Geological Society, London, Special Publications Online First

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Geological Society, London, Special Publications, first published September 24, 2013; doi 10.1144/SP390.3

Notes

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Abstract: The Helgeland Nappe Complex (HNC), part of the Uppermost Allochthon of the north-central Norwegian Caledonides, originated near the Laurentian margin and was transferred to Baltica during the closure of Iapetus in Late Silurian–Early Devonian time. The islands of Rødøy, Bolvær and Leka, located in the Sauren–Torghatten (S–T) nappe of the HNC, are composed of ultramafic and mafic basement rocks unconformably overlain by metaconglomerates and fine-grained metasedimentary rocks. Geochemical and isotopic characteristics of the basement rocks are consistent with formation in a supra-subduction zone setting. Overlying metasedimentary rocks record an increasing proportion of continental detritus supplied to the basins through time. Precambrian cratonic source regions supplied cobbles and other detritus. This source area may have been located in modern SE Greenland/Labrador or in the Lower Nappe of the HNC. The second alternative best accounts for the short transport distances required by the coarse-grained conglomerates. The maximum age of deposition is constrained by the age of the youngest zircon grain dated at 471 $\pm$ 8 Ma. Final sedimentation, nappe thrusting and nappe stacking occurred in rapid succession during *c.* 480–475 Ma.

Supplementary material: Geochemical analyses and Nd isotopic data are available at http://www.geolsoc.org.uk/SUP18654

The Scandinavian Caledonides record an important part of the Early Palaeozoic Caledonide–Appalachian orogeny related to the closure of the Iapetus Ocean (McKerrow *et al.* 2000). The Middle–Late Ordovician Taconian phase (*c.* 470–450 Ma) is interpreted as the product of an arc–continent collision along the Laurentian margin (Stanley & Ratcliffe 1985; Yoshinobu *et al.* 2002; Roberts 2003). In the Silurian–Early Devonian Scandian phase, oblique plate convergence culminated in the closure of the Iapetus Ocean and the collision of Baltica and Laurentia. It was during this phase at *c.* 420–400 Ma that the Uppermost Allochthon, the structurally highest of four major allochthons that compose the Scandinavian Caledonides, was uprooted from Laurentia and transported on to the Baltic margin (e.g. Roberts & Gee 1985; Stephens *et al.* 1985; Roberts 2003). Early tectonic models for closure of Iapetus showing orthogonal collision (Wilson 1966) are now understood to be too simplistic. Recent tectonic reconstructions indicate that sinistral orogen-parallel strike-slip motion accompanied Scandian contraction and accretion (Roberts *et al.* 2007).

The Uppermost Allochthon contains oceanic assemblages and continental rocks containing rare fauna of Laurentian affinity (Roberts *et al.* 2007). The constituent nappe complexes of the Uppermost Allochthon record a complex pre-Scandian peri-Laurentian history of formation and assembly from Neoproterozoic to Early Ordovician time (Barnes *et al.* 2007); amalgamation, metamorphism and magmatism of these nappes has been ascribed to Taconian tectonism by Roberts *et al.* (2002) and Yoshinobu *et al.* (2002).

In north-central Norway, the Helgeland Nappe Complex (HNC) is the structurally highest part of the Uppermost Allochthon (Fig. 1). Five nappes have been recognized in the southern HNC, which can be divided into two groups. One group is composed of the Upper, Lower and Horta Nappes and consists of migmatitic gneiss, calc-silicate rocks and marble, with no exposed depositional basement (Thorsnes & Løseth 1991; Barnes *et al.* 2007). The

From: Corfu, F., Gasser, D. & Chew, D. M. (eds) *New Perspectives on the Caledonides of Scandinavia and Related Areas*. Geological Society, London, Special Publications, **390**, http://dx.doi.org/10.1144/SP390.3

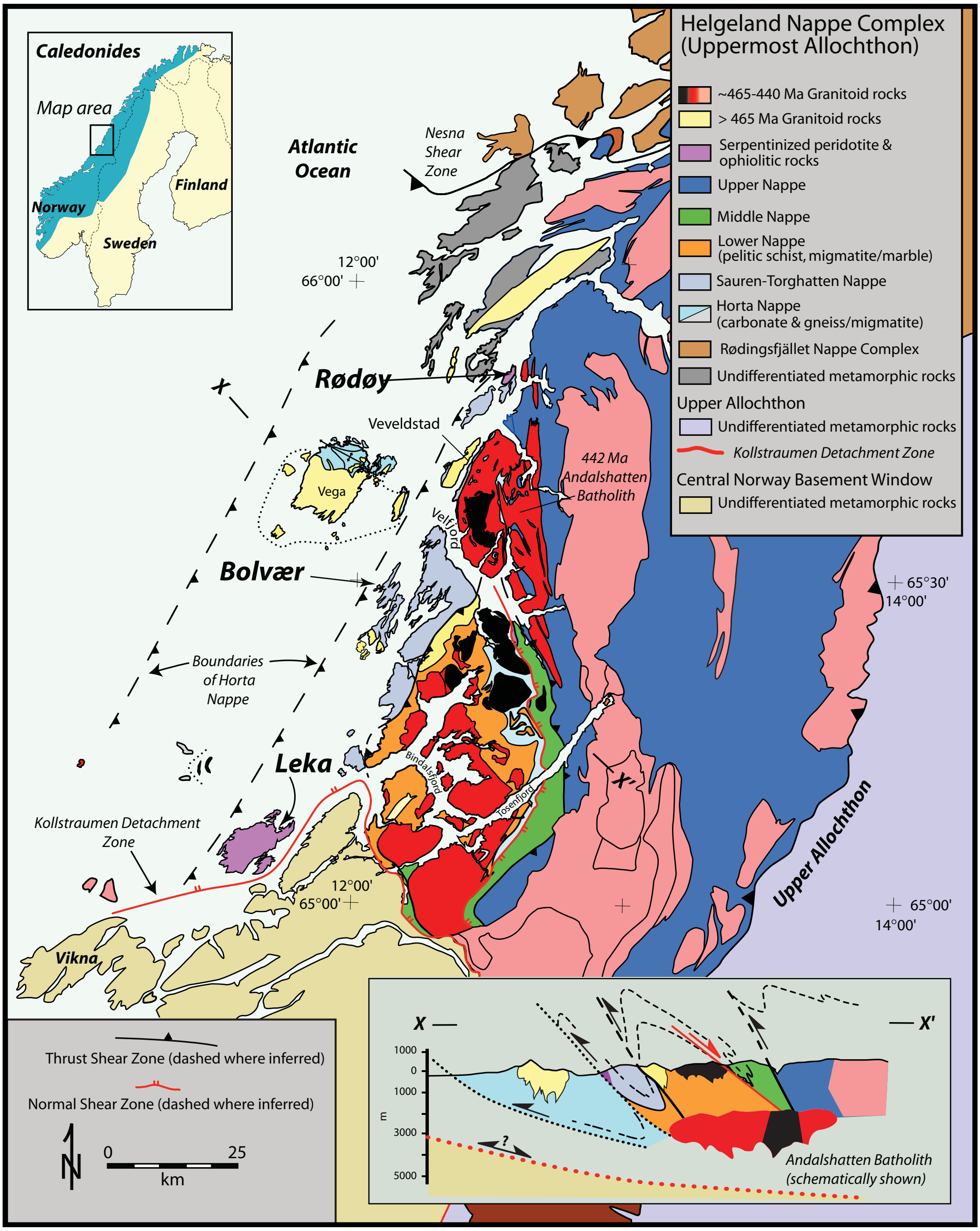

Fig. 1. Tectonostratigraphic map displaying the major units within the Helgeland Nappe Complex, Uppermost Allochthon, Scandinavian Caledonides, west-central Norway. The HNC is composed of at least five nappes (from lowest to highest): Horta, Sauren–Torghatten (S–T), Lower, Middle and Upper nappes (Barnes *et al.* 2007). The islands of Rødøy and Bolvær belong to the S–T Nappe. This study evaluates whether Leka also should be considered part of the S–T Nappe. Age of Andalshatten pluton from Anderson *et al.* (2013).

second group, comprising the Middle and Sauren–Torghatten (S–T) Nappes, is composed of metaconglomerates, marble, calc-silicate schist and pelitic schist deposited on discontinuously exposed ultramafic and mafic meta-igneous rocks (Thorsnes & Løseth 1991; Heldal 2001). The latter group of nappes is important because they preserve fragments of Iapetan oceanic crust and the first sediments to be deposited on this crust.

The best-preserved primary features of ophiolitic basement and their supracrustal cover sequences in the HNC are exposed on three islands – Rødøy, Bolvær and Leka – which are located immediately offshore of the mainland of north-central Norway (Fig. 1). This study presents petrologic, geochemical, isotopic and geochronological data on the basement rocks and cover sequences from Rødøy and Bolvær. Data are also presented for sedimentary strata on the island of Leka, which has not been formally assigned to an HNC nappe but which also exposes ophiolitic basement and a sedimentary cover sequence. The results of this study identify similar meta-igneous basement rocks exposed on all three islands. In each study area, metasedimentary rocks directly overlie ophiolitic basement and record a changing tectonic and depositional environment in which continental detritus becomes more important with time. They indicate that the Leka ophiolite and its cover sequence belong to the S–T Nappe together with Rødøy and Bolvær. Together, the geological history of these three islands provides the opportunity to place the S–T nappe in the larger context of the arc complexes and ophiolite fragments that crop out in the Norwegian and British Caledonides and the Appalachians.

