despite the similarities of the two terranes, previous geochronology in the Jämtland region has not resulted in the *c*. 500 Ma age found in Norrbotten. Zircons from metamorphic rocks from the Jämtland area and nearby regions give U–Pb ages of 441 ± 10 Ma, 423 ± 5 Ma, and 453 ± 19 Ma (ion probe, Williams & Claesson 1987) and 423 ± 26 Ma (lower intercept, Claesson 1987). Similarly, titanites and monazites from associated metamorphic rocks give overlapping U–Pb ages of 425–444 Ma and 435–440 Ma, respectively (Gromet *et al*. 1996). All ages are significantly younger than the 500 Ma Finnmarkian event. Exceptions to these younger ages are Ar–Ar ages of 471–486 Ma from hornblendes and in particular an age of *c*. 485 Ma from hornblendes around garnet in an eclogite (Dallmeyer & Gee 1988). However, several of these ages show saddle-shaped spectra suggesting excess argon in the hornblendes, and the researchers themselves indicated that the older *c*. 485 Ma age is probably not geologically significant (Dallmeyer & Gee 1988, p. 193).

Geochronology

We attempted to resolve these apparent contradictions by determining Sm–Nd mineral isochrons from Jämtland eclogites and garnet pyroxenites or peridotites from both the central and eastern belts. Three of these dates from a peridotite in the central belt were presented previously (Brueckner *et al*. 2004), but are reviewed here to present a complete dataset. Samples with sample numbers including '99' or '00' were collected during the summers of 1999 and 2000. Three samples (83-FrO, 84-54 and 84-60) were collected in 1983 and 1984 when Van Roermund (1985, 1989) was mapping the area. The sample localities are shown on a generalized map of the Jämtland region (Fig. 1b). Detailed petrography and whole-rock and mineral chemistry have been provided by Van Roermund (1985, 1989) and, for the peridotites, by Brueckner *et al*. (2004).

Eastern belt samples

Samples analysed from the eastern belt are an eclogite (Tj99-1A), a garnet peridotite (84-54) and a garnet pyroxenite (84-60). Sample Tj99-1A is from the mineralogically and texturally complex Tjeliken eclogite, a very large body that forms a distinctive mountain of the same name (Fig. 1). The lower contact of the eclogite is in contact with quartzo-feldspathic rocks. HP garnet–phengite–omphacite–quartz gneisses occur locally at this interface. Recent thermobarometric work on the gneisses using garnet–clinopyroxene–phengite resulted in P–T estimates around 16.5 kbar and 650–680 °C (Litjens 2002). The collected sample is a massive, medium-grained (garnets are 1–2 mm) omphacite–garnet–quartz–phengite–rutile rock in which the garnets contain inclusions of the associated minerals, largely concentrated in the core. The sample is retrograded to plagioclase–diopside symplectites and contains significant amounts of secondary amphibole, plagioclase and epidote.

Samples 84-54 and 84-60 are from a garnet-bearing peridotite from the north shore of Store Jougdan (Fig. 1) that were collected by Van Roermund (1989) when he was mapping the area. Sample 84-54 is strongly sheared and foliated peridotite containing olivine–garnet–spinel–orthopyroxene but no clinopyroxene. Amphibole is a common secondary mineral locally forming thin layers parallel to foliation. The relatively large garnet grains (up to 10 mm) are elongated parallel to foliation, riddled with spinel, show prograde zoning and were interpreted to be secondary (Van Roermund 1989). These factors and the lack of clinopyroxene were considered likely impediments for successful geochronology. Sample 84-60, a garnet pyroxenite, was located and analysed much later, and is a much better candidate for dating because it contains fresh garnet and clinopyroxene in addition to orthopyroxene. The garnet is zoned with dark cores and light rims. The dark colour in the core is partly the result of the high concentrations of spinel inclusions in the garnet core. The garnets are also chemically zoned, showing an increase in the Mg/Fe ratio for core to rim (Van Roermund 1989). An attempt was made to separate the cores from the rims and to analyse them separately to see if they give essentially the same ages, as would occur during a single cycle of prograde metamorphism, or widely different ages, as would occur if the rims formed during a much later episode of metamorphism than the cores.

Central belt samples

Samples from the central belt include an eclogite (E99-1); a medium-grained garnet pyroxenite (83-FrO) and two garnet pyroxenites containing very large garnets (Fr00-12, Fr00-13). The eclogite is from one of several metre- to decimetre-sized boudins at Sipmik Creek (Fig. 1). All boudins contain clean fresh garnets but the clinopyroxene is usually retrograded to symplectite and coarse clots of hornblende and plagioclase are common. Fortunately, we found one boudin that contained large (*c*. 10 cm) garnet porphyroblasts riddled with fresh omphacite (1–2 mm) inclusions, and this was therefore selected for analysis. The omphacite and other inclusions (quartz and rutile) define a pronounced schistosity, suggesting that garnet growth was synkinematic. Relatively high P–T equilibration estimates for this eclogite (*c*. 18 kbar and 780 °C; Van Roermund 1985) led us to hope that a date could be obtained from this sample.

