

Granitic magmatism of Grenvillian and late Neoproterozoic age in Finnmark, Arctic Norway—Constraining pre-Scandian deformation in the Kalak Nappe Complex

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Abstract

The Caledonian Orogen in Arctic Norway is characterized by a variety of nappes thrust from west to east onto the Baltic Shield. Traditionally, this has been regarded as the product of two orogenic events: an earlier Finnmarkian (540–490 Ma) and a later Scandian event (400–425 Ma). However, ion microprobe U–Pb zircon dating of discordant plutonic rocks within the lowermost nappes demonstrates that some of the deformation must have taken place in a Grenville (Sveconorwegian) event. This view is supported by the 981 ± 7 Ma, 978 ± 9 Ma and 973 ± 4 Ma ages of the Repvåg, Hårvika and Siedgoaivi adamellite bodies. These bodies cut the Sørøy Succession, apparently after an earlier deformation event. On these grounds a Grenville (Sveconorwegian) event is responsible for the D2 deformation within the Olderfjord and Kolvik nappes. Within the overlying Havvatnet Imbricate Stack, early deformation took place in the Neoproterozoic, “Porsanger Orogeny”. Evidence for this event is provided by the Litlefjord and Revsneshamn adamellite bodies dated at 841 ± 6 Ma and 839 ± 10 Ma and pegmatitic intrusions, dated at 826 ± 6 Ma and 833 ± 9 Ma, which show clear discordant structural relationships cutting F_2 fold structures that affect the Klubben Psammite, the oldest unit of the Sørøy Succession. Within the uppermost nappe (Sørøy-Seiland nappe) syn-deformational migmatitic leucosomes in the Eidvågeid Paragneiss yield crystallization ages of 709 ± 4 Ma. This age is indistinguishable from zircon overgrowths within the underlying Havvatnet Imbricate Stack. Hence, juxtaposition of these nappes predates Scandian tectonism and occurred during the Snøfjord event at c. 710 Ma. The component nappes of the KNC show decreasing ages of anatexis on moving up the nappe pile. Such temporal and spatial patterns are consistent with episodic terrane amalgamation from Grenvillian times. The KNC provides evidence for punctuated crustal anatexis and episodic orogenic deformation of c. 980 Ma (Grenvillian-Sveconorwegian), c. 840 Ma (Porsanger) and c. 710 Ma (Snøfjord) age, overprinted by intense Scandian deformation. These data support the notion of a Grenville segment extending between Greenland and Baltica and require a radical revision to the tectonometamorphic evolution of the KNC. The KNC represents a collage of exotic, diachronously accreted, terranes overthrust by Llandovery flysch of Laurentian affinity. © 2005 Elsevier B.V. All rights reserved.

Keywords: Kalak Nappe Complex; Porsanger; Sørøy Succession; Caledonides; Scandian; Finnmarkian; Grenvillian; Sveconorwegian; Snøfjord

1. Introduction

The tectonic development of orogenic systems can be considered in terms of two end member scenarios—collisional and accretionary. For example, the closure of the Tethyan ocean with formation of the Alpine-

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Himalayan mountain belt is a classic example of continent–continent collision. In contrast, the Pacific Ocean, which has never completely closed since its formation, is bounded by accretionary orogens formed through ongoing cycles of plate convergence. Distinguishing between these end members or determining their relative importance in ancient orogenic belts, depends on robust temporal constraints on deformation structures in each segment of the orogen.

The Kalak Nappe Complex (KNC), a major allochthon within the Caledonian orogenic belt in Arctic Norway, has been classically regarded as a product

of the continent–continent collision between Baltica and Laurentia. Early studies from this region played a major role in defining the events that underpin our understanding of the evolution of the Scandinavian Caledonides (Sturt et al., 1978; Gee, 1975). However, the discovery of an earlier Neoproterozoic deformation phase (Porsanger Orogeny) within the KNC questioned the standard model for the evolution of Baltica (Daly et al., 1991). In particular, the existence of the Porsanger Orogeny undermined the assumption that the metasediments of the KNC belonged to a continental margin sequence—the Sørøy Succession—deposited on Baltica during the opening