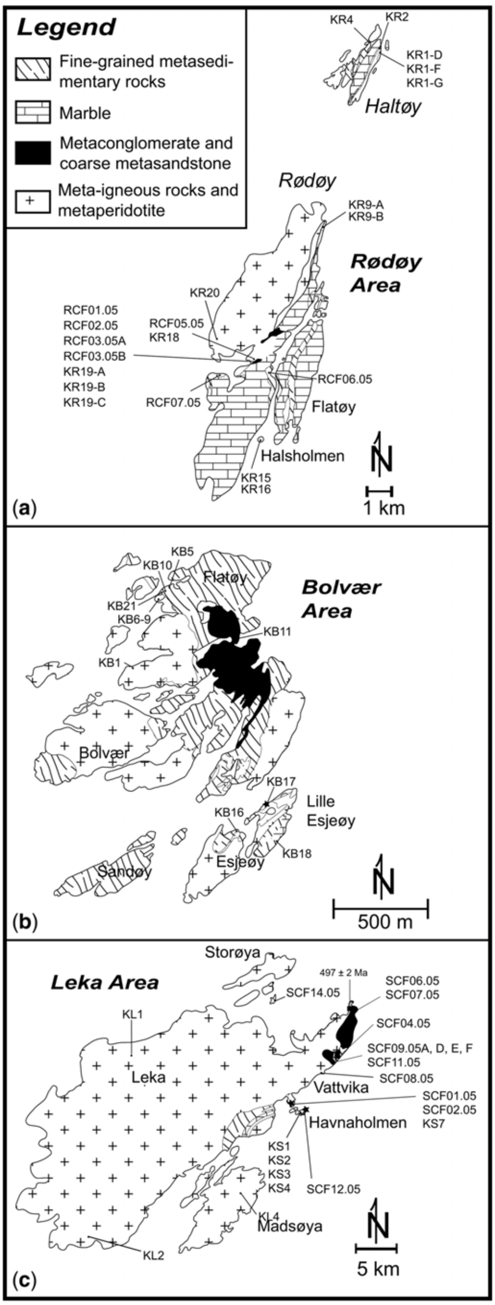

Fig. 2. Geological maps with sample locations of (**a**) Rødøy (after Bang 1985), (**b**) Bolvær (after Heldal 2001) and (**c**) Leka (after Gustavson 1975*b*). The metasedimentary rocks exposed along the northeastern shore of Leka belong to the Skei Group. Sample locations are indicated; locations of geochronology samples are shown as stars.

Geology of the Sauren–Torghatten Nappe

The Sauren–Torghatten Nappe was defined by Yoshinobu *et al.* (2002) to consist of a sequence of medium- to high-grade metasedimentary rocks that overlie and are structurally interleaved with discontinuous ophiolitic fragments (Sturt *et al.* 1984; Bang 1985; Heldal 2001). The S–T Nappe is separated by a thrust fault from the overlying migmatitic Lower Nappe (Fig. 1). Its contact with the structurally lower units (informally termed the 'Horta nappe' by Barnes *et al.* 2007) is not exposed.

The largest and most complete exposures of S–T basement rocks are at the islands of Rødøy and Bolvær, both of which lie north of and along regional strike with the Leka ophiolite (Fig. 1). These basement rocks are unconformably overlain by metamorphosed cover sequences that consist of variable proportions of metaconglomerate, psammite, pelitic and semi-pelitic schist, calc-silicate schist and marble (e.g. Stephens *et al.* 1985; Heldal 2001; Roberts *et al.* 2001).

Rødøy

The Rødøy study area includes the islands of Rødøy, Haltøy, Flatøy and Halsholmen (Fig. 2a).

Basement rocks are metamorphosed harzburgite, dunite and gabbro. The contact between basement gabbros and the metasedimentary rocks was interpreted by Bang (1985) to be an erosional unconformity based on topographic relief on the basement and weathering of the gabbroic basement and by comparison with unconformities on other ophiolites in the Norwegian Caledonides. The overlying metasedimentary rocks include polymict metaconglomerate, mafic metaconglomerates, marble, greenschist, pelitic schist and sparse fine-grained metasandstone. Cobbles sampled for this study are metamorphosed gabbro, anorthositic gabbro, anorthosite, basite and marl. The cobbles are deformed and vary from 2 to 30 cm in length. The metamorphic grade of Rødøy samples varies from greenschist to lower amphibolite facies (Bang 1985). No geochronology has been reported for rocks from Rødøy.

Bolvær

The Bolvær Complex (Fig. 2b) is predominantly composed of layered metagabbro with smaller amounts of serpentinite, metapyroxenite, amphibolite and meta-quartz diorite (Heldal 2001). Polyphase deformation, some of which pre-dates deposition of the cover sediments, is recorded in the ultramafic–mafic rocks and has been attributed to early deformation in an oceanic setting, with later emplacement on to a continental margin (Heldal 2001). The unconformity at the top of the Bolvær Complex is characterized by an irregular surface, carbonate-filled fractures and altered mafic rocks. In adopting a similar interpretation by Sturt *et al.* (1985) from Leka, Heldal (2001) interpreted these features to be a fossil subaerial weathering zone. Basal, mafic breccias were interpreted as locally derived talus deposits (Heldal 2001).

Above the unconformity, normally graded metamorphosed sandstone and siltstone beds were interpreted as shallow-water turbidite deposits (Heldal 2001). A metaconglomerate lens within these beds contains rounded anorthositic gabbro cobbles. Other polymict metaconglomerate horizons contain cobbles of ultramafic rocks, gabbro, chert, carbonate, psammite, quartzite and calc-silicate schist.

U–Pb data for detrital zircon have been reported from two metasedimentary rocks from Bolvær. Barnes *et al.* (2007) analysed zircon from a 70 cm-long micaceous metasandstone cobble from Bolvær collected *c.* 100 m stratigraphically above the basement rocks of the Bolvær Complex. Ninety-seven U–Pb ages obtained by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) define four dominant age populations at 3000–2600, 1900–1640, 1500–1300 and 1200–980 Ma. The sample lacks concordant grains younger than *c.* 975 Ma. McArthur (2007) collected a basal metasandstone immediately overlying the gabbroic basement. Thirty-seven zircon grains defined two dominant age populations: an Archaean (2900–2650 Ma) group and a Palaeoproterozoic (1900–1800 Ma) group. U–Pb ages of two grains are older than 3100 Ma. This sample lacked zircon younger than 1100 Ma.

Leka

Leka and the surrounding islets are composed of ultramafic and mafic basement rocks that constitute the Leka ophiolite and by metasedimentary sequences of the Skei Group that unconformably overlie the ophiolite (Fig. 2c; Prestvik 1972; Sturt *et al.* 1985). Metamorphic grade reached upper greenschist facies, and some evidence of relict amphibolite facies metamorphism exists in the gabbroic rocks (Prestvik 1972; Sturt *et al.* 1985). A quartz keratophyre from the northeastern point of Leka yielded a U–Pb zircon age of 497 ± 2 Ma (Dunning & Pedersen 1988).

The Skei Group consists of metamorphosed conglomerate, greywacke, schist and minor marble. It unconformably overlies the deeply eroded ophiolitic basement along the eastern edge of Leka and on the island of Havneholmen (Fig. 2c; Sturt *et al.* 1985; Sturt & Ramsay 1994). The unconformity was interpreted as a subaerial erosional surface characterized by irregular topography and a palaeoweathering zone (Sturt *et al.* 1985).

The only direct age determinations for the metasedimentary sequence come from chemostratigraphic dating of the Skei Group marble. The Sr and C isotopic compositions of the Skei Group marble are characteristic of deposition during Ordovician time (Barnes *et al.* 2007). In addition, detrital zircon U–Pb data have been reported from two clastic metasedimentary samples. Barnes *et al.* (2007) analysed zircon from a large ($60 \times 5 \times 10$ cm) fine-grained metasandstone cobble from a conglomerate horizon in the lower portion of the Skei Group. The dominant age populations are 2900–2600 and 1950–1700 Ma. There is a spread of ages that range from 1650 to 1350 Ma and a smaller population at 1100–1050 Ma. Two grains have ages greater than 3000 Ma. McArthur (2007) analysed sparse zircon from the Havna formation, a turbidite sequence that was interpreted by Sturt *et al.* (1985) to be stratigraphically higher than the metaconglomerate horizon that yielded the cobble analysed by Barnes *et al.* (2007). The zircons from the turbidite are generally euhedral. Unlike the other samples, no Precambrian age zircons were analysed. Most ages are between 500 and 480 Ma. The oldest population at 550 Ma is defined by two concordant grains and one discordant grain. One concordant grain has an age of 471 ± 8 Ma.

Sample descriptions

Samples were collected from exposed ophiolitic basement, from overlying conglomeratic deposits and from associated medium- to fine-grained clastic deposits that typically overlie or are intercalated with the finer-grained clastic rocks. Sample locations are shown on Figure 2.

Most basement samples and meta-igneous cobbles display greenschist facies assemblages, but a few contain hornblende and are transitional to amphibolite facies. Few vestiges of primary igneous or sedimentary mineral assemblages remain. One exception is sample KB1 from Bolvær, which is a weakly metamorphosed clinopyroxenite. The majority of the basement rocks are metagabbro or meta-anorthosite. Gabbroic rocks typically consist of actinolitic to tremolitic amphibole + an epidote group mineral ± chlorite. Plagioclase is present as relicts of partly albitized primary crystals that now consist of granular subgrains and as matrix albite crystals.

The majority of meta-igneous cobbles are also metagabbro and meta-anorthosite, but a few fine-grained metabasic rocks were collected. In contrast to the basement rocks, the coarse-grained meta-igneous cobbles lack amphibole; they contain clinozoisite ± biotite ± chlorite and many are infused with calcite. Sample KR-19B with *c.* 34.8 wt% SiO_2 and 21.7 wt% CaO is an extreme example of a calcite-infused metagabbro. Plagioclase shows the same style of recrystallization as in the basement samples.