Only one peridotite body of the *c*. 20 bodies that were examined in the central belt contains both clinopyroxene and garnet, although there is evidence that some other bodies had similar assemblages but were retrograded. This important 100 m long lens occurs on a ridge on the north side of the eastern end of Lake Friningen (Fig. 1) and is easily visible from the other side of the lake. It is largely dunite and harzburgite, but garnet lherzolite occurs along the upper contact of the body and in boulders below the body. A conspicuous 0.5 m thick garnet pyroxenite dyke cuts the lens and smaller garnet pyroxenite dykes were found in the rubble at the base of the body, where they are associated with garnet lherzolite. Sample 83-FrO,

collected from the large dyke during the earlier study by Van Roermund (1989) is a massive garnet–clinopyroxene–orthopyroxene rock with surprisingly pale red garnet (2–4 mm) and pale green clinopyroxene. The garnet is riddled with tiny spinels (<0.1 mm). Samples Fr00-12 and Fr00-13 are from the boulder field beneath the body and contain very dark red, coarse (5 cm diameter) garnet mosaics with veinlets and islands of clinopyroxene with some orthopyroxene and olivine. The matrix between the large garnets is largely composed of medium- to coarse-grained clinopyroxene and garnet. The garnets are riddled with tiny spinels, a feature that appears to be characteristic of the Jämtland peridotite bodies. The large garnets and associated minerals, designated M_1 by Van Roermund (1989), were overprinted by a garnet–spinel–orthopyroxene–clinopyroxene assemblage (M_2) interpreted by Van Roermund (1989) to have formed during a second episode of high-pressure metamorphism (see Brueckner *et al*. (2004) for more detailed descriptions and discussions). As with sample 84-60, an attempt was made to separate dark red (core) and pale red (rim) garnets from sample Fr00-13 to see if different ages could be obtained.

A geochemical study of the Friningen body (Brueckner *et al*. 2004) indicates that it was derived from the subcontinental lithosphere, rather than the sub-oceanic lithosphere as was generally believed earlier (Zwart 1974; Qvale & Stigh 1985; Bucher-Nurminen 1991). Clinopyroxene from several samples in this body show enriched trace element patterns that suggest metasomatism of the type that would be anticipated in the subcontinental lithosphere and not the oceanic lithosphere. These clinopyroxene grains give scattered, but largely middle Proterozoic model ages (T_{DM}) that would not be expected in the late Proterozoic or early Palaeozoic (<608 Ma, Svenningsen 2001) oceanic lithosphere of either the Ægir Sea or Iapetus. In addition, Re–Os patterns from sulphides suggest an origin for the peridotite protoliths at least as old as early Proterozoic, and possibly as old as late Archaean. The trace element data, Sm–Nd model ages, and Re–Os patterns from sulphides are remarkably similar to those of peridotite from the Western Gneiss Region (Jamtveit *et al*. 1991; Brueckner *et al*. 2002; Beyer *et al*. 2004). Taken together, geochemical data suggest that the peridotite bodies of the Seve Nappe Complex in the Jämtland area are not ophiolite fragments, but peridotite lenses derived from the subcontinental lithosphere. This mantle occurred either beneath Baltica, or, as we propose herein, beneath a microcontinent that had previously rifted away from Baltica.

Analytical techniques

Pure mineral separates were obtained by magnetic separation and hand-picking techniques and leached in hot, concentrated HNO_3 and HCl solutions and a cold, dilute HF solution. One inclusion-rich garnet sample was subjected to a robust HF leaching procedure based on methods described by Amato *et al*. (1999) and Baxter *et al*. (2002): roughly 1 g of finely powdered garnet was immersed in 3 ml concentrated HF for 2 h before being leached in $HClO_4$, HCl and HNO_3. Approximately 80% of sample is dissolved by this procedure, including almost all of the inclusions. The samples were spiked and dissolved, and Nd, Sm and Sr were separated using TRU-SPEC resins and Alpha-Hiba solutions. Isotopes were analysed on a VG 54-30 mass spectrometer at Lamont–Doherty Earth Observatory of Columbia University. The results are shown in Table 1. Sm–Nd isochrons were calculated using the Isoplot/Ex program of Ludwig (1998). $^{147}Sm/^{144}Nd$ errors are taken to be 0.3%. The errors in $^{143}Nd/^{144}Nd$ were estimated using the relationship $(x^2 + y^2)^{1/2}$ where x is the standard deviation (2σ) of replicate standard analyses (0.000021, $n = 20$) during the time most of the data were obtained and y is the standard deviation of the mean (2σ) of each individual run. All ratios are normalized and corrected for machine fractionation. The data are presented in Table 1 and are plotted on standard Sm–Nd isochron diagrams in Figure 2 except for sample 84-54 (see below). Remarkably, all ages are consistent with each other within error.

Results

Eastern belt samples

The garnet separates from the eclogite forming Tjeliken Mountain (Tj99-1A, Fig. 2a) required repeated analyses because of their high concentrations of Nd-rich clinopyroxene inclusions, despite very careful hand-picking of the garnet separates under a binocular microscope (i.e. grt 1 and grt 2 in Table 1). The age based on these two garnets and the other phases (478 ± 43 Ma) has a large error because of the low Sm/Nd ratios of the garnets, caused by the presence of these inclusions. The robust HF leaching technique of finely powdered garnet described above preferentially removed the inclusions and resulted in garnet analyses with much lower Nd concentrations (0.5 ppm) and much higher Sm/Nd ratios, which in turn produced a much more precise age (Fig. 2a) of 463.7 ± 8.9 Ma (MSWD = 3.2). It is possible that leaching garnet may fractionate Sm from Nd, resulting in a spurious Sm/Nd ratio and an incorrect age. However, based on the studies cited above and the fact that the determined date is within error of all the other Sm–Nd ages determined from Jämtland, we feel that the age is close to the peak of eclogite-facies metamorphism.