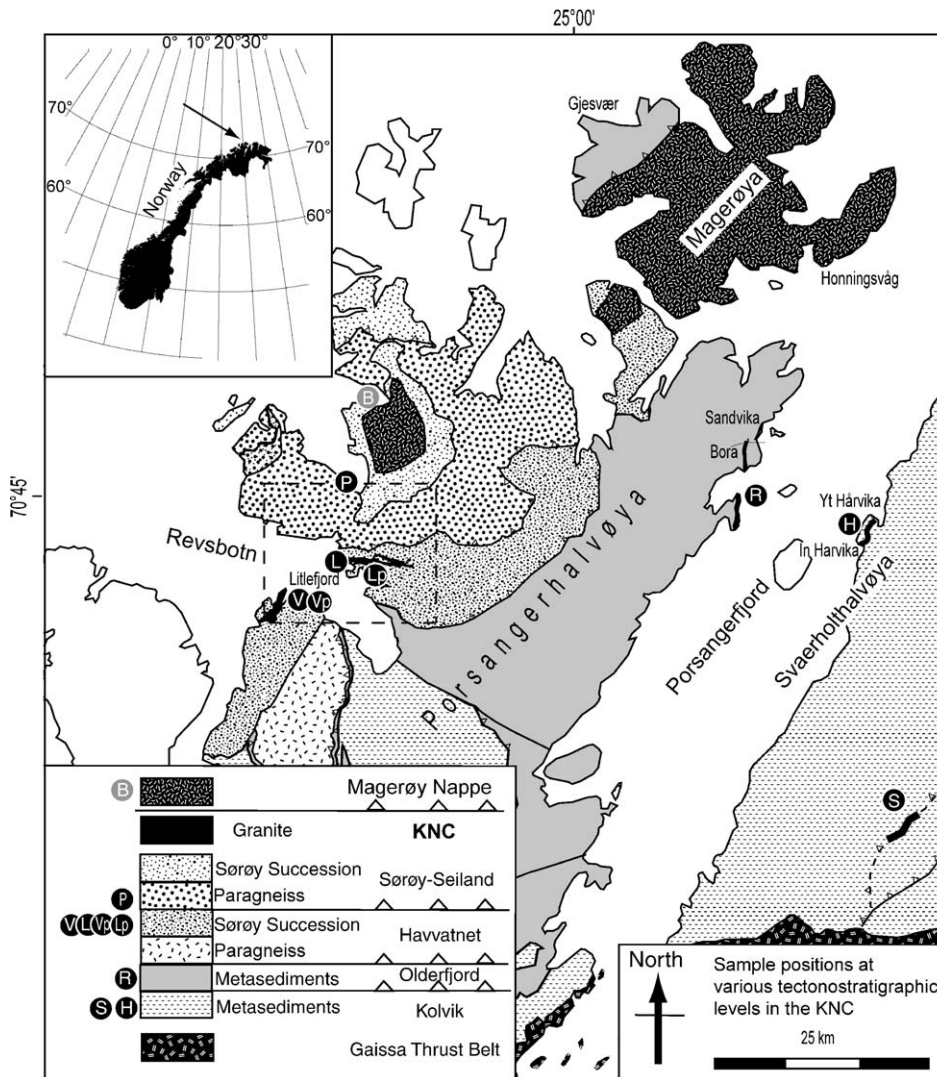


Fig. 1. Sketch geological map of western Finnmark (modified after Gayer et al., 1987). Insets show the location of the Kalak Nappe Complex in northern Scandinavia and a simplified tectonostratigraphy for the Kalak Nappe Complex, indicating the position of the dated samples. P, Snøfjord leucosome; L, Litlefjord Granite; LP, Litlefjord Pegmatite; R, Repvåg Granite; H, Hårvika Granite; V, Revsneshamn Granite; VP, Revsneshamn Pegmatite; S, Siedgoaivi Granite; B, Bakfjord Granite 438 ± 2 Ma (Kirkland et al., 2005a). Area of structural map (Fig. 2) of Litlefjord region is denoted by dashed line.

of the Iapetus Ocean. Moreover, the Porsanger Orogeny was thought to have affected the entire KNC based on assumptions that both the stratigraphy and deformation history could be correlated regionally (Daly et al., 1991).

The aim of this paper is to re-evaluate the age, geographic extent and structural significance of early deformation events affecting the KNC, including the putative Porsanger Orogeny. The paper reports the results of detailed structural mapping and U–Pb zircon geochronology of granites, pegmatites and migmatitic leucosomes from four of the major nappes that make up the KNC (Fig. 1). The results demand a radical reappraisal of the tectonic history of the KNC and demonstrate that the early history of the KNC is driven by accretionary tectonics. They also serve to improve our understanding of the palaeogeography of the North Atlantic region during the Neoproterozoic.

2. Geological background

2.1. Regional setting

The Caledonian belt in Scandinavia is divided into Autochthon, Parautochthon, Lower, Middle, Upper and Uppermost Allochthons (Roberts and Gee, 1985). This tectonostratigraphy contains metamorphic rocks of both lower Palaeozoic and Precambrian age with metamorphic grade generally increasing to the west. The Lower and Middle Allochthons comprise shelf and continental rise successions envisaged as indigenous to the Baltoscandian margin (Roberts and Gee, 1985; Paulsson and Andréasson, 2002). However, the Upper and Uppermost Allochthons are composed of more exotic units, some of which are inferred to have a Laurentian affinity (e.g., Kirkland et al., 2005a).

Within the Finnmark Caledonides, four first order nappe complexes are recognised (Roberts, 1985). The structurally lowest and easternmost is the Gaissa Nappe Complex, consisting of low-grade, Neoproterozoic to early Ordovician metasedimentary rocks and is thought to represent the Lower Allochthon (Sundvoll and Roberts, 2003). The Laksefjord Nappe Complex overlies the Gaissa Nappe Complex to the west. It is composed of greenschist- to amphibolite-facies metasedimentary rocks of inferred late Neoproterozoic to early Cambrian age (Roberts, 1985), and reflects the lowermost unit of the Middle Allochthon. The Kalak Nappe Complex (KNC) dominates much of the area of Finnmark and is classically considered as part of the Middle Allochthon (Gee et al., 1985; Roberts, 1985). However, the KNC has also been correlated with the lower part of the Upper Allochthon (Seve nappes) by Zachrisson (1986). The

rocks of both the Middle and Upper allochthon were considered to represent the outer margin of Baltica (e.g., Roberts, 2003a).

The KNC is made up largely of unfossiliferous siliciclastic metasediments, originally known as the Sørøy Succession (Ramsay, 1971). These rocks were thought to be a conformable stratigraphic sequence of shallow marine sands to more pelitic deposits to limestones and ultimately deeper marine pelagic and turbiditic deposits reflecting deep basinal conditions (Ramsay, 1971; Roberts, 1968a; Speedyman, 1972, 1983; Sturt et al., 1978). This sequence was believed to have been deposited on the Baltica continental margin of the Iapetus Ocean (Sturt et al., 1978).

Units such as the Falkenes Limestone/Åfjord Pelite and the Hellefjord Schist, previously considered and defined as belonging to the upper part of the Sørøy Succession (Ramsay, 1971) are now excluded from it (Kirkland et al., 2005a; Slagstad et al., 2006) on geochronological, geochemical and structural grounds. The Hellefjord Schist, previously regarded as the youngest component of the Sørøy Succession (Roberts, 1968a, 1985), has been shown to be an early Silurian deposit, affected only by Scandian deformation. It has thus been reassigned to the Magerøy nappe of the Upper or Uppermost Allochthon (Fig. 1; Kirkland et al., 2005a).

The term “Sørøy Succession” now refers only to the original lower units, i.e., the Klubben Psammite and the overlying Storelv Schist. The Klubben Psammite is composed dominantly of psammite and minor interbedded pelitic schist (Roberts, 1968b, 1973; Ramsay, 1971; Binns, 1989) and is widely migmatized (Roberts, 1973; Siedlecka and Roberts, 1996). Contacts between the Klubben Psammite and the dominantly pelitic Storelv Schist are transitional (Ramsay, 1971; Kirkland et al., 2005a).

The uppermost nappe of the KNC is intruded by voluminous mafic, ultramafic and alkaline intrusions of the Seiland Igneous Province (SIP, Robins and Gardner, 1975) which are related to late Neoproterozoic rifting (Andréasson, 1987; Roberts et al., 2006).