The metasedimentary rocks include metapelitic schist (Rødøy and Bolvær), metawackes and psammite (Leka), metaconglomerates and metacarbonates (all three localities). The metapelitic rocks are typically retrogressed to chlorite- and muscovite-rich assemblages; the peak metamorphic assemblage was biotite + garnet + staurolite + plagioclase + quartz. Some former metapelites are infused with calcite (e.g. sample KB22) but lack pervasive high-grade mineral assemblages indicative of a Ca-rich bulk composition. We therefore interpret the introduction of calcite to post-date peak metamorphic conditions. Metasandstone samples from the Skei Group on Leka are characterized by the greenschist facies assemblage epidote + chlorite + albite + quartz ± calcite, whereas metawackes from the stratigraphically higher exposures at Havna contain hornblende + plagioclase + quartz with retrograde(?) albite and chlorite.

Analytical methods

Major and trace element geochemical data on meta-igneous and metasedimentary rocks were obtained by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at Texas Tech University. A subset of samples was analysed for the rare earth elements (REE) Th, Hf, Ta, U, Pb, Rb and Cs contents by ICP-MS at Washington State University. Detection limits are 0.01% for major elements and 2 ppm for Rb, Sr, Zr, Y, Nb and Ba. Detection limits for REE are 0.1 except for Eu, Ho and Lu, which are 0.05 ppm.

Sm–Nd isotopic data were obtained by thermal ionization mass spectrometry (TIMS) at the University of Wyoming. Between 100 and 300 mg of sample were dissolved in HF-HNO_3. After conversion to chlorides, a third of the sample was spiked with ^{87}Rb, ^{84}Sr, ^{149}Sm and ^{146}Nd. REE were separated by conventional cation-exchange procedures, and Sm and Nd were isolated using di-ethyl-hexyl orthophosphoric acid columns. All isotopic measurements were made on a VG Sector multi-collector mass spectrometer at the University of Wyoming. An average ^{143}Nd/^{144}Nd of 0.511846 ± 11 (2σ) was measured for the La Jolla Nd standard. Uncertainties in Nd isotopic ratio measurements are ±0.00001 (2σ). Blanks are <50 pg for Nd and Sm, and no blank correction was made. Uncertainties in Nd and Sm concentrations are ±2% of the measured value; uncertainties on initial ε_{Nd} are ±0.3 epsilon units.

Geochemical data

Fifty-seven meta-igneous and metasedimentary rocks from Rødøy, Bolvær and Leka were analysed for major and trace elements (see Supplementary material). Analysed samples include ophiolitic basement rocks from Rødøy and Bolvær and meta-igneous and metasedimentary cobbles from conglomerates and finer-grained metasedimentary rocks from Rødøy, Bolvær and Leka. The effects of greenschist to middle amphibolite facies metamorphism are pervasive among the analysed samples. Moreover, many samples from Rødøy and Bolvær have suffered intense retrogression (e.g. Heldal 2001) and contain abundant intergranular calcite. This secondary carbonate alteration is widespread in rocks older than 440 Ma in the HNC, including in the 475 Ma Ylvingen pluton (Oalmann *et al.* 2011), suggesting that it results from a post-nappe stacking and intrusion event. In any case, interpretations made on the basis of the geochemical data from such altered rocks are necessarily tentative.

Meta-igneous basement rocks

Basement rocks from Rødøy, Bolvær and Leka include variably metamorphosed dunite, pyroxenite, gabbro, diabase and quartz keratophyre. The SiO_2 contents of the basement rocks are mainly in the range 36–60 wt% (Fig. 3), although quartz keratophyre from Leka is more silica-rich. Abundances of FeO(t), CaO, Al_2O_3, Sc, Cr and Ni vary widely. Leka diabase is higher in FeO(t) and TiO_2 and lower in K_2O and Al_2O_3 compared to the intrusive basement rocks (Fig. 3a, b). Most of the samples are characterized by low near-chondritic REE abundances and have patterns with positive slopes and positive Eu anomalies (Fig. 4). However, a fine-grained metadiabase (KR16) has REE abundances of *c.* 10 times that of chondrites, a slightly positive slope and a negligible Eu anomaly (Fig. 4); this pattern is similar to that of an average of greenstones from the Skei Group at Leka (Prestvik & Roaldset 1978).

Meta-igneous cobbles

The majority of the sampled cobbles are meta-igneous rocks with protoliths of gabbro, anorthosite, gabbroic anorthosite, trondhjemite, metabasite and keratophyre. These cobbles exhibit a range of SiO_2, Sc, Ni and Cr similar to those of the basement rocks, but have higher K_2O and Al_2O_3 (Fig. 3a). This, coupled with their higher loss on ignition, suggests that the cobbles are more pervasively altered than the basement rocks.

One cobble from Rødøy (KR1-G) has a REE pattern that is identical to diabase sample KR16. However, most meta-igneous cobbles have the same lower REE contents and patterns that characterize most of the basement rocks (Fig. 4).

The high and scattered concentrations of CaO, MgO, FeO(t), Al_2O_3, Sc, Ni and Cr for most of the basement rocks and a large proportion of the cobbles are suggestive that these samples are cumulates of plagioclase $\pm$ pyroxene or olivine (Fig. 3). This conclusion is consistent with the low abundances of TiO_2, P_2O_5, Zr and the REE for all but one of the basement rocks: a metadiabase (Figs 3 & 4).

In contrast, crystal accumulation cannot explain the high and scattered abundances of the alkalis and Ba (Fig. 3). Such high values for metabasic rocks are suggestive of enrichment of fluid-mobile elements during the intense retrogression that affected the metasedimentary samples in particular.

Because most of the samples represent cumulate compositions and because many are enriched in fluid-mobile elements, the use of most discrimination diagrams is problematic. The Th–Hf–Ta discrimination diagram of Wood *et al.* (1979) and Wood (1980) may be among the most robust because all of the elements used in this scheme are incompatible in mafic magmas and relatively immobile during metasomatism. Element ratios should therefore be less affected by crystal accumulation or metasomatic alteration. However, Ta is at or below detection limits in nearly all of the analysed samples. Because Nb/Ta for MORB-(mid-ocean ridge basalt) source-depleted mantle is *c.* 15 (McDonough 2005), we used Nb/15 as a proxy for Ta content. In this plot, all of the analysed basement samples plot in the field of supra-subduction zone magmas (Fig. 5).

Nd isotopic data

Initial Nd isotopic ratios from meta-igneous basement rocks, metaconglomerate clasts and fine-grained metasedimentary rocks are calculated for 480 Ma, the estimated depositional age of the metasedimentary sequences based on the youngest ages of detrital zircon in the Skei Group turbidite from Leka (McArthur 2007), and a pelitic schist from the S–T nappe reported by Barnes *et al.* (2007).

Meta-igneous basement rocks

Most of the basement rocks have very low concentrations of Sm (0.1–0.5 ppm) and Nd (0.2–0.9 ppm) (Supplementary material) that reflect primary cumulate assemblages. Two samples that may represent liquid compositions, samples KR18 and SCF08.05, have higher Sm (2.4 and 4.7 ppm) and Nd (6.3 and 16.4 ppm) concentrations. The basement rocks have $^{147}Sm/^{144}Nd$ values (0.1726–0.3683) comparable to that of modern MORB (0.178–0.220) and higher than the $^{147}Sm/^{144}Nd$ of continental crust (0.100–0.130) (Fig. 6; Goldstein *et al.* 1984). The initial ε_{Nd} values of these rocks are between +6.5 and +9.5 (uncertainty ± 0.3 epsilon units), which overlap but on average are slightly lower than values for contemporary MORB (+8 to +11). The isotopic data collected for this study from Rødøy, Leka and Bolvær generally overlap previously published values for the Leka ophiolite (Furnes *et al.* 1992; Fig. 6).

Meta-igneous cobbles

The Sm and Nd concentrations in the meta-igneous cobbles are comparable to those of the basement rocks (Supplementary material). The $^{147}Sm/^{144}Nd$ ratios of the meta-igneous cobbles (0.1346–0.2780) overlap with the basement rocks, but extend to lower values. Cobbles with isotopic values which are indistinguishable from the underlying basement rocks were sampled from the mafic metaconglomerate on Rødøy, the anorthositic gabbro metaconglomerate lens on Bolvær and the polymict metaconglomerate on Leka.

Meta-igneous cobbles with ε_{Nd} values lower than the basement rocks (-1.1 to $+4.1$) were sampled from polymict metaconglomerates at Rødøy and Leka. The Rødøy meta-igneous cobble population comprises the majority of this second group and is distinguished by the large number of clasts with initial ε_{Nd} values from -1.1 to $+3.2$. Two meta-igneous cobbles from the island of Havneholmen, east of Leka, have ε_{Nd} values of -0.1 and $+4.1$. Each of the cobbles with ε_{Nd} values <7 is characterized by significant subgrain development and subsequent albitization of primary feldspars, and generally by abundant white mica. We therefore interpret the lower ε_{Nd} of these basement meta-igneous rocks as the result of exchange with fluids that carried unradiogenic Nd.

Metasedimentary cobbles

Metasandstone cobbles have $^{147}Sm/^{144}Nd$ values from 0.1137 to 0.1308 and unradiogenic initial ε_{Nd} values from -16.5 to -10.6. These cobbles are clearly distinct from the meta-igneous cobbles described above. Compared to the metasandstone cobbles, a marl cobble from Rødøy has lower Sm (0.1 ppm) and Nd (0.5 ppm) contents, higher $^{147}Sm/^{144}Nd$ (0.1493) and more radiogenic initial ε_{Nd} value ($+1.7$; Fig. 6).