The first peridotite sample (84-54) from Store Jougdan yielded the least precise result and is not plotted in Figure 2. There was insufficient Nd in the orthopyroxene to obtain a satisfactory analysis and it is not clear that amphibole should be included in the age calculation because it could be secondary, as suggested by its very high, or crustal, $^{87}Sr/^{86}Sr$ ratio (Table 1). The resulting age, considering all points, of 466 ± 63 Ma is too imprecise to decide whether metamorphism was Finnmarkian or the *c*. 458 Ma age determined from all other samples in Jämtland. Furthermore, if amphibole and the other hydrous phases within this rock are secondary, caused by the introduction of fluids, it is likely that the Sm–Nd characteristics of the whole rock were changed as well.

Accordingly, a second sample (84-60) was located in our collections late in this study, which is much less altered than 84-54 and contains primary clinopyroxene. An attempt was made to separate the cores from the rims based on colour and to analyse each fraction separately. A low-precision age of 464 ± 16 Ma (MSWD = 2.1) is obtained when all fractions are considered (two core grts, two rim grts, two cpxs and wr). The large error is the result of an unsatisfactory first analysis of the rim garnet (poor precision and a large Sm correction). Deleting the first rim garnet analysis and considering only the two garnet cores and one garnet rim (Fig. 2b) results in a precise isochron age of 459.6 ± 4.2 Ma (MSWD = 0.95), consistent with the other ages obtained from the Jämtland area. The two core garnets plus all other phases define an age (460.3 ± 4.8 Ma, MSWD = 1.2) that is essentially identical to the age defined by the second rim garnet analysis plus all other fractions (458.7 ± 4.9 Ma, MSWD = 1.6). The garnet cores do not give any indication of having formed significantly before 460 Ma.

Central belt samples

The ages from the central belt are likewise consistent. The eclogite boudin from Sipmik Creek (E99-1) yields a three

Table 1. *Sm–Nd and Sr isotope results from minerals and whole-rock samples of eclogite, garnet pyroxenite and garnet peridotite from the Seve Nappe Complex in the Jämtland Area of the Swedish Caledonides*

Sample		Sr (ppm)	$^{87}Sr/^{86}Sr$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
Eastern belt							
Eclogite							
Tj99-1A	cpx	116	0.705896 ± 13	0.970	1.81	0.325	0.513188 ± 09
	amph			2.13	5.34	0.242	0.512960 ± 09
	grt 1			1.29	1.75	0.445	0.513572 ± 07
	grt 2			0.912	1.16	0.475	0.513632 ± 33
	grt 4 (leached)			0.990	0.466	1.29	0.516095 ± 09
	wr			3.63	12.4	0.177	0.512700 ± 05
Garnet peridotite							
84-54	amph	55.8	0.724025 ± 10	1.36	4.72	0.174	0.512811 ± 10
	opx			0.0020	0.0067	0.182	0.512612 ± 57
	grt			0.164	0.126	0.787	0.514673 ± 13
	wr			0.132	0.440	0.181	0.512780 ± 09
84-60	cpx 1	120	0.721075 ± 19	1.37	5.43	0.153	0.512543 ± 09
	cpx 2			1.35	5.27	0.155	0.512511 ± 35
	grt core 1			0.635	0.435	0.883	0.514740 ± 27
	grt core 1			0.635	0.435	0.883	
	grt core 2			0.604	0.371	0.986	0.515039 ± 09
	grt rim 1			0.705	0.419	1.02	0.515304 ± 129
	grt rim 2			0.572	0.335	1.03	0.515175 ± 09
	wr			0.834	2.29	0.221	0.512726 ± 22
Central belt							
Eclogite							
E99-1	cpx	94.9	0.712755 ± 13	0.157	0.353	0.269	0.513117 ± 23
	amph			0.376	0.868	0.262	0.513083 ± 17
	QF			0.227	1.01	0.136	0.512718 ± 10
	grt 3			0.0937	0.0355	1.60	0.517067 ± 23
	grt 4			0.0973	0.0420	1.40	0.516588 ± 115
	grt 6			0.103	0.0449	1.39	0.516461 ± 20
	wr			0.255	0.756	0.204	0.512999 ± 27
Garnet pyroxenite							
83-FrO	cpx	110	0.704054 ± 08	0.105	0.373	0.171	0.512520 ± 11
	grt			0.0293	0.00910	1.95	0.517793 ± 83
	wr			0.689	2.29	0.182	0.512561 ± 13
Fr00-12	cpx 1	21.9	0.704576 ± 11	0.271	1.84	0.0892	0.511891 ± 11
	cpx 2	22.9	0.704611 ± 08	0.318	2.12	0.0905	0.511869 ± 11
	grt			0.0785	0.134	0.355	0.512660 ± 14
	wr			0.0879	0.471	0.113	0.511952 ± 26
Fr00-13	cpx	29.1	0.705563 ± 16	0.986	5.13	0.116	0.512076 ± 14
	grt core			0.0899	0.153	0.355	0.512773 ± 16
	grt rim			0.0873	0.135	0.391	0.512850 ± 26
	opx			0.0404	0.179	0.136	0.512099 ± 26
	wr			0.104	0.226	0.277	0.512537 ± 14