2.2. Nappe units

The KNC comprises a number of thrust-sheets and imbricate stacks traditionally assumed to have been formed by repetition of the Sørøy Succession and underlying basement gneisses. West of Porsangerfjord numerous thrusts have been mapped which imbricate a dominantly clastic succession, i.e., composed of Klubben Psammite and Storelv Schist with an overlying nappe consisting of Hellefjord Schist (Gayer et al.,

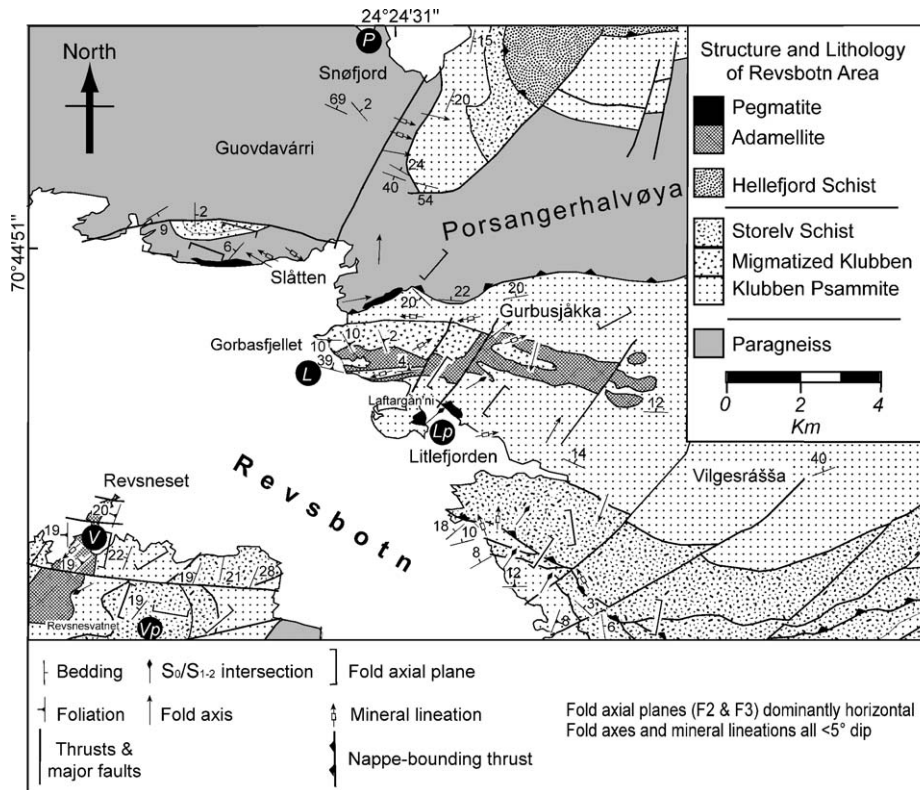


Fig. 2. Geological map of the Litlefjord area, Finnmark, with structural observations. Note bi-variance in fabric orientation (lineation, fold axis, S_0/S_1 intersection) either NE–SW parallel to thrust nappe orientation (orthogonal to thrusting) or E–W parallel to thrust vector. This trend is also reflected in granite orientation, parallel to thrust contacts or rotated into E–W orientation. Sample position labels as in Fig. 1 (modified after Gayer et al., 1985 and field mapping 2002, 2003).

1985; Ramsay et al., 1985a,b; Kirkland et al., 2005a; Figs. 1 and 2). East of Porsangerfjord few thrusts have been mapped within a succession dominated by interbedded shallow marine/fluviol sandstones and pelites (Rice et al., 1989; Fig. 1). Regional correlation of individual nappes forming the KNC has resulted in only partial agreement (see Rice, 1984 for compilation). For the purposes of this paper six allochthonous units have been outlined following those used by Daly et al. (1991) and Kirkland et al. (2005a). These nappe units are first order headings compatible with upper, middle, lower and lowermost groupings of Gayer et al. (1987). From the most easterly and lowest in the tectonostratigraphy, the defined nappes are the Kolvik nappe, Olderfjord nappe, Havvatnet Imbricate Stack and Sørøy-Seiland nappe (Fig. 1). However, it should be remembered that additional thrust contacts exists between many of these higher order nappe divisions and their tectonic significance is unresolved.

The lower part of the lithostratigraphy originally defined on Sørøy (Ramsay, 1971), i.e., comprising the Klubben Psammite and Storelv Schist has been recognised on Porsangerhalvøya (Sturt et al., 1978) and

eastwards into Svaerholthavøya as far east as Nordkinnhalvøya (Siedlecka et al., 1996). However, this system of lithological correlation as discussed by Townsend et al. (1989) implies greater similarity both in terms of petrography and stratigraphic thickness than is actually observed.

2.3. Existing constraints on deformation

Tectonometamorphic events affecting the KNC were originally ascribed to the (c. 540–490 Ma) Finnmarkian Orogeny (Sturt et al., 1978), thought to involve large-scale nappe transport onto the margin of Baltica and closely associated with the concept that magmatism in the Seiland Igneous Province (SIP) was syn-orogenic (Sturt et al., 1975, 1978). However, the Finnmarkian has also been regarded as a subduction-related event that developed offshore Baltica (Ramsay, 1973; Torsvik and Rehnström, 2001) with a 505–500 Ma Sm–Nd age for high-grade metamorphism of eclogite-bearing nappes in northern Sweden (Mørk et al., 1988) and a c. 490 Ma age for subsequent exhumation and retrogression based

on Ar–Ar from hornblende (Dallmeyer and Gee, 1986). Recent U–Pb zircon dating shows that the gabbroic SIP magmatism occurred over a much shorter time interval in the Ediacaran (560–570 Ma) (Roberts et al., 2004, 2006).

An important deformational event of Silurian–Early Devonian age, known as the Scandian Orogeny (Gee, 1975) also affected the KNC (Dallmeyer, 1988a,b; Dallmeyer and Reuter, 1989) and may have been responsible for the majority of deformation and nappe emplacement (Andersen et al., 1982; Dallmeyer, 1988a; Krill and Zwaan, 1987, 1988). However, while the Finnmarkian and Scandian have been regarded as separate orogenic episodes (Zwann and Roberts, 1978; Roberts, 1985), recent Ar–Ar dating of whole-rock grain size fractions has been used to suggest diachronous orogenic activity spanning the period from Finnmarkian to Scandian (Rice and Frank, 2003).