Fine-grained metasedimentary rocks

Two of the basal fine-grained metasedimentary rocks, a chloritic schist from Bolvær and a metapelite from Leka have $^{147}Sm/^{144}Nd$ values of 0.1509 and 0.2204 and initial ε_{Nd} values of -2.5 and -0.4 (Supplementary Table 2). Three metagreywacke samples from the upper portion of the Skei Group at Havna, Leka were analysed. One sample consists of multiple thin graded turbidite beds. The other two samples represent the fine- and coarse-grained fractions of a single normally graded turbidite bed. The $^{147}Sm/^{144}Nd$ values range from 0.1455 to 0.1978 and initial ε_{Nd} values are -3.2 for the composite sample (plotted on Fig. 6), -5.7 for the fine-grained fraction and $+5.5$ for the coarse-grained fraction. Pelitic schists from Rødøy and Bolvær and the black schist from Leka have relatively high Sm and Nd concentrations (2.7–8.9 and 14.2–51.2 ppm, respectively), low $^{147}Sm/^{144}Nd$ (0.1025–0.1155) and negative initial ε_{Nd} values (-18.7 to -13.5). These rocks all occupy stratigraphically high positions in their respective stratigraphic sections.

Plotted as a function of stratigraphic position, the Nd isotopic composition of basement rocks and metasedimentary cover defines a trend from radiogenic oceanic basement to more unradiogenic Nd isotopic compositions of the sedimentary succession with increasing stratigraphic position. This pattern of increasing influence of continental input up-section is exhibited on all three islands (Fig. 7).

Discussion

Tectonic correlations

Leka has not been formally assigned to a nappe within the HNC and is traditionally classified as a unique nappe unit (Thorsnes & Løseth 1991; Barnes *et al.* 2007), although lithologic comparisons have prompted some workers to associate the Leka ophiolite informally with other ultramafic and mafic rock occurrences in the S–T Nappe (Gustavson 1975*a*, 1978; Bang 1985; Heldal 2001). This study documents many common features that Leka shares with two tectonic fragments, Rødøy and Bolvær, in the S–T Nappe. Similarities include ultramafic-mafic basement rocks with supra-subduction zone trace element characteristics, and overlying metasedimentary sequences that show up-section progressions of detritus with isotopically juvenile to evolved signatures. Moreover, metasandstone and metasandstone cobbles from Bolvær and Leka contain nearly identical Precambrian detrital zircon age populations (Barnes *et al.* 2007; McArthur 2007).

U–Pb zircon age data from other studies also tie Leka to the S–T Nappe. Detrital zircon from a metasandstone located in the S–T Nappe near Vevelstad (AND-60), like the Havna metagreywacke studied by McArthur (2007), are dominated by 500–480 Ma ages (Barnes *et al.* 2007). The Vevelstad metasandstone also contains two older grains with Archaean and Mesoproterozoic ages comparable to those in the Leka and Bolvær metasandstone cobbles and the Bolvær metasandstone. These lines of evidence suggest that Leka should be formally assigned to the S–T Nappe.

Geological history of the S–T Nappe

Basement rocks. The basement rocks at each island consist of metamorphosed ultramafic and mafic rocks. Ultramafic rocks, primarily harzburgite and dunite, are best exposed on Rødøy and Leka, whereas only small amounts of serpentinite and pyroxenite crop out on Bolvær. Layered gabbroic rocks are prominent at each study location. Ophiolite stratigraphy is preserved only at Leka; however, previous workers have interpreted the basement rocks

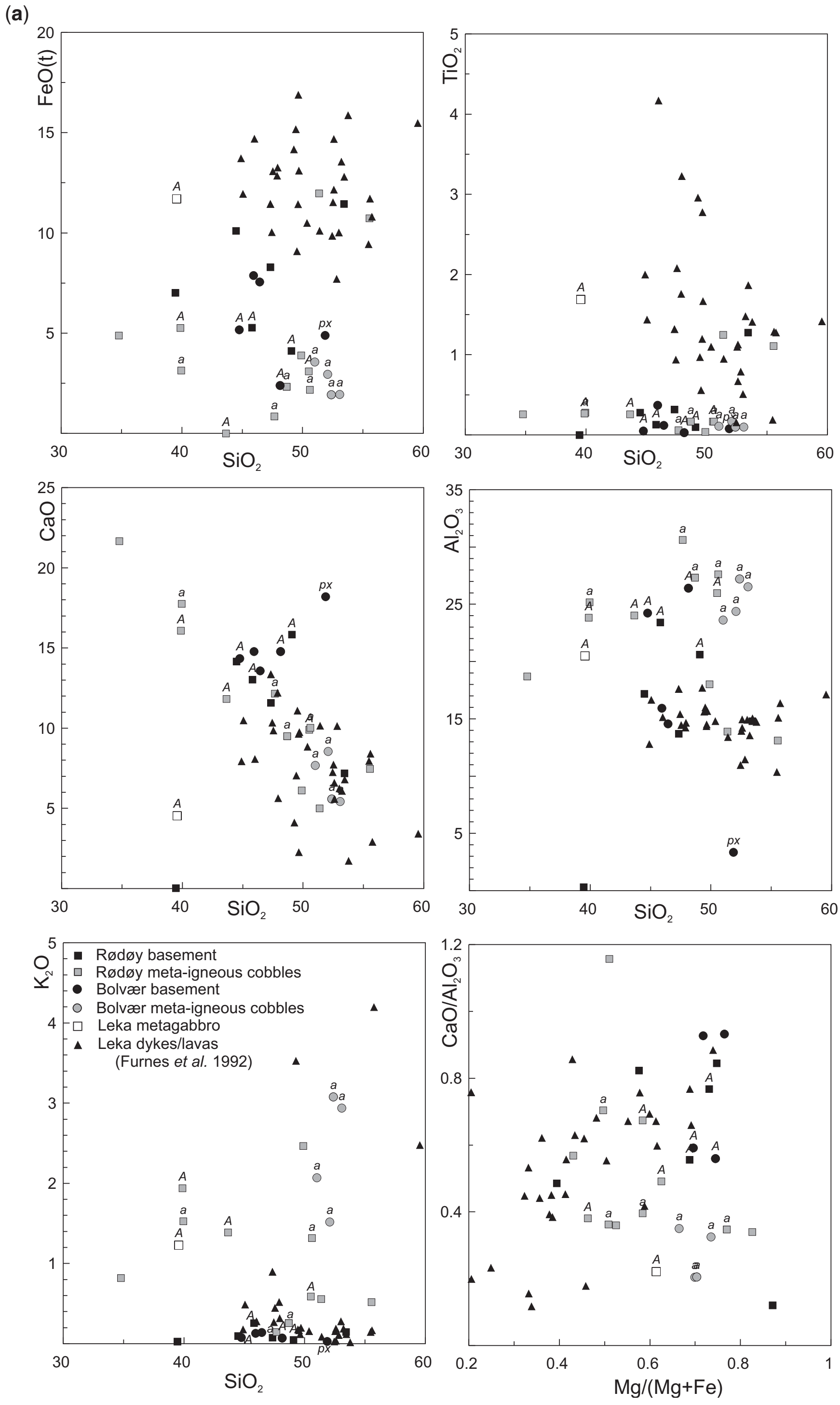

Fig. 3. Selected (**a**) major element and (**b**) trace element Harker diagrams for basement and meta-igneous cobbles from Rødøy, Bolvær and Leka. Data from this study and Furnes *et al.* (1988). A indicates anorthositic gabbro/anorthosite from the basement; a indicates anorthositic gabbro/anorthosite cobble; px indicates pyroxenite.

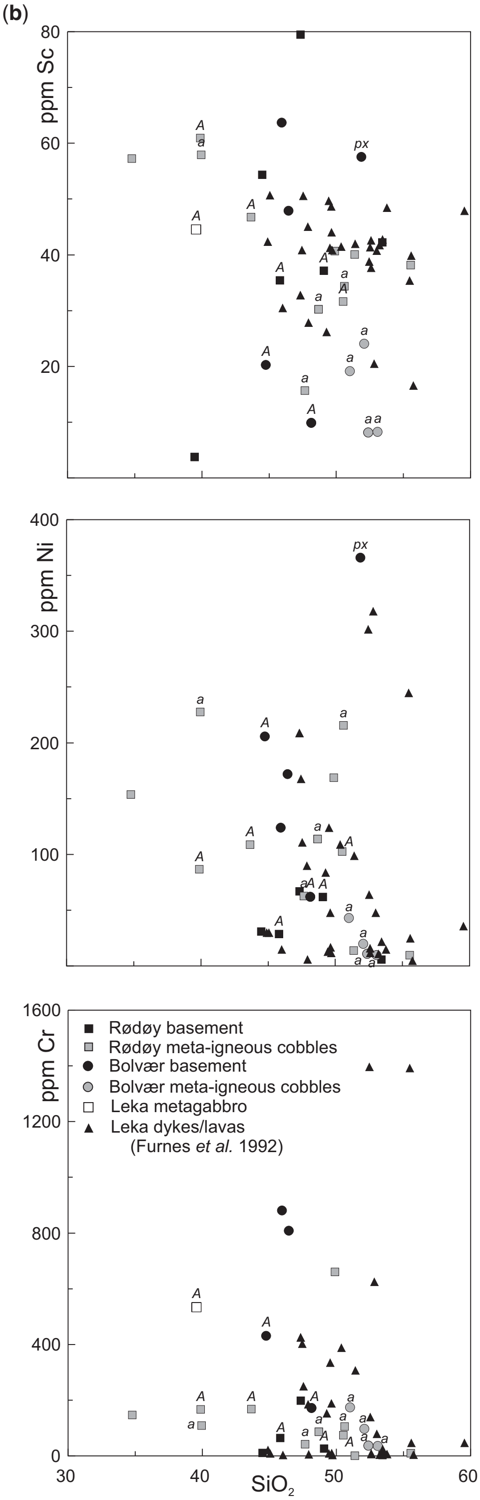

Fig. 3. *Continued.*

at Rødøy and Bolvær as ophiolite fragments based on lithologic comparisons with the well-studied 497 Ma Leka ophiolite (Bang 1985; Dunning & Pedersen 1988; Heldal 2001).