garnet–clinopyroxene–hornblende–whole-rock–QF (quartz-rich fraction) age (Fig. 2c) of 454.8 ± 9.7 Ma (MSWD = 4.3). This age was not easy to determine because of the extremely low Nd concentration of the garnet (0.04 ppm). Precise garnet analyses were not possible without dissolving large amounts of garnet (*c.* 500 mg). The whole rock plots to the left of clinopyroxene, a feature very characteristic of some quartz-bearing country rock eclogites (Fig. 2c; see also Fig. 2a). The whole rock is the sum of its minerals and the only way the configuration shown in Figure 2c could occur is by failure to analyse a REE-rich mineral of low Sm/Nd ratio. Accordingly, we analysed the non-magnetic fraction of the sample, which is dominated by quartz and secondary plagioclase (labelled QF in Table 1 and Fig. 2c). The analysis yields surprisingly high Sm and Nd concentrations (Table 1) and a Sm/Nd ratio lower than the whole rock. Quartz and feldspar contain trivial amounts of Sm and Nd, leading us to believe that the fraction contains apatite, a non-magnetic mineral that is present in trace amounts in thin section (Van Roermund 1985). We suggest that apatite may be a phase present in eclogites where the whole rock plots to the left of clinopyroxene and other primary eclogite phases and may also be responsible for the low abundance of Nd in garnet.

The ages from the Friningen peridotite are slightly, but not statistically significantly, different from those reported by Brueckner *et al.* (2004) when the ages were recalculated with a newer version of the Isoplot/Ex program. Reliable analyses were difficult to obtain because of the low Nd concentrations in the garnet (Table 1). Success occurred only by dissolving large amounts of garnet. Three garnet pyroxenites from the Friningen peridotite yield nearly identical ages (Figs. 2d–f) of 452.8 ± 7.5 Ma (83-FrO, MSWD = 0.27), 448 ± 17 Ma (Fr00-12; MSWD = 1.1) and 445 ± 17 Ma (Fr00-13; MSWD = 1.6). The mineral ages from Fr00-12 and Fr00-13 (Fig. 2e and f) are somewhat less precise than most other ages determined in this study, probably because the garnet is zoned in both samples and the points defined by the rim and core from Fr00-13 (Fig. 2f) do