Ar–Ar mineral ages on muscovite, amphibole and nepheline indicate that Scandian thermal effects were widespread (Dallmeyer, 1988a) throughout the KNC. The effect of the Scandian event in Finnmark can clearly be seen within the overlying Magerøy nappe where Llandovery fossils provide a maximum age for the deformation (Føyen, 1967). Scandian metamorphism is also recorded by metamorphic zircon growth at 428 ± 5 Ma (Kirkland et al., 2005a) and by Rb–Sr dating of the Gjesvaer migmatite complex at 410 ± 28 Ma (Andersen et al., 1982). Pervasive deformation structures throughout the entire nappe complex represent the effects of broadly ESE- to E-directed compression associated with the Scandian Orogeny (Gayer et al., 1987; Kirkland et al., 2005a,b).

An earlier tectonometamorphic history was revealed by the Litlefjord Granite, which cuts F₂ folds in the Havvatnet Imbricate Stack (Fig. 2). This granite has been dated imprecisely by a U–Pb zircon discordia intercept of 804 ± 19 Ma (Daly et al., 1991). The D2 deformation was ascribed to the Porsanger Orogeny, which was constrained between 0.8 and 1.2 Ga (Daly et al., 1991), the older constraint based on the youngest Sm–Nd model ages from the Hellefjord Schist and presumed “basement” paragneisses (Aitchison, 1990). The older limit on the age of the Porsanger Orogeny is poorly known because the Hellefjord Schist, which had provided most of the young Sm–Nd ages (c. 1.2 Ga) is now known to be a separate entity of early Silurian age (Kirkland et al., 2005a). On the basis that the Sørøy Succession occurred throughout the KNC, Daly et al. (1991) suggested that the Porsanger Orogeny affected the entire nappe complex and suggested possible correlations with the Grenville or Knoydartian orogenies.

The possible correlation between the Porsanger and Grenville orogenies is relevant to the debate on the extent and timing of Grenville events especially its continuation from SW Scandinavia northwards between Greenland and Scandinavia (Karlstrom et al., 2001) to Svalbard (Gee et al., 1995). In SW Scandinavia, a correlative event resulted in major reworking of the Baltic Shield during the Sveconorwegian Orogeny (1.2–0.9 Ga; Andersson et al., 1996, 1999 and references therein). However, Sveconorwegian effects have hitherto been recognised only as far north as Molde in the Western Gneiss Region (Tucker et al., 1990). Regional correlation of Grenville events (Karlstrom et al., 2001; Meert and Torsvik, 2003) is important because they led to the formation of the Rodinia supercontinent (Dewey and Burke, 1973; McMenamin and McMenamin, 1990).

Daly et al. (1991) also discussed a possible correlation between the Porsanger Orogeny and pre-Caledonian deformation of the Moine Supergroup in Scotland, an event now termed the Knoydartian Orogeny (Vance et al., 1998; Rogers et al., 1998; Tanner and Evans, 2003). This event is important as it has a bearing not only on the North-Atlantic region but on the development and break-up of Rodinia (Cawood et al., 2004). Recent research suggests that there may be three contractional “orogenic” events affecting the Moine Supergroup at c. 820, 740 and 670 Ma (Storey et al., 2004). Larger scale correlation of these events may help to furnish more actualistic palaeogeographic reconstructions for the Neoproterozoic.

2.4. Metamorphic grade across the KNC

Within the KNC there is a pronounced decrease in metamorphic grade towards the east. Peak metamorphism reached upper amphibole facies in the west but only mid- to low-greenschist facies in the east (Roberts, 1985). The garnet isograd runs through Nordkinnhalvøya, while the sillimanite zone is reached on Porsangerhalvøya. Gayer et al. (1987 and references therein) demonstrated a progressive westward and structurally upward increase in temperature, based on garnet-biotite thermometry, e.g., from c. 500 °C in the east to c. 650 °C in the west on Porsangerhalvøya (Rice, 1987a). However, considerable complexities exist in interpreting the metamorphic map pattern due to the presence of several metamorphic events from the Neoproterozoic to the Silurian. Based on work from the Corrovarre nappe, a correlative of the Sørøy-Seiland nappe, in the uppermost tectonostratigraphic level of the KNC, Zwann and Van Roermund (1990) recognised a three-phase polymetamorphic history. They tentatively associated the first metamorphic mineral growth phase with contact meta-