Ophiolitic basement rocks at the three islands have similar major, trace and REE characteristics (Figs 3 & 4) permitting the interpretation from Leka that the magmas have supra-subduction zone affinities (Furnes *et al.* 1988, 1992) to be extended to Rødøy and Bolvær. The low Ti content of gabbros is commonly associated with magmas generated during the early stages of intra-oceanic back-arc basin spreading above a subduction zone (Serri 1981; Beccaluva *et al.* 1983). The low Nb and Ta contents of the ultramafic-mafic basement rocks relative to Hf and Th (Fig. 5) are also distinctive characteristics of supra-subduction zone magmatism (e.g. Pearce *et al.* 1984; Saunders *et al.* 1991; Hawkins 2003).

The isotopic data provide additional evidence for subduction zone influence. The initial ε_{Nd} values extend from contemporary MORB towards less-radiogenic values and require a contribution from an isotopically evolved component, which could have been crustal sediments that were incorporated into depleted mantle magmas during subduction processes. Alternatively, the slightly radiogenic initial ε_{Nd} could indicate incorporation of an arc magma component. The Sm–Nd data collected in this study from Rødøy, Bolvær and Leka overlap data collected by Furnes *et al.* (1992) from the Leka ophiolite (Fig. 6). These data indicate that the Rødøy and Bolvær basement rocks have juvenile isotopic characteristics comparable to the Leka ophiolite and are compatible with a depleted mantle origin.

Metaconglomerates. Mafic and polymict metaconglomerates were deposited on the basement rocks at Bolvær, Rødøy and Leka. Although the cobbles have been more extensively affected by later carbonate alteration than the basement rocks, the geochemical similarities between the meta-igneous cobbles and meta-igneous basement rocks are more prominent than the differences. Each island preserves mafic cobbles with geochemical characteristics that closely mirror those of the mafic basement rocks, in agreement with field evidence that suggests many cobbles may have been locally derived from the ophiolitic basement. Chondrite-normalized REE patterns of the analysed cobbles are similar to the basement rocks (Fig. 4).

Sub-angular mafic clasts in mafic metaconglomerate occur as blocks in metasedimentary breccias that are likely talus deposits derived from a local source (Sturt *et al.* 1985; Heldal 2001). Although some cobbles in the mafic metaconglomerates are smaller and rounded, a more distal source may not

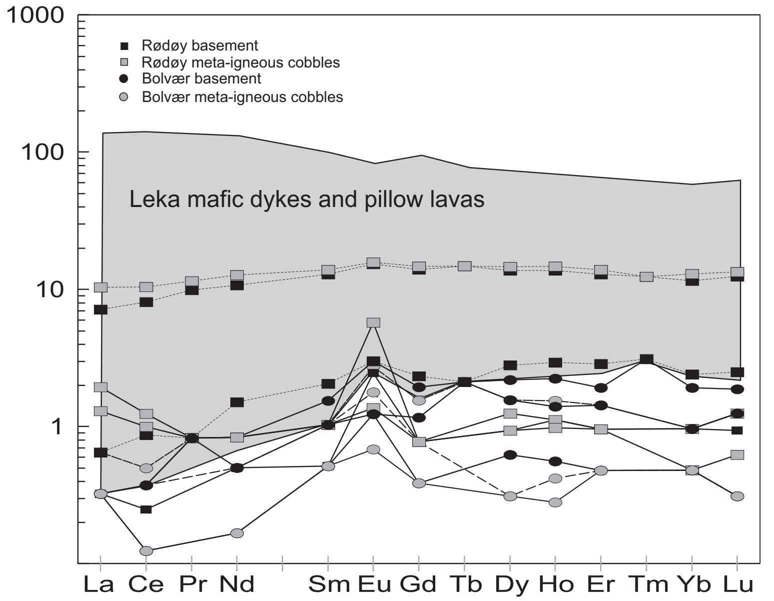

Fig. 4. REE diagrams for basement and meta-igneous cobbles from Rødøy, Bolvær and Leka. Data from this study and Prestvik & Roaldset (1978).

be required if these rocks weather readily and become rounded during transport over short distances because of their mafic composition: three rounded cobbles from the Rødøy mafic metaconglomerate have major and trace element characteristics comparable to the mafic basement rocks (Fig. 3) and

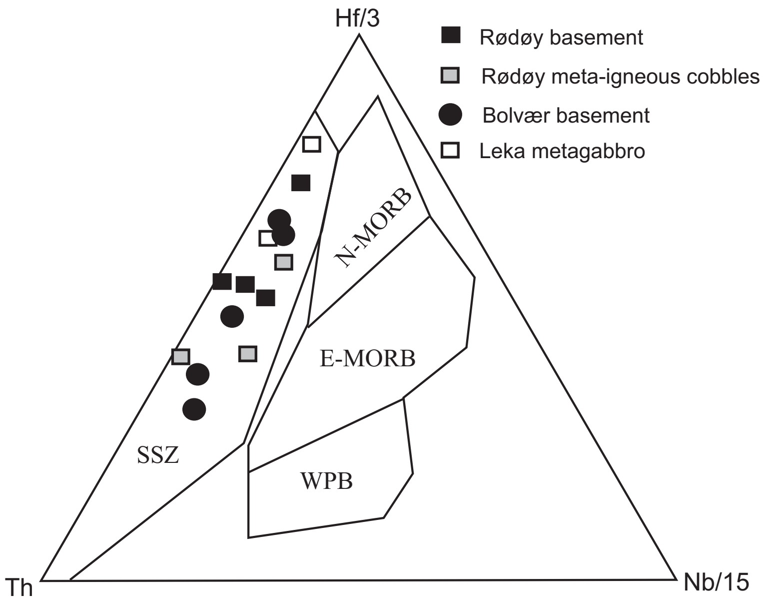

Fig. 5. Th–Hf/3–Nb/15 discrimination diagram after Wood *et al.* (1979) and Wood (1980) indicating supra-subduction zone affinities of Rødøy, Bolvær and Leka basement rocks and meta-igneous cobbles. WPB, within-plate basalt; SSZ, supra-subduction zone basalt; E-MORB, enriched mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt.

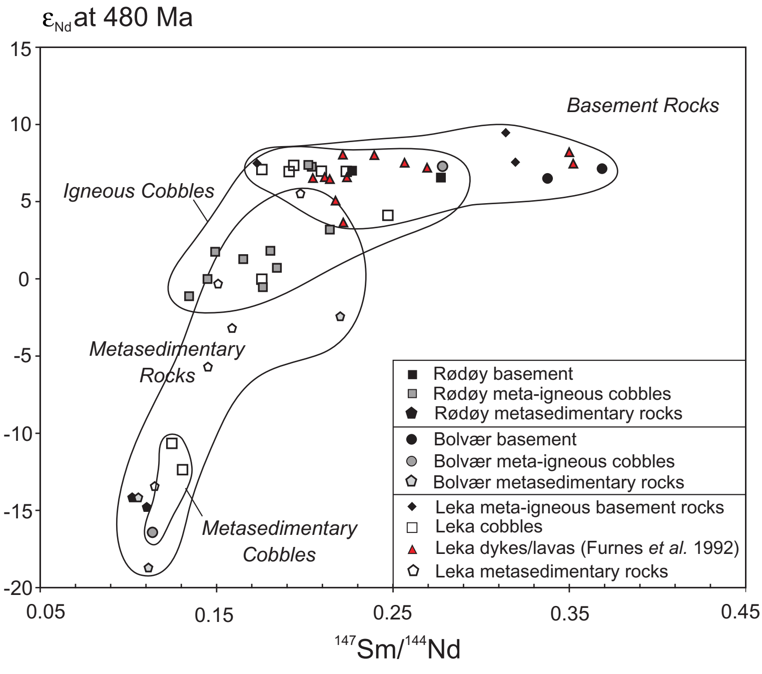

Fig. 6. Sm–Nd isotopic compositions of basement rocks and cover sequences from Rødøy, Bolvær and Leka. Initial ε_{Nd} are calculated for 480 Ma. Data from this study and Furnes *et al.* (1992).

also have isotopically juvenile characteristics ($\varepsilon_{Nd} = +7.3$ and $+7.4$) that are similar to the basement rocks and indicate a depleted mantle, presumably oceanic source. We infer that the mafic metaconglomerates were derived locally from the mafic basement.

Coarse polymict metaconglomerates crop out on each island. The Bolvær polymict metaconglomerates occur high in the stratigraphic section and are interlayered with chlorite and sericite schists. Most of the cobbles are metasedimentary, and are exotic with respect to an oceanic environment. At Rødøy and Leka the polymict metaconglomerates were deposited directly upon gabbroic basement rocks. Similarities in petrologic, geochemical and isotopic characteristics suggest that a portion of the cobble populations in the polymict metaconglomerates on Rødøy and Leka may have been derived from the mafic basement rocks. The REE patterns of gabbro, anorthositic gabbro and anorthosite cobbles from Rødøy strongly resemble those of the mafic basement rocks (Fig. 4). About half of the mafic cobbles have radiogenic ε_{Nd} values that are indistinguishable from the basement rocks and consistent with derivation from an oceanic source (Fig. 6). Few to no ultramafic cobbles were observed, either because the ultramafic portion of the basement was not exposed and therefore unavailable to supply detritus, or because the ultramafic cobbles did not survive weathering and transport.

In contrast to the isotopically juvenile cobbles, most Rødøy cobbles and two Leka cobbles have intermediate initial ε_{Nd} values (-1.1 to $+4.1$) unlike those of the basement rocks. One possible explanation is that these cobbles have a source different than the local basement, such as an arc with less extreme depleted mantle isotopic compositions. Alternatively, and more likely, the Nd isotopic compositions were affected by alteration in the presence of CO_2-bearing fluids. The Rødøy cobbles are generally more altered (i.e. greater chlorite and calcite content and more seriticized feldspar) than the isotopically juvenile Bolvær and Leka cobbles. These observations suggest that cobbles interacted with CO_2-rich fluids, which differentially mobilized Sm and Nd and caused a decrease in initial ε_{Nd} and $^{147}Sm/^{144}Nd$ values (cf. Frost & Frost 1995).