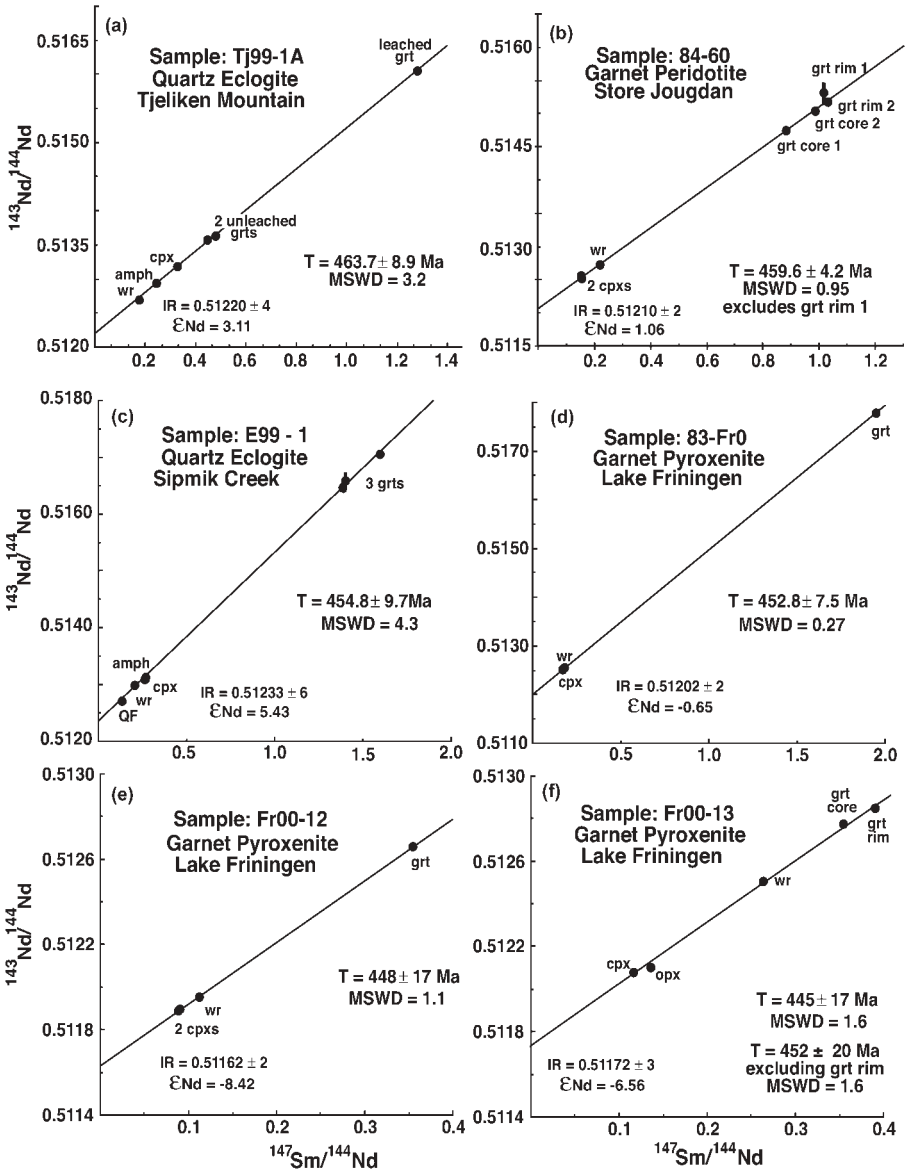

Fig. 2. Sm–Nd mineral isochrons of eclogites and garnet pyroxenites from the Seve Nappe Complex in the Jämtland area of the Swedish Caledonides. Errors are smaller than the plotted points unless noted with an error bar. Ages were calculated using the Isoplot/Ex program of Ludwig (1998).

not quite fall on the same line (MSWD = 1.6) suggesting that they may define different ages. A regression for Fr00-13 of cpx–opx–wr–core garnet yields an age of 452 ± 20 Ma (MSWD = 1.6) whereas a similar regression of cpx–opx–wr–rim garnet gives 439 ± 20 Ma (MSWD = 1.7). Both ages are easily within error and so their slight apparent age difference is not significant. Nevertheless, the colour change from core to rim suggests there was some diffusion and/or re-equilbration with neighbouring phases, possibly during retrogression. Therefore the age of 452 ± 20 Ma obtained by excluding the rim analysis from the regression is probably more accurate, albeit less precise, and therefore is considered the best age for this sample. There does not appear to be any significant evidence for metamorphism prior to 460 Ma, in agreement with the results from sample 84-60 from the Store Jougdan peridotite.

All ages from both belts are within error of each other (Fig. 3). A weighted average of the six ages judged to be most reliable (i.e. all ages shown in Fig. 2) gives 457.9 ± 4.5 Ma (95% confidence, Fig. 3). There does not seem to be evidence that the eastern belt was metamorphosed at a different time than the central belt (Fig. 3). The two reliable, and statistically indistinguishable, ages from Tj99-1A and 84-60 from the eastern belt give a composite age of 460.3 ± 3.7 (MSWD = 0.69) whereas the four ages from the central belt (E99-1, 83-FrO, Fr00-12, Fr00-13) give a composite age of 452.9 ± 5.3 Ma (MSWD = 0.16). The ages are within error and hence are indistinguishable.

Discussion

A gratifying result of this study is that Sm–Nd mineral isochrons can yield consistent ages from a single terrane so that a metamorphic event can be dated by this method to a relatively high precision. This precision is unusual, as one of us (H.K.B.) can testify, because the same method in other terranes such as the Western Gneiss Region of Norway (Griffin & Brueckner 1980) and the Bohemian Massif of the Variscide Belt (Brueckner *et al*. 1991) has yielded ages that can span several tens of

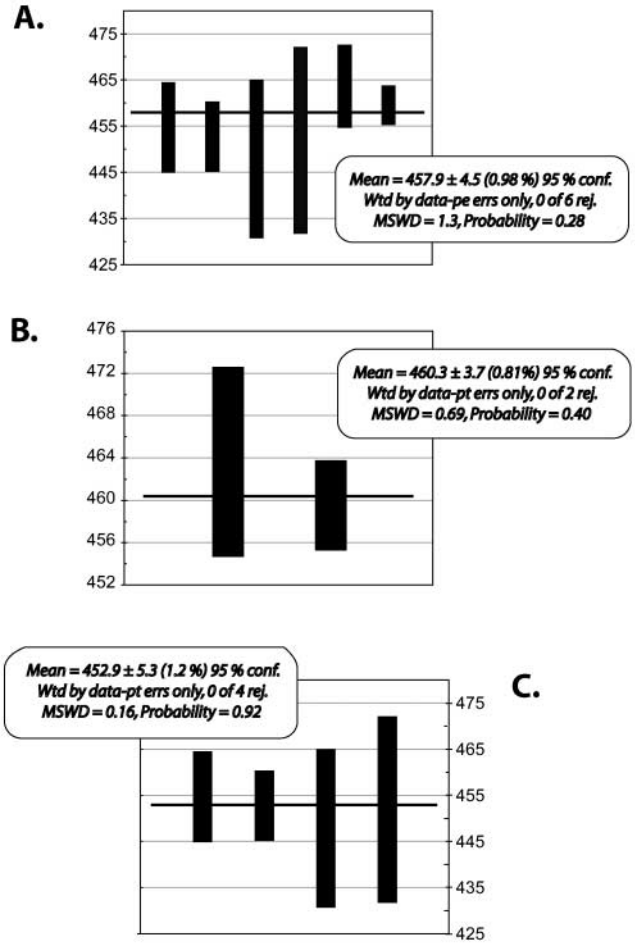

Fig. 3. Weighted averages for eclogite and garnet pyroxenite ages from all samples analysed from the Jämtland area (**a**), for two samples from the eastern belt (**b**) and from four samples from the central belt (**c**). Averages were calculated using the Isoplot/Ex program of Ludwig (1998).