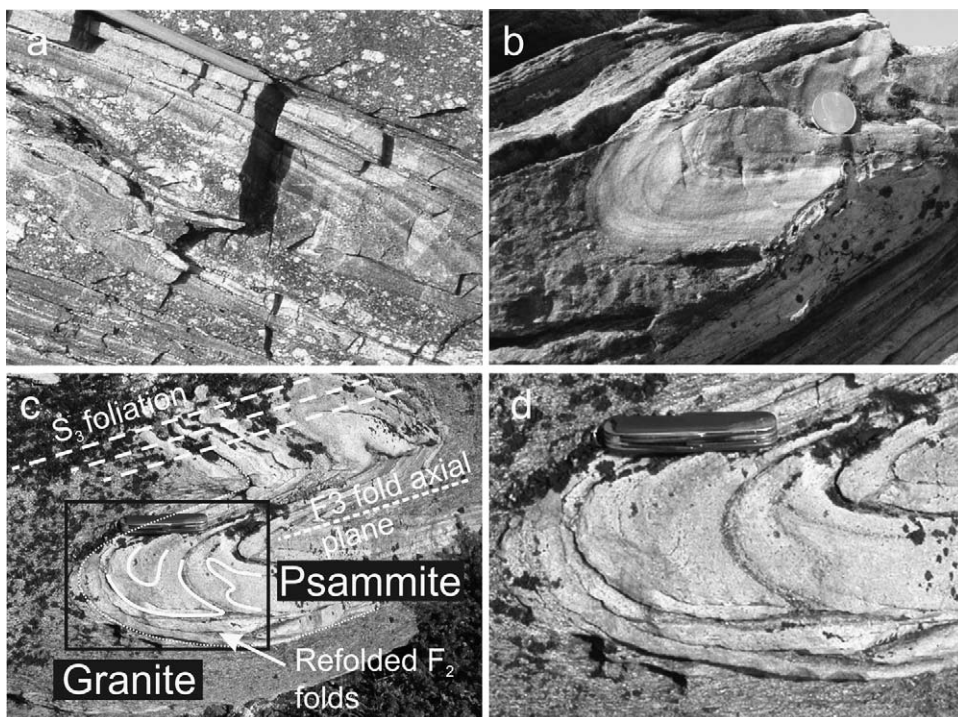


Fig. 3. (a) Outcrops of the Hårvika Granite folded with psammite host rock (note pencil for scale); (b) Repvåg Granite at Bora, showing granite infolded with Psammite in east vergent folds. (c) Photograph of psammite–granite relationships in hanging wall of Repvåg Granite at Sandvika with interpretative overlay identifying D2 structures. The area within the box is enlarged in Fig. 3d. Knife is 9 cm long. (d) Enlargement of refolded F_2 folds in psammite within larger scale F_3 fold deforming both Psammite and Repvåg Granite. Note strong axial planar S_3 foliation.

1969). Such regional correlations can be tested by dating intrusive igneous bodies with clear structural relationships, and, in favourable circumstances, by dating fabric-forming metamorphic minerals.

In many cases, later deformation obscures much of the field evidence by transposing earlier fabrics. In order to characterize the development of early deformational fabrics within the KNC, we have implemented a systematic structural and geochronological assessment of granitic bodies throughout the complex, paying critical attention to the field relationships of the various bodies selected for geochronology.

This paper re-evaluates the age, geographic extent and structural significance of the Porsanger Orogeny and other early deformation events affecting the KNC. The paper reports the results of detailed structural mapping and U–Pb zircon geochronology of granites (including the Litlefjord Granite), pegmatites and migmatitic leucosomes from the Kolvik, Olderfjord, Havvatnet and Sørøy-Seiland nappes (Fig. 1). These intrusive bodies display different relationships to the internal deformation structures of the enclosing metasediments and are used to place temporal constraints on the various deformation phases.

4. Field relationships and sample descriptions

U–Pb zircon data are presented from four granitic bodies, two pegmatites and one migmatitic leucosome (Fig. 1). Two of the granite intrusions, the Repvåg and Litlefjord granites, have been dated previously by Daly et al. (1991). The samples and data are presented below in tectonostratigraphic order (i.e., from east to west and from the bottom upwards) from the Hårvika (ck102c) and Siedgoaivi (ck184) granites from the Kolvik nappe, the Repvåg Granite (7/84-8) from the overlying Olderfjord nappe, the Litlefjord (7/84-7(2), 7/84-6b) and Revsneshamn (ck077) granites and two eponymous pegmatites (ck014b, ck074) from the Havvatnet Imbricate Stack and a migmatitic leucosome (ck003) from the Sørøy-Seiland nappe.

4.1. Kolvik nappe

4.1.1. Hårvika Granite (ck102c)

The Hårvika Granite occurs within the Kolvik nappe (Fig. 1). It outcrops on the eastern side of Porsangerfjord opposite the Repvåg Granite (Daly et al., 1991, see below) and is exposed for a strike length of c. 3 km north-