Cobble sources were not restricted to depleted mantle/oceanic sources, but also included detritus derived from isotopically evolved sources. Polymict metaconglomerates on Bolvær and Leka contain cobbles derived from continental crust, as evidenced by unradiogenic initial ε_{Nd} and $^{147}Sm/^{144}Nd$ values characteristic of upper continental crust. The clasts are up to 70 cm in length and suggest a proximal source area. The absence of isotopically

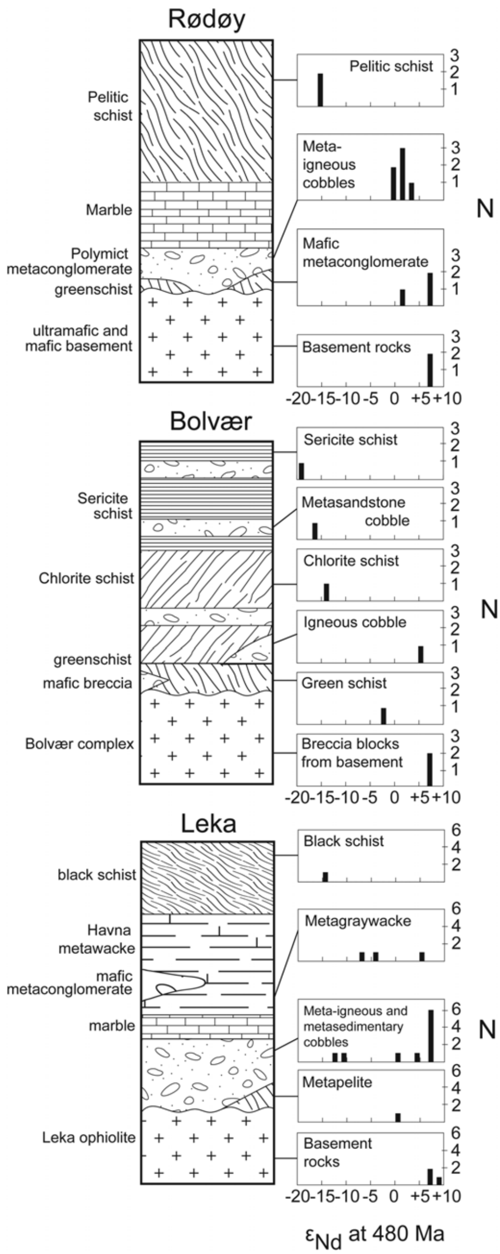

Fig. 7. Schematic stratigraphy and histograms of initial ε_{Nd} (at 480 Ma) for Rødøy, Bolvær and Leka, showing general trend of decreasing initial ε_{Nd} up-section, interpreted to reflect increasing continental input with time.

evolved cobbles in the Rødøy dataset may either reflect the relatively small volume of the preserved metaconglomerate outcrop so that few or none of these metasedimentary cobbles were exposed, or suggest that Rødøy was located further from the source of the metasedimentary clasts and only locally derived mafic cobbles were deposited.

Fine-grained metasedimentary rocks. The isotopic data from the supracrustal metasedimentary rocks at all three islands indicate a shift in sediment provenance from mixed oceanic and continental to predominantly continental with time (Fig. 7). Metasedimentary rocks from the lowest portion of the stratigraphy have isotopically intermediate compositions, suggesting that they are composed of a mixture of oceanic and continental sources (Fig. 7).

The Havna metagreywacke unit on Leka is interpreted to be a shallow-marine turbidite deposit and is located up-section from the polymict metaconglomerate and thin marble layer. The $^{147}Sm/^{144}Nd$ ratios of all Havna metagreywacke samples are higher than values typical of continental crust. The initial ε_{Nd} value of the composite turbidite sample is -3.2, but the discrepancy in initial ε_{Nd} values between the fine- (-5.7) and coarse-grained horizons ($+5.5$) of the Havna metagreywacke is attributed to incomplete mixing or unsorting of sediment from different sources during turbidity current deposition. Contrasting Nd isotope compositions have been observed in sand-mud pairs from modern deep-sea turbidites (McLennan *et al.* 1989). The juvenile material in the coarse-grained fraction may have been shed from proximal oceanic arcs, whereas the continental signature of the fine-grained fraction could be derived from a distant cratonic source.

Continental input is most pronounced in the stratigraphically highest fine-grained metasedimentary units. The source of the fine-grained pelitic and black schists is distinct from the source of the stratigraphically lower units. These rocks are muscovite-rich and have the greatest K_2O content of any sampled unit. The stratigraphically high metasedimentary rocks have unradiogenic Nd isotopic characteristics consistent with crustal sources ($\varepsilon_{Nd} = -18.7$ to -13.5; $^{147}Sm/^{144}Nd = 0.1025-0.1155$).

The change in provenance and/or grain size could be attributed to several possible factors. (1) Sediment provenance may reflect changes in the type of sources that were exposed and susceptible to weathering at the time of deposition. For example, the ophiolite surface may have been covered with sediment when the uppermost fine-grained sediments were deposited. (2) The sedimentary record may reflect the increasing proximity of the ophiolite-floored basins to a continental landmass. This could account for the increasing influx of continental material, but does not require a decrease in grain size. (3) Tectonism and erosion along an active continental margin coupled with syn-sedimentary faulting of the ophiolitic basement can explain the very coarse nature of the polymict metaconglomerates at the base and middle of the stratigraphic section. The fine-grained pelitic and black schists at the top of the sections may have originated from more distal continental sources and have been deposited after tectonic activity had diminished.

In summary, this study documents similarities in petrological, geochemical, isotopic and age characteristics among the packages at each island group. The ultramafic-mafic basement rocks likely formed in a supra-subduction zone setting. Mafic metaconglomerates containing locally derived ophiolitic material are preserved at each island and are considered to have a local ophiolitic provenance. Polymict metaconglomerates at each island contain cobbles that were likely derived from the mafic basement rocks in addition to isotopically evolved metasandstone cobbles. Two metasandstone cobbles from Bolvær and Leka contain nearly identical detrital zircon age populations and provide strong evidence that Bolvær and Leka received detritus from the same continental source region. Finally, the stratigraphic record from all three of the island groups preserves a change in sediment provenance from oceanic to continental source with time.

Sediment provenance

U–Pb zircon age data presented by Barnes *et al.* (2007) and McArthur (2007) help to constrain sediment provenance. The concordant zircon populations from Leka and Bolvær metasandstone cobbles are Precambrian in age with peaks at approximately 2750, 1850, 1450 and 1100 Ma. The basal metasandstone from Bolvær contains only Precambrian age zircon grains with peaks at 2750 and 1925 Ma, sparse Early Archaean grains (3200 and 3100 Ma) and two Mesoproterozoic grains (1450 and 1050 Ma). These zircon age distributions are similar to those identified by Barnes *et al.* (2007) in samples of migmatitic metasandstone in the Lower Nappe, suggesting that possible sources of the cobbles were proximal Proterozoic sandstone units similar to those in the Lower Nappe of the HNC.

In contrast, the turbiditic greywacke from Leka described by McArthur (2007) contains only Cambrian and Early Ordovician age zircons, the youngest of which indicate deposition during Early Ordovician time. Similar ages of deposition were inferred from the youngest zircons dated in metasedimentary units from the S–T and Upper nappes by Barnes *et al.* (2007).

Baltica and Laurentia are potential sources for the Precambrian age detrital zircon grains. Two Laurentian source regions are evaluated. An east Greenland source is considered because many palaeogeographic reconstructions place west-central Norway adjacent to the east Greenland Caledonides prior to opening of the Atlantic Ocean (e.g. Torsvik & Cocks 2004). Archaean age orthogneisses of the North Atlantic craton (mostly 2800–2700 Ma) form a portion of the east Greenland basement; however, older Archaean rocks (i.e. 3200 Ma) are scarce (e.g. Thrane 2002). Large volumes of calc-alkaline granitoid magmas were generated in the Palaeoproterozoic along the east Greenland margin and have ages comparable to those from the Helgeland Nappe Complex (Thrane 2002; Kalsbeek *et al.* 2008; Rehnstrøm 2010; Augland *et al.* 2012). An east Greenland source cannot account for the robust Early and Late Mesoproterozoic age populations, however. Moreover, in contrast to what is observed in the HNC, records of Ordovician age magmatism or westward emplacement of outboard terranes and ophiolites are not preserved in east Greenland (e.g. Kalsbeek *et al.* 2001).

The analysed Precambrian age zircon populations are most compatible with a SE Greenland/Labrador source region (Fig. 8). Archaean sources, including 3200 Ma rocks, are located in the Superior and North Atlantic cratons (e.g. James *et al.* 2002). In Palaeoproterozoic time, a mosaic of Archaean cratons were sutured by orogenic belts to form Laurentia (e.g. Hoffman 1988). In SE Greenland and Labrador these suturing events are represented by the Torngat, Ketilidian and Nagssugtoqidian orogenic belts (e.g. van Gool *et al.* 2002) and the associated igneous and metamorphic activity that peaked at *c.* 1800 Ma (e.g. Hoffman 1989). Convergent margin magmatism in the early Mesoproterozoic is recorded in the Labradorian, Pinwarian and Elsonian Orogens in NE Labrador (e.g. Gower 1996; Wasteneys *et al.* 1997; Gower & Krogh 2002). The Grenville continent–continent collisional orogen provides the most likely source for the late Mesoproterozoic material (e.g. Rivers 1997). The zircon age spectra from the metasandstone cobbles and Bolvær metasandstone strongly resemble those from siliciclastic units of the Dalradian Supergroup of Scotland, specifically the Argyll and Southern Highland groups, which have been assigned an east Laurentian provenance (Cawood *et al.* 2003) (Fig. 8).