millions of years. This consistency was unexpected in the Jämtland region because the garnets in both the eclogites and garnetiferous basic and ultramafic rocks were commonly riddled with inclusions and were zoned for major elements (Van Roermund 1989). Two of the samples (84-60 and Fr00-13) were so strongly zoned that it was relatively easy to separate the cores from the rims on the basis of colour. Yet analyses of the cores and rims did not yield significantly different dates, and, for sample 84-60, an age calculated using both the core and rim analyses yielded one of the most precise ages obtained in this study (459.6 ± 4.2 Ma).

There is no significant age difference between the garnet pyroxenites or peridotite and the eclogites in the host gneisses, suggesting that the peridotites were probably introduced into the continental crust as spinel peridotites at relatively shallow levels and were converted into garnet-bearing assemblages at the same time as the eclogites when the host gneisses reached eclogite-facies conditions (Brueckner & Medaris 2000). This interpretation is also consistent with our earlier work on the Friningen garnet peridotite (Fig. 1), which indicated that early garnet is replaced by spinel that is overgrown again by secondary garnet (Brueckner *et al*. 2004).

The 458 Ma mean age determined by the Sm–Nd mineral isochron method is older than most of the dates obtained from the region determined by other methods. Zircons from metamorphic rocks usually give ages that overlap Sm–Nd mineral isochron ages (see, e.g. Gilotti *et al*. 2004), but all but one of the published U–Pb ages from the Jämtland region are significantly younger than the 458 Ma age reported here (Claesson 1987; Williams & Claesson 1987). Furthermore, the U–Pb ages span a significant amount of time, from 423 to 452 Ma, whereas the Sm–Nd dates are within error of each other. The young U–Pb ages led Gromet *et al*. (1996) and Essex *et al*. (1997) to suggest that perhaps the Norrbotten and Jämtland terranes of the Seve Nappe were metamorphosed at two different times, despite the fact that they both contain similar eclogites and orogenic peridotites and despite their similar tectonostratigraphies. But there was always the possibility that the Jämtland terrane underwent Finnmarkian metamorphism and then was re-metamorphosed during the Scandian. The one tantalizing 485 Ma Ar–Ar date from hornblende around garnet (Dallmeyer & Gee 1988) kept this possibility alive, even though the researchers themselves doubted the validity of the age. In addition, the spread of younger ages (from 423 to 485 Ma if the Ar–Ar ages are included) could conceivably have been considered the result of different degrees of partial re-equilibration during Scandian metamorphism. The consistent dates present herein should dispel this possibility and add weight to the probability of a single metamorphic event that is significantly younger than the Finnmarkian, yet not young enough to be Scandian. The geological similarity of the Norrbotten and Jämtland terranes does not necessarily require that they were metamorphosed and deformed at the same time, as discussed at greater length below.

We consider it unlikely that the 458 Ma age can be interpreted as a cooling age that significantly postdates the peak temperature of metamorphism. If the 500 Ma age from the Norrbotten terrane is taken to be the thermal maximum in the Jämtland terrane, the roughly 43 Ma required to close the Sm–Nd system would indicate extremely slow cooling. This situation is not unheard of, and has been used to explain the large spread of ages from the Adirondacks during the Grenville Orogeny, where the Sm–Nd mineral ages are significantly younger than U–Pb zircon ages (Mezger *et al*. 1992). However, the Sm–Nd mineral ages from the Jämtland terrane are older than most of the U–Pb ages, which is the opposite of the situation with the Adirondack ages. In addition, the striking consistency of the six reliable Sm–Nd ages would indicate that the entire Jämtland terrane cooled at the same extremely low rate, a situation that seems unlikely given the large size of the area involved and the large number of low-angle faults of significant displacement within the terrane. The consistency of these ages gives us confidence that they provide the closest date determined so far for the eclogite-forming metamorphism in the Jämtland area.

We have modelled this metamorphism as the result of the subduction of the edge of Baltica into the mantle beneath a composite terrane composed of the Virisen Volcanic Arc and a microcontinent that had previously rifted away from Baltica (see Brueckner & Van Roermund 2004, fig. 3). We suggested that the amalgamation of the microcontinent and the Virisen Arc occurred previously, during the 500 Ma Finnmarkian Orogeny. Roughly 42 Ma then passed as the ocean between the composite terrane and Baltica narrowed and closed, culminating in the subduction of Baltica. We proposed that this event be called the Jämtlandian Orogeny. We recognize that other models can be proposed to explain the conditions required to form HP eclogites, but the subduction model has the advantage of also explaining

the presence of orogenic peridotite bodies within these HP or UHP terranes. A mantle wedge would overlie a slab of subducted continental crust making it not only possible, but even likely, that fragments of this mantle would be transferred laterally and/or downward into the crust as it was undergoing eclogite-facies metamorphism. Both the HP terranes in the Seve Nappe Complex and the HP rocks of the Tromsø Nappe are associated with such orogenic peridotites. Even if the subduction model is rejected, however, the evidence is compelling that at least a small portion of the Baltic margin underwent HP metamorphism during the Lower Ordovician.