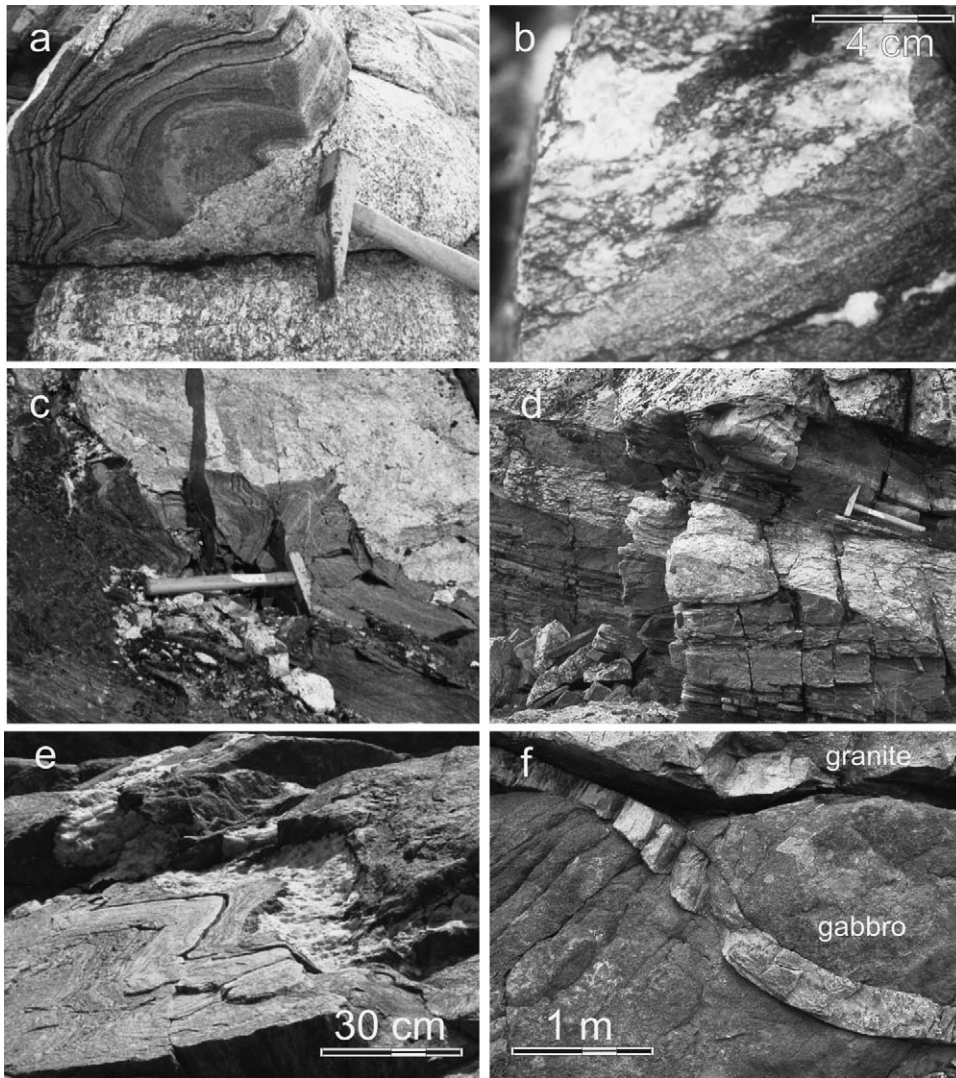


Fig. 4. (a) Outcrop of the Litlefjord Granite at Gorbasfjellet showing the granite cutting an F_2 fold in the Klubben Psammite on its hanging-wall contact. (b) A truncated F_2 fold in Klubben Psammite in the foot-wall contact of the Litlefjord Granite. (c) Litlefjord Pegmatite cutting F_2 folds within xenolith of Klubben Psammite. (d) Litlefjord Pegmatite cutting F_2 fold in Klubben Psammite. (e) Revsneshamn Pegmatite at Revsneshamn near the Revsneshamn Granite in-folded in east vergent F_3 folds. (f) Vein of Litlefjord Granite cutting gabbro body near the foot-wall contact of the uppermost (northern) granite sheet.

wards from indre Hårvika. The Hårvika and Repvåg granites trend N–S parallel to the broad trace of the enclosing nappes (Fig. 1) and may be parts of the same body, though they have been placed in separate nappes by Gayer et al. (1987).

Sample ck102c was collected 600 m east of the coast at Harvikneset. It contains quartz, plagioclase, K-feldspar, biotite, muscovite and accessory zircon and titanite, typical of the Hårvika Granite. It exhibits a strong S_3 foliation defined by biotite which is axial planar to F_3 folds that deform both the granite and the enclosing

psammite (Fig. 3a). The Hårvika Granite cuts psammite units on its eastern margin, which are probably equivalent to the Klubben Psammite. This correlation is based on petrography and Sm–Nd data from Svaerholthavøya (Fig. 1), where the psammites yield an average t_{DM} age of 1.81 Ga, which lies within the range of the Klubben Psammite (1.65–1.82 Ga) (Kirkland and Daly, 2004). On its western margin, the granite cuts garnet mica schist whose lithology and Sm–Nd t_{DM} model age of 1.76 Ga suggests a correlation with the Storelv Schist (Kirkland and Daly, 2004).

4.1.2. Siedgoaivi Granite (ck184)

The Siedgoaivi Granite is an intensely foliated, NE-trending, linear body parallel to an inferred thrust contact (Siedlecka and Roberts, 1996) within the Kolvik nappe (Fig. 1). It contains small K-feldspar augen wrapped by a biotite-defined foliation as well as quartz, plagioclase, muscovite and accessory zircon and titanite. Shear bands consistent with eastward-directed movement transect the granite. The Siedgoaivi Granite cuts pelitic units on all its contacts which have been equated with the Storelv Schist (Olesen et al., 1990 and references therein).

4.2. Olderfjord nappe

4.2.1. Repvåg Granite (7/84-8)

The Repvåg Granite cuts the Klubben Psammite within the lower levels of the Olderfjord nappe, outcropping as a thin sheet close to the shore at Porsangerfjord trending northwards for 11.2 km from Innerneset (Fig. 1). The Repvåg Granite is petrographically similar to the Hårvika Granite. It is a peraluminous (ASI = 1.03), moderately LREE-enriched (La/Sm_n = 3.3) S-type monzogranite (Table 2).

The Repvåg Granite is infolded with the Klubben Psammite in F₃ folds (Fig. 3b) and has generally conformable contacts with the enclosing psammite. However, at one locality it is possible to demonstrate a cross-cutting relationship between the granite and a bedding-parallel biotite foliation in the psammite. The generally conformable character of the Repvåg Granite reflects intense D₃ deformation aligning all earlier structural elements into parallelism with the lithological banding within the migmatitic psammites and semipelites of the Klubben Psammite. The Repvåg Granite has a strong D₃ foliation defined by all component minerals. Locally, F₃ folds affecting the enclosing Klubben Psammite re-fold F₂ folds that fold a biotite foliation (Fig. 3c and d). Thus, the enclosing psammite is affected by three deformation phases whereas the granite has suffered only one (Fig. 3c and d). On this basis, dating the Repvåg Granite provides a minimum age for the deformation in the Olderfjord nappe.

Zircons were separated from sample 7/84-8, one of the samples previously analysed by Daly et al. (1991), who reported a poorly constrained Rb–Sr errorchron age of 851 ± 130 Ma with an initial ⁸⁷Sr/⁸⁶Sr ratio of 0.722 ± 7. Sample 7/84-8 has a low Rb/Sr ratio of 2.63, and was chosen in the hope that it would contain a higher proportion of magmatic zircon, i.e., less inherited material.

4.3. Havvatnet Imbricate Stack

4.3.1. Litlefjord Granite (7/84-7(2) and 7/84-8b)

The Litlefjord Granite intrudes inverted amphibolite-facies metasediments of the Klubben Psammite within the Havvatnet Imbricate Stack (Gayer et al., 1985) on the west coast of Porsangerhalvøya (Fig. 2). Importantly, though generally concordant, the Litlefjord Granite, cuts regionally correlated F₂ folds (Daly et al., 1991) in both its hanging wall and footwall (Fig. 4a and b). A U–Pb zircon age of 804 ± 19 Ma and a Rb–Sr whole-rock isochron age of 813 ± 62 Ma were interpreted to date the intrusion of the Litlefjord Granite. This showed that the D₂ deformation affecting the Klubben Psammite was a pre-Caledonian event, termed the Porsanger Orogeny, which, by correlation, was argued to have affected the entire KNC (Daly et al., 1991).

The granite forms north-dipping sheets, close to the coast, which appear to coalesce eastwards (Figs. 1 and 2). The rocks cut by the Litlefjord Granite in its hanging wall have been variably interpreted as either Klubben Psammite (Daly et al., 1991) or Eidvågeid Paragneiss (Gayer et al., 1985). Mapping (Fig. 2) shows that the granite cuts both Klubben Psammite and its migmatized equivalents. Unequivocal outcrops of Klubben Psammite with heavy mineral bands occur at the contact near Gurbusjåkka, while farther west its migmatized equivalents have outcrops of graded and heavy mineral banded psammite to their north. A sharp contact between the Klubben Psammite and the Eidvågeid Paragneiss lies about 350 m northwest of the granite, manifest as a pronounced topographic ridge. In addition, a small gabbroic body is also intruded by the granite (Fig. 4f).