Additional evidence corroborates a proximal SE Greenland/Labrador location for the HNC in Early Ordovician time when the analysed sediments were deposited. The meta-igneous basement rocks on Rødøy, Bolvær and Leka share common supra-subduction zone characteristics with many ophiolites preserved in Newfoundland, such as the Bay of Islands ophiolite (484 Ma) and ophiolites of the Dunnage Zone (505–489 Ma) which formed

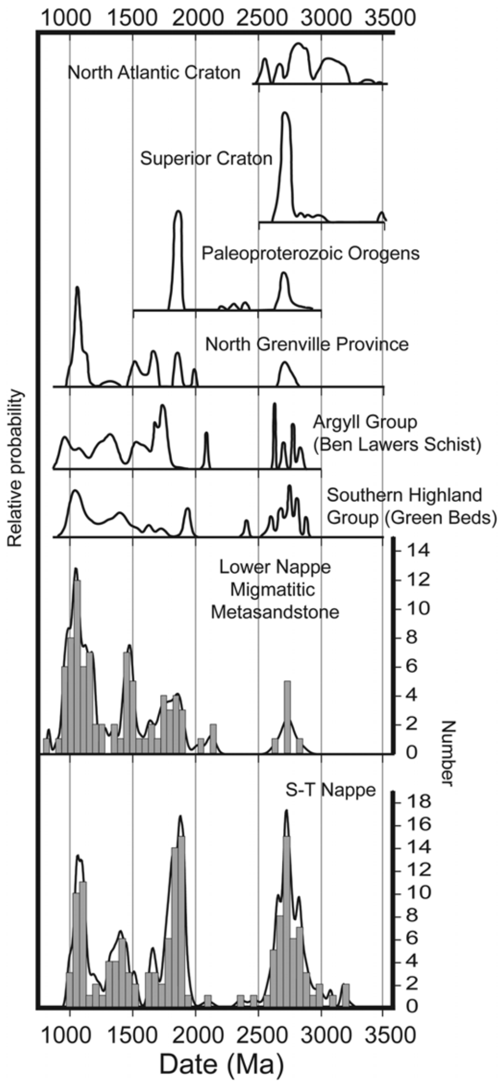

Fig. 8. Comparison of pooled concordant detrital zircon ages from S–T nappe samples from Barnes *et al.* (2007) and McArthur (2007) compared to zircon age distributions of potential source regions in southeastern Greenland/Newfoundland (Cawood & Nemchin 2001). The S–T Nappe age populations are also compared to age populations from the Argyll Group and Southern Highlands Group of the Dalradian Supergroup of Scotland (Cawood *et al.* 2003) and from the Lower Nappe of the HNC (Barnes *et al.* 2007).

during a similar time frame as the Leka ophiolite (497 Ma) (Dunning & Pedersen 1988; Jenner *et al.* 1991; van Staal *et al.* 1998, 2004). Since east Greenland does not preserve any ophiolitic rocks, the occurrence and character of ultramafic-mafic rocks in the HNC is more consistent with a SE Greenland/Newfoundland provenance than an east Greenland provenance.

Detrital zircon age populations from the Bolvær and Leka metasandstone cobbles and Bolvær metasandstone are comparable to those from Lower Nappe migmatitic gneisses (Fig. 8) and suggest that rocks from the Lower Nappe could have contributed detritus to the S–T Nappe and Leka (Barnes *et al.* 2007). Furthermore, the youngest concordant Precambrian zircon ages in the Bolvær and Leka samples are Neoproterozoic and consistent with a sedimentary protolith such as the Neoproterozoic Lower Nappe (Trønnes & Sundvoll 1995). A short transport distance is implied by the coarse character of the metaconglomerates and would require the Lower Nappe or similar rocks to be located proximal to the S–T Nappe in Early Ordovician time. The SE Greenland/Labrador-like zircon age spectra could indicate that the Lower Nappe was a rifted fragment of SE Greenland or Labrador.

The Havna metagreywacke was derived from a different source than the two metasandstone cobbles. The Havna metagreywacke unit is located up-section from the polymict metaconglomerate and thin marble layer and has been interpreted to be a shallow-marine turbidite deposit (Sturt *et al.* 1985). Isotopic data from a coarse fraction of the turbidite deposit indicate a depleted mantle component ($\varepsilon_{Nd} = +5.5$) and suggest that this sediment may have been derived, at least in part, from a primitive arc.

The dominant zircon age population in the Havna metagreywacke is *c.* 500–480 Ma with sparser 550–510 Ma ages and one 471 ± 8 Ma grain (McArthur 2007). The euhedral shape of most zircon grains suggests a proximal source; however, a viable source for the Late Cambrian–Early Ordovician zircons has not been identified in the HNC. Many supra-subduction zone ophiolites, including the Leka ophiolite, formed between 500 and 470 Ma and crop out in the Upper and Uppermost Allochthons of the Norwegian Caledonides and Newfoundland (e.g. Dunning & Pedersen 1988; Slagstad 2003). An ophiolitic source for the population is however improbable because magmatism of this type is unlikely to have produced large volumes of zircon. Although a volcanic arc might produce more zircon, arc remnants are absent from the HNC geologic record. Plutonic rocks are abundant in the HNC, but no plutons older than 482 Ma are known (Barnes *et al.* 2007). It follows that the source for the Late Cambrian–Early Ordovician age zircons never was or is no longer associated with the HNC. The 500–480 Ma age zircon population may have originated from primitive arcs that formed in association with the

500–470 Ma supra-subduction zone ophiolites that are now preserved in the Upper Allochthon (e.g. Slagstad 2003). Also of note is the lack of Proterozoic age zircons which may indicate that the basin was isolated from sources with Precambrian age elements, including the one that provided metasandstone cobbles to the polymict metaconglomerates that lie stratigraphically below the Havna metagreywacke.

Sources of the latest Neoproterozoic–Early Cambrian age zircons are also cryptic. Rift-related magmatism was active in Newfoundland prior to the 540–535 Ma late rift-to-drift transition associated with rifting of a block or blocks from the Laurentian margin into the Iapetus Ocean (Cawood *et al.* 2007). This magmatism produced the Skinner Cove Formation, an alkali volcanic suite of oceanic affinity, at *c.* 550 Ma and the tonalitic to granodioritic Lady Slipper pluton at *c.* 555 Ma (Cawood *et al.* 2001). Other rift-related magmatism is represented by the *c.* 555–550 Ma Tibbit Hill volcanic rocks in the Quebec Appalachians (Kumarapeli *et al.* 1989). Subduction processes could have consumed other rift-related igneous bodies that may have formed near the Laurentian margin in the Late Cambrian. Although the source of the entire metagreywacke zircon population is enigmatic, a primitive oceanic arc is one possible source.

Implications for the tectonic evolution of S–T Nappe

The convergence of Laurentia and Baltica resulted in the generation of numerous Cambrian–Ordovician age (500–470 Ma) supra-subduction zone ophiolites and arc complexes in the Iapetus Ocean that are preserved as remnants in the Norwegian Caledonides and the Appalachian Orogen (Dunning & Pedersen 1988; Cawood & Suhr 1992; van Staal *et al.* 1998; Zagorevski *et al.* 2006). The best records of Iapetus Ocean magmatism in the HNC are preserved in the S–T Nappe on the islands of Rødøy, Bolvær and Leka.

Rifting of the ophiolitic rocks at Rødøy, Bolvær and Leka to form the basement of depositional basins occurred between *c.* 497 and 480 Ma, the age of the Leka ophiolite and the estimated maximum age of sediment deposition in the S–T nappe (Barnes *et al.* 2007; McArthur 2007). Metasedimentary sequences, including carbonates and clastic sediments from both oceanic and continental sources, were deposited upon deeply eroded ultramafic-mafic basement rocks. The depositional environment of the metaconglomerates is unclear. Although Sturt *et al.* (1985) have proposed a subaerial environment of deposition, we note that the Leka polymict metaconglomerate is overlain by the Skei Group marble and Havna Formation turbidic metagreywacke, both of which require a marine depositional setting. Furthermore, the carbonate fracture fillings cited by previous workers (Sturt *et al.* 1985; Heldal 2001) as evidence for subaerial weathering on Bolvær and Leka may also originate during serpentinization of oceanic crust in submarine environments (Schroeder *et al.* 2002). Moreover, if similar features in younger rocks on islands near Vega (Oalmann 2010) also represent a fossil weathering zone of the same age, then this event affected at least two nappes and has to be younger than 475 Ma.

Isotopic characteristics of metasedimentary rocks document a progression from mixed oceanic and continental to continental provenance through time and provide important constraints on the proximity of the ophiolite basement rocks to oceanic, continental and arc sources. The boulders and cobbles of depleted mantle material in the talus deposits and mafic and polymict metaconglomerates probably have a local, ophiolitic source. Large (>70 cm across) isotopically evolved metasandstone cobbles also crop out in the polymict metaconglomerates. The large size of some depleted mantle and continental cobbles indicates a high-energy environment and short transport distances. These observations require that, in Early Ordovician time: (1) the ophiolitic basement rocks were exposed and available to contribute very coarse detritus to the basin; (2) the ophiolitic basement was characterized by significant topographic relief; (3) the basins were located near a continental landmass; and (4) the proximal landmass may have been a tectonically active continental margin with significant topographic relief (Heldal 2001).

As discussed above, the Havna metagreywacke provides evidence for a third source, an enigmatic primitive arc, which contributed detritus to the S–T Nappe.

The stratigraphically highest units at each island are fine-grained pelitic and black schists that were derived from isotopically evolved continental sources. Potential sources are not preserved in the study areas. Given their fine-grained character, it is probable that they are far-travelled and were derived from a relatively distal source.

Precambrian-age detrital zircon populations from the Bolvær and Leka metasandstone cobbles and the Bolvær quartz diorite are nearly identical to those from the Lower Nappe (Barnes *et al.* 2007). A Lower Nappe source best accounts for the short transport distance required by the large cobbles and suggests that the Lower Nappe may have been a rifted piece of modern SE Greenland/Labrador (cf. Barnes *et al.* 2007).