The question then arises whether there is any evidence elsewhere for an Early Ordovician collision along the western margin of Baltica. A large number of igneous intrusion ages have been obtained from the Scandinavian Caledonides that coincide or nearly coincide with the 458 Ma average obtained in this study (see Tucker *et al*. 2004, for most recent dates and a review). Ironically, however, these intrusions could be used as evidence against simultaneous HP metamorphism, as subducted crustal terranes should not be intruded by melts derived from below. Fortunately for the subduction model, these intrusions occur within or are associated with rocks that contain fossils of Laurentian affinity (Tucker *et al*. 2004). Thus it is likely that the magmas invaded terranes that occurred well outboard of Baltica rather than the edge of Baltica itself. A number of mafic complexes occur along most of the length of the Scandinavian Caledonides that give intrusion ages in the range of 445–435 Ma (Andréasson *et al*. 2003). These mafic complexes are believed to be associated with a rifting of the Baltic margin. It would be difficult to reconcile simultaneous rifting with the collisional event proposed here. However, the mafic intrusion ages are significantly younger than the 458 Ma age of metamorphism in Jämtland and can be reconciled with a model in which the Baltic margin underwent rifting and the opening of marginal basins roughly 15–20 Ma after HP metamorphism (Andréasson *et al*. 2003). Thus the ages from igneous intrusions neither provide corroborative evidence for a collision nor disprove it.

The best evidence for the Jämtlandian Orogeny would be metamorphic recrystallization ages from elsewhere in the Scandinavian Caledonides. The ages do not have to be from HP or UHP rocks, as metamorphism could affect rocks to different degrees along the collisional belt. As far as we are aware, however, the only evidence for any metamorphism is Ar–Ar cooling ages of *c*. 447 Ma obtained from micas in metamorphic rocks that occur along the SW coast of the Western Gneiss Region (Andersen *et al*. 1998). These metamorphic rocks (i.e. the Høyvik Group) occur below the Devonian basins of the Western Gneiss Region, but above the Western Gneiss Region basement (Andersen *et al*. 1998). The Høyvik Group and the underlying Dalsfjord Suite were originally interpreted as being exotic to Baltica (Andersen & Andresen 1994), in which case they would not provide any additional evidence for a collision affecting Baltica. However, recent dates and reinterpretations of the tectonostratigraphy suggest that the Høyvik Group and Dalsfjord Suite belong to the middle allochthon (i.e. Baltica itself; Corfu & Andersen 2002). If so, a belt of 450 Ma old metamorphic rocks of Baltic affinity could conceivably extend up through the Western Gneiss Region and hence to the Jämtland terrane that is the subject of this paper. It is even possible that some of the classic eclogites of the Western Gneiss Region formed during the Early Ordovician (Brueckner & Van Roermund 2003; Brueckner 2006), particularly those that occur in units correlated with the Blåhø Nappe (Roberts & Stephens 2000). Further mapping and geochronology should explore this possibility.

Concurrent metamorphism of both sides of Iapetus

Zircons separated from an eclogite in the Tromsø Nappe of the uppermost allochthon give a nearly identical age (452 ± 2 Ma, Corfu *et al*. 2003) to that determined in this study for the Jämtland area. The zircon age is corroborated by ages of 451–450 Ma for titanites (Corfu *et al*. 2003). These combined results create two interesting and interrelated dilemmas. How can two apparently similar terranes within the same nappe complex (i.e. the Norrbotten and the Jämtland terranes) give two different ages whereas, at the same time, two very different terranes within two different nappe complexes (i.e. the Seve Nappe of the Upper Allochthon and the Tromsø Nappe of the uppermost allochthon) give essentially the same age of metamorphism? The first issue was discussed previously by Brueckner & Van Roermund (2004), who noted that the western margin of Baltica could have had a uniform shelf stratigraphy along much of its length during the opening of the Ægir Sea and Iapetus. Subsequent outboard subduction of this passive margin sequence beneath incoming arc terranes, first as a rifted microcontinent during the Finnmarkian Orogeny and then as the Baltic margin proper during the Jämtlandian Orogeny, could result in similar tectonic and metamorphic histories and result in similar tectonostratigraphies at the end of each orogeny (see Brueckner & Van Roermund 2004, fig. 3a and b).