The Litlefjord Granite is an S-type adamellite, containing quartz, K-feldspar, plagioclase, biotite, muscovite, garnet, zircon and titanite. Plagioclase tends to form euhedral to subhedral lath-shaped crystals, suggesting early crystallization, whereas K-feldspar and quartz, although often of a larger size than the plagioclase, tend to be interstitial and therefore crystallized later. Occasional lenses of tourmaline, up to 1 m long and 35 cm wide, are also present. The granite shows a consistency in mineralogy and texture over much of its outcrop except that phyllosilicates become more abundant towards the margins.

Biotite and muscovite define a strong foliation that is found ubiquitously throughout the granite. F₃ folds, which deform the granite and enclosing psammite, are broadly coaxial to F₂ folds within the country rock. The granite exhibits a strong S₃ foliation parallel to the earlier S₂ foliation in the country rock. The F₂ folds within the Klubben Psammite fold an earlier biotite-defined

Table 2

Geochemical and isotopic data for selected samples of Repvåg Granite, Revsneshamn Granite, Litlefjord Granite and the gabbro body cut by it

Sample Lithology	7/84-12A Repvåg Granite	7/84-13 Repvåg Granite	7/84-8 Repvåg Granite	7/84-4A Litlefjord Granite	7/84-6 Litlefjord Granite	7/84-7(2) Litlefjord Granite	ck075 Revsneshamn Granite	ck077 Revsneshamn Granite	CK002 Gabbro
SiO ₂	73.08	73.55	71.99	74.31	71.91	72.74	73.50	71.53	46.72
TiO ₂	0.48	0.45	0.51	0.32	0.38	0.36	0.32	0.44	0.95
Al ₂ O ₃	13.06	13.00	13.32	12.91	14.17	13.70	13.16	13.90	13.83
Fe ₂ O ₃	3.08	2.87	3.23	2.11	2.29	2.31	2.14	2.86	9.59
MnO	0.03	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.14
MgO	0.54	0.51	0.58	0.41	0.41	0.46	0.36	0.65	15.03
CaO	1.44	1.33	1.50	1.16	1.43	1.34	1.08	1.05	8.60
Na ₂ O	2.92	2.78	2.85	3.28	3.76	3.44	3.46	3.54	1.19
K ₂ O	4.89	5.22	5.00	4.52	4.87	4.97	4.73	5.06	1.99
P ₂ O ₅	0.09	0.08	0.09	0.13	0.15	0.15	0.14	0.24	0.10
LOI	0.34	0.36	0.43	0.37	0.26	0.30	0.82	0.62	2.10
Total	99.94	100.17	99.53	99.54	99.66	99.80	99.73	99.93	100.24
Nb	11	11	11	13	11	11	11	13	2
Zr	241	226	253	186	185	180	174	225	100
Y	53	49	51	31	32	38	42	28	19
Sr	92.9	81.7	99.8	51.2	68.6	67.9	74.4	131.4	194
Rb	272.2	281.4	262	295	291.3	288.6	245.4	217.4	147
U	6	8	8	2	1	4	6	3	b.d.
Th	28	26	29	15	14	18	17	20	4
Pb	21	23	21	19	19	18	22	28	b.d.
Zn	33	30	34	26	28	30	29	39	66
Cu	6	8	9	b.d.	2	1	b.d.	7	65
Ga	17	16	16	18	20	19	19	19	13
Ni	6	6	3	2	4	b.d.	b.d.	b.d.	438
Co	49	50	46	43	45	43	6	6	54
Cr	43	37	60	20	45	42	9	14	1014
V	34	36	38	28	32	31	25	41	159
Sc	4	5	9	7	7	5	6	11	29
Ba	547	526	576	235	315	306	324	464	84
Cs	20	14	11	15	22	19	6	10	10
La	42.81	43.76	44.54	16.89	19.26	27.59	11.98	13.68	5.64
Ce	87.91	88.83	89.77	36.02	40.81	54.48	30.26	30.92	12.19
Pr	10.04	10.34	10.88	4.49	4.76	6.51	3.77	3.86	2.00
Nd	38.40	40.01	39.66	24.62	20.69	27.99	16.34	15.75	9.01
Sm	8.24	8.49	8.17	5.89	4.53	6.50	4.33	3.95	2.65
Eu	0.95	0.95	1.03	0.53	0.71	0.92	0.60	0.73	1.03
Gd	8.24	7.76	7.70	4.15	4.87	6.77	4.65	3.52	3.77
Dy	9.19	8.94	9.17	5.24	5.46	8.69	6.95	4.30	3.75
Er	5.05	4.98	5.03	2.90	3.23	4.99	4.62	2.69	2.14
Yb	4.84	4.62	5.47	2.80	3.39	4.97	5.41	2.89	1.99
Lu	0.74	0.63	0.81	0.42	0.56	0.79	1.01	0.45	0.28
Rb/Sr	2.93	3.44	2.63	5.76	4.25	4.25	3.30	1.65	0.76
⁸⁷ Sr/ ⁸⁶ Sr	0.82739	0.84502	0.81422	0.91033	0.86197	0.86037	–	–	–

$^{87}\text{Rb}/^{86}\text{Sr}$	8.58	10.1	7.68	16.99	12.47	12.48	–	–	–
$^{147}\text{Sm}/^{144}\text{Nd}$	–	0.1284	–	0.1446	–	–	–	–	0.1778
$^{143}\text{Nd}/^{144}\text{Nd}$	–	0.512068 (18)	–	0.512240 (10)	–	–	–	–	0.512809 (20)
t_{DM} (Ma)	–	1731	–	1760	–	–	–	–	999
ϵ_{Ndi}	–	–2.57	–	–2.18	–	–	–	–	5.37 (at 840 Ma)
T Zr Sat °C	822	817	827	801	793	793	794	816	521
U–Pb Crys age	c.980	c.980	c.980	c.840	c.840	c.840	c.840	c.840	–
A/NK	1.29	1.27	1.32	1.25	1.24	1.24	1.22	1.23	3.36
A/CNK	1.03	1.03	1.04	1.04	1.01	1.02	1.03	1.05	0.70
FeOt	2.77	2.58	2.91	1.90	2.06	2.08	1.93	2.58	8.63
Alkali-lime index	6.38	6.67	6.34	6.64	7.20	7.07	7.11	7.54	–5.41
Q'	37.1	37.1	36.1	38.1	30.5	33.2	35.4	32.7	–
ANOR	19.3	17.1	19.7	16.1	18.1	16.8	14.2	11.4	–