In terms of palaeogeography, these data imply that in Early Ordovician time the S–T Nappe basin(s) was in a position capable of receiving detritus from exposed mafic basement rocks, a cryptic Cambrian–Early Ordovician age primitive arc(s) and continental crust containing Precambrian age elements, proposed to be SE Greenland/Labrador and/or the Lower Nappe (Fig. 9). The data may be interpreted as a record of the approach of an ophiolite-floored oceanic basin(s) towards a continental margin, presumably Laurentia or a related microcontinent. Alternatively, or in addition to this interpretation, the progression from polymict metaconglomerates to fine-grained metasedimentary rocks may record variable tectonic activity in the continental and/or oceanic source regions. The coarse metaconglomerates could indicate a tectonically active source region(s), whereas the fine-grained metasedimentary units may have been deposited during a period of less tectonic activity or progradation of continental-sourced sedimentation.

These data may also have implications regarding the position of Rødøy, Bolvær and Leka relative to a continental margin (Fig. 9). Bolvær and Leka received significant amounts of coarse- and fine-grained detritus from a continental source(s). The largest metasandstone cobbles were deposited on Leka, possibly indicating that Leka was closer to the continental source than Bolvær. The absence of coarse, continental-derived detritus on Rødøy may indicate that Rødøy was further removed from the continental source.

U–Pb zircon age data from previous studies have implications for the timing of sedimentation and nappe imbrication in the HNC (Yoshinobu *et al.* 2002; Barnes *et al.* 2007). The youngest concordant detrital zircon grain from the Havna metagreywacke, assuming it represents a crystallization age rather than a time of lead loss, places the maximum age of sedimentation in the S–T Nappe at 471 ± 8 Ma. This age estimate of final sedimentation is consistent with an estimate based on the average age (480 ± 8 Ma) of the three youngest detrital zircons (471 ± 12, 482 ± 10, 483 ± 10 Ma) in a pelitic schist from the S–T Nappe (Barnes *et al.* 2007).

Nappe imbrication by 475 Ma is suggested by several dates, including anatexis of the Horta Nappe at *c.* 478 Ma. This event is interpreted to have produced the parental magmas of the 475 ± 4 Ma (Barnes *et al.* 2007) granodioritic Vega pluton, which Barnes *et al.* (2007) tentatively assigned to the adjacent and structurally lower Horta Nappe. The S–T and Horta nappes were presumably juxtaposed by 475 Ma. Second, the *c.* 478 Ma granitic Botnafjellet pluton intrudes the Neoproterozoic-age Lower Nappe and contains Cambrian–Ordovician age zircons presumably inherited from a younger, structurally lower source. Barnes *et al.* (2007) interpret these ages as evidence that the Lower Nappe was juxtaposed with a younger nappe, possibly the Horta Nappe, by 478 Ma. Third, a U–Pb metamorphic titanite age from the Middle Nappe and a K–Ar age from an Upper Nappe amphibole indicate that cooling below amphibolite conditions, presumably following nappe stacking and associated metamorphism, occurred by *c.* 475 Ma (James *et al.* 1993; Barnes *et al.* 2007). Although the overlap in errors precludes determination of an exact sequence of events that occurred in the S–T Nappe, it can be concluded that final sedimentation in the HNC and nappe imbrication occurred in close succession.

Such a rapid sequence of sedimentation and imbrication is not unique: the Klamath Mountains province of western North America provides

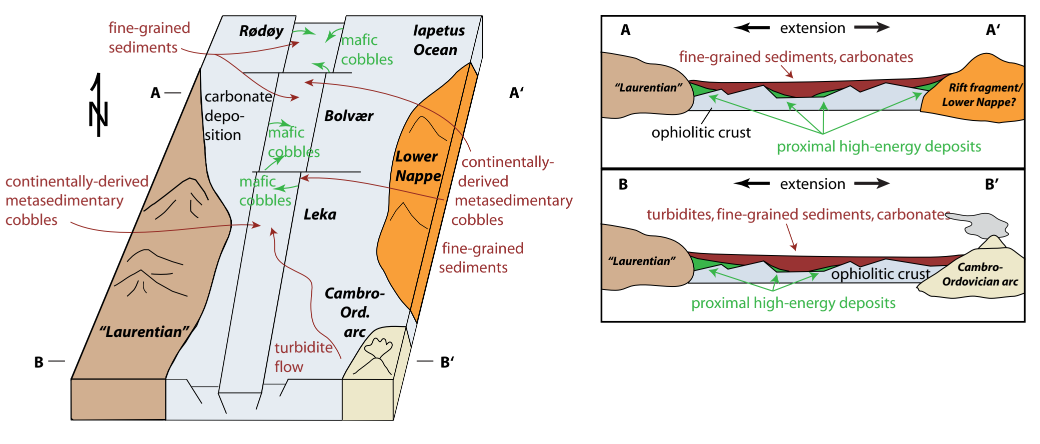

Fig. 9. Block diagram showing possible locations of Rødøy, Bolvær and Leka in Cambro-Ordovician time. Cross-sections A–A′ and B–B′ show the proximal depositional environment of basal conglomerates on extending oceanic crust, followed by more widespread deposition of finer-grained sediments.

another example of a rapid sequence of events where thrusting occurred shortly after sedimentation. The maximum depositional age of the Upper Jurassic Galice turbidite is 153 Ma, constrained by the age of the youngest detrital zircon (Miller *et al.* 2003). During the Nevadan Orogeny, rocks of the Galice Formation were thrust beneath the Rattlesnake Creek terrane along the Orleans fault. Movement along the Orleans fault is very well constrained and occurred between 153 and 151 Ma, immediately following deposition of the Galice Formation (Harper *et al.* 1994). The near coincidence of sedimentation and thrusting in the Late Jurassic history of the Klamath Mountains province is comparable to the estimated timing observed in the HNC. Although the overlap in errors precludes determination of the exact sequence of events that occurred in the S–T Nappe, it is clear that final sedimentation and imbrication of the Helgeland nappes occurred in rapid succession.

Conclusions

The islands of Rødøy, Bolvær and Leka in west-central Norway preserve similar meta-igneous basement rocks and overlying supracrustal successions that are composed of the following.

- Ultramafic and mafic meta-igneous rocks with geochemical characteristics suggesting formation in a supra-subduction zone setting. Nd isotopic values of the mafic rocks are slightly less radiogenic than contemporary MORB and indicate that mafic magmas formed from a depleted mantle source with a minor isotopically evolved component, such as small volumes of sediment assimilated during subduction processes or during magma ascent through oceanic crust.
- Two metaconglomerate types were deposited on the basement rocks: mafic metaconglomerates and polymict metaconglomerates. Massive metasedimentary breccias are composed of mafic boulders and likely represent subaerial or submarine talus deposits (Sturt *et al.* 1985; Heldal 2001). Polymict metaconglomerates contain detritus from isotopically juvenile to intermediate sources and evolved sources, inferred to be dominated by oceanic and continental provenance, respectively. Because of the large size of the clasts ($\leq$70 cm) we infer they were derived from proximal sources, including the mafic basement rocks and an adjacent continental landmass.
- Finer-grained metasedimentary sequences vary up-section from metasandstones to fine-grained schists. The initial ε_{Nd} values of the lower units are intermediate between oceanic and continental values, suggesting that they are composed of a mixture of sources. The proportion of continental detritus supplied to the basins increased with time. The stratigraphically highest fine-grained pelitic schists and black schist were derived almost exclusively from continental sources.

This study proposes that the Rødøy, Bolvær and Leka ultramafic-mafic rocks are correlative units that may represent segmented pieces of a once-continuous section of peri-Laurentian oceanic island-arc/back-arc system (e.g. Pedersen *et al.* 1988; Slagstad 2003) that formed in the Late Cambrian Iapetus Ocean. We assign Leka to the S–T Nappe together with Rødøy and Bolvær based on these similarities.

Two distinct source regions, an old cratonic source and an Ordovician source, are identified from detrital zircon age assemblages. An old cratonic source supplied cobbles and other detritus to Bolvær and Leka. The Precambrian-age zircon populations are consistent with a modern SE Greenland/Labrador provenance. It is notable that the zircon age spectra from these samples, as well as from other samples from the S–T Nappe, are nearly identical to age spectra from the Lower Nappe. We suggest that the sandy sediment and large metasedimentary cobbles deposited on the S–T Nappe and Leka may have originated from the Lower Nappe, which was possibly a rifted fragment of modern SE Greenland/Labrador (cf. Barnes *et al.* 2007).

The Havna metagreywacke from Leka contains latest Neoproterozoic–Early Ordovician-age detrital zircons derived from an enigmatic source not preserved in the HNC. The source of the sparse latest Neoproterozoic–Middle Cambrian-age grains is cryptic, but is possibly related to magmatism associated with the rift-to-drift transition along the Laurentian margin during 540–535 Ma (e.g. Cawood *et al.* 2001).

The depositional environment of the Havna turbidites was likely located in a shallow-marine setting at this time, as evidenced by the underlying marble and the turbiditic character of the metagreywacke. Furthermore, an Early Ordovician marine setting is consistent with a contribution of isotopically juvenile sediment and Cambrian–Ordovician-age zircons from an oceanic arc. The stratigraphically highest units in the study areas are fine-grained schists that were derived from a continental source and presumably accumulated in a position removed from oceanic influences.

Sedimentation in the HNC ended by *c.* 480 $\pm$ 8 Ma and was immediately followed by juxtaposition and high-grade metamorphism of the Upper and Lower nappes at *c.* 478 Ma (Barnes *et al.* 2007).

This research was supported by National Science Foundation grant EAR-0439750 to C. Frost at the University of Wyoming and C. Barnes and A. Yoshinobu at Texas Tech. We thank the Norwegian Geological Survey for logistical support and A. Yoshinobu for assistance with several illustrations. The authors thank T. Andersen and L. Eivind Augland for thoughtful suggestions regarding the manuscript.

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