The second issue, also mentioned briefly by Brueckner & Van Roemund (2004), can be resolved by proposing that the HP terranes in Tromsø Nappe and the Seve Nappe in Jämtland evolved independently on opposite sides of Iapetus. As noted previously, all but the final (Scandian) collisions recorded by the uppermost allochthon are believed to have occurred along and just outboard of the Laurentian margin when western Iapetus began to develop subduction zones, arcs and microcontinents. Evidence for this Laurentian ancestry for the uppermost allochthon includes palaeomagnetic reconstructions (Hartz & Torsvik 2002; Roberts 2003) that show Baltica at a higher latitude (i.e. closer to the South Pole) than Laurentia, which was generally between the equator and 30°S from the late Cambrian until the late Silurian. The high latitude of Baltica precluded the deposition of thick carbonates on its passive margin, which instead was overlain by mostly clastic sediments, as discussed above, whereas the warmer Laurentian passive margin was characterized by the deposition of the thick carbonates that dominate much of the uppermost allochthon (Roberts *et al*. 2002). These reconstructions and stratigraphic arguments are consistent with the observation that many sedimentary units of the uppermost allochthon contain Ordovician fauna of Laurentian affinity (Pedersen *et al*. 1992). The Tromsø Nappe itself is a crystalline terrane and lacks fossils that would document its Laurentian affinity. However, it lies structurally above units correlated with the Seve and Köli Nappe Complexes, which places it within the uppermost allochthon. It also lies structurally above the Lyngen Nappe, a large ophiolite complex overlain by carbonate shelf sediments similar to the Laurentian carbonates discussed above (Andresen & Steltenpohl 1994). There is also isotopic evidence for a Laurentian connection within the Tromsø Nappe. Pb isotopes from titanites from the Tromsø eclogites have elevated $^{207}Pb/^{204}Pb$ ratios indicating derivation from old crust that seems more consistent with Laurentia than Baltica (Corfu *et al*. 2003). Furthermore, the Tromsø Nappe is dominated by marble, calc-silicates, garnet–mica schist and gneiss, and seems more like a

Laurentian sequence (Krogh *et al*. 1990) than the quartzite-dominated sequences that occur within the Seve Nappe Complex. Finally, the Tromsø Nappe, and in particular the large Tromsdalstind eclogite that occurs within it, is composed of a variety of igneous rocks that include tonalites and trondhjemites. Zircon from these more felsic rocks gives an U–Pb age of 493 +5/−2 Ma and this age is interpreted as dating rifting of the Laurentian margin. These observations indicate very little similarity between the Jämtland terrane and the Tromsø Nappe other than that they both underwent HP metamorphism at the same time, and the simplest way to accommodate these simultaneous metamorphisms is to place the two terranes on the opposite sides of Iapetus.

The evidence presented above suggests that there is no major obstacle to the proposed Jämtlandian Orogeny in what is now central Sweden, but at the same time, there is little evidence that this event occurred elsewhere along the Baltic margin during the Early Ordovician, with the possible exception of the Høyvik Group as discussed above. Further work may show this event to be more extensive than at present realized. However, it is also possible that collisions involving subduction of continental crust into the mantle may involve relatively small crustal fragments (peninsulas and microcontinents, for example) and thus may form only a small fraction of an orogen.

Conclusions

This study yielded two interesting results. First, the 457.9 ± 4.5 Ma HP metamorphism that affected the Jämtland terrane is the first Ordovician tectonic event to be documented in the Scandinavian Caledonides that occurred along the eastern margin of Iapetus and affected the western margin of Baltica. Nearly identical ages have been determined from units that collided on the other side of Iapetus, including the collision that formed the eclogites of the Tromsø Nappe. The second result is that the 457.9 Ma age determined in this study is nearly 50 Ma younger than ages from essentially identical rocks 500 km to the north. Perhaps it should not be surprising that nearly identical processes involving essentially identical units (i.e. Baltica and an outboard terrane) could occur at two or more different times. Nor should it be surprising that events can occur simultaneously in different parts of an ocean basin. Nevertheless, the ages we have determined from Jämtland, as well as the ages from Norrbotten, should be further tested using a variety of radiometric schemes to see if the ages from both terranes are correct. In addition, the intervening 300 km between the two terranes should be the focus of intense mapping and fieldwork, as two collisions at different times should leave obvious structural signatures.

The 458 Ma HP event documented in this study brings to five the number of HP or UHP collisions that marked the accretionary evolution of the Scandinavian Caledonides (the Finnmarkian at 500 Ma, the 'Jämtlandian' at 458 Ma, a separate 450 Ma event on the other side of Iapetus, a 420 Ma event in the Bergen Arcs (Bingen *et al*. 2004), and finally the culminating Scandian orogeny at 400 Ma). In addition, there is evidence of a 400 Ma HP collision (and perhaps a 360 Ma UHP collision) in the Caledonides of northern Greenland (the North-East Greenland Eclogite Province; see Gilotti 1993; Brueckner *et al*. 1998; Gilotti & Krogh Ravna 2002; Gilotti *et al*. 2004) and a 400 Ma collision in Liverpool Land in Central Greenland (Hartz *et al*. 2005). A large number of collisions are probably inevitable as an ocean basin littered with arcs, microcontinents, plateaus, peninsulas, etc. closes during the later stages of the Wilson Cycle. But it is, perhaps, surprising that so many of these collisions resulted in the subduction of sialic crustal fragments into the mantle to eclogite-facies depths and that these fragments were able to return to the surface. We have suggested that these cycles of subduction and exhumation be called 'dunk tectonics' (Brueckner & Van Roermund 2004) and that they are terminated only by the final closure of the ocean and the culminating collision between the two bordering landmasses, a collision that is itself a subduction–eduction cycle. We regard it as unlikely that the Caledonian system is unique in this regard. The signatures of these events, eclogite-facies assemblages associated with mantle-derived peridotite bodies, should be sought in every mountain belt.

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