Major oxides (weight percent) and trace elements (parts per million) were determined by X-ray fluorescence spectrometry at Leicester University with analytical precision of better than 0.5 and 3%, respectively, following the procedures of Harvey (1989) and Harvey and Atkin (1982) on agate-milled whole-rock powders. b.d. = below detection limit. Trace element values in bold type were determined by isotope dilution TIMS. Rare-earth elements (REE) were analysed by inductively coupled plasma emission spectrometry following Walsh et al. (1981) and Harvey et al. (1996). Sm–Nd and Rb–Sr were determined by isotope dilution mass spectrometry at University College Dublin (Menuge, 1988). Sm–Nd analyses, including those previously reported by Daly et al. (1991), have been normalised to a $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.51185 for the La Jolla standard. Two sigma errors on $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are reported as the last two significant digits. Maximum uncertainty in $^{87}\text{Sr}/^{86}\text{Sr}$ values is 0.01% (2σ). Depleted mantle model ages (t_{DM}) ages were calculated using the DePaolo (1981) model. T Zr Sat is the zircon saturation temperature in degrees centigrade (Watson and Harrison, 1983). Literature sources for plotting parameters are as follows: A/NK and A/CNK (Shand, 1943); modified Alkali lime index (Frost et al., 2001); Q' and ANOR (Strecheisen and Le Maitre, 1979) from the improved Mesonorm for granitoid rocks by Mielke and Winkler (1979).

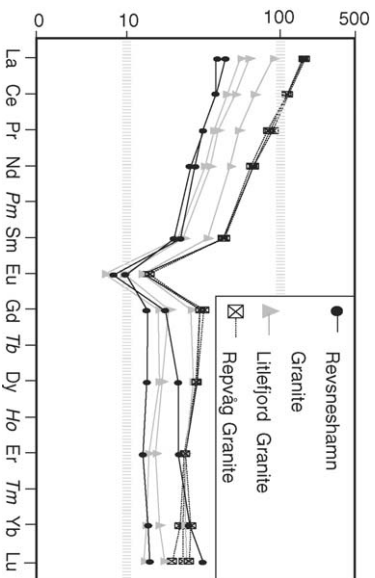


Fig. 5. Chondrite-normalized (Boynnton, 1984) REE profiles of granitic rocks in Finnmark.

foliation. The granite has F_3 -folded apophyses, which show discordant relationships, cutting the bedding within the Klubben Psammite.

Chemically the Litlefjord Granite is a peraluminous, calc-alkaline, S-type monzogranite with moderate enrichment of its light REE pattern ($\text{La}/\text{Sm}_n = 2.6$) (Table 2 and Fig. 5). On the Y–Nb tectonic discrimination diagram (Pearce et al., 1984), it plots as a volcanic arc granite. It has a high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.717 ± 7 (Daly et al., 1991), consistent with a sedimentary source containing detritus with a long-lived crustal history.

Zircons were separated from sample 7/84-6, chosen because of its lower Rb/Sr ratio (4.25) compared with the sample (7/84-4a, Rb/Sr = 5.76) dated by Daly et al. (1991), on the basis that this might reduce the proportion of inherited zircon. A second batch of zircon crystals was also separated from sample 7/84-7(2), again with a relatively low Rb/Sr ratio (4.25).

4.3.2. Revsneshamn Granite (ck077)

The Revsneshamn Granite outcrops as a linear body within the Havvatnet Imbricate Stack (Figs. 1 and 2) up to 5 km long and from 600 m to over 1 km in thickness. It trends broadly NNE–SSW on the southern side of Revsbotn, directly opposite the Litlefjord Granite (Figs. 1 and 2). The two bodies may be part of the same intrusion. The granite is a strongly foliated adamellite containing quartz, K-feldspar, plagioclase and biotite. A striking feature of the granite is large, up to 4 cm long, pink phenocrysts of augened K-feldspar, which weather proud of the matrix. It is a calc-alkaline, peraluminous ($\text{ASI} = 1.4$, Table 2) S-type granite, moderately LREE enriched ($\text{La}/\text{Sm}_n = 1.9$) (Table 2, Fig. 5) with an unfractionated heavy REE pattern, similar to the Litlefjord Granite. It plots within the volcanic-arc field on the Y–Nd discrimination diagram of Pearce et al. (1984).

The granite is generally concordant with the enclosing Klubben Psammite. Rafts of psammite contain an intense foliation parallel to the S_3 foliation within the country rock and the enclosing granite. The granite appears as a massive body with a strong foliation that anastomoses around the rigid K-feldspar grains. This foliation appears to be that associated with F_3 folding within the country rocks. No clear field evidence of the granite cutting F_2 folds is present. Rice (1987b) shows the granite cross-cut by metabasite bodies. Sample ck077 was collected at Revsneshamn settlement some 220 m south west of the pier.

4.3.3. Litlefjord Pegmatite (ck014b)

Numerous pegmatite bodies occur close to both the Litlefjord and Revsneshamn granites. At Laftargåppi (Fig. 2), a large pegmatite mass (Litlefjord Pegmatite, 150 m by 30 m) intruding the Klubben Psammite is exposed in lensoid profile by a road cut. As with the Litlefjord and Revsneshamn granite bodies the contacts are generally conformable, although at one point on Kvalnes Klubben (Fig. 2) the Litlefjord Pegmatite cuts F_2 folds at a shallow angle (Fig. 4d). In addition it truncates F_2 folds within a 10 m long xenolith of Klubben Psammite (Fig. 4c). Sample ck014b was collected from the road cut at Laftargåppi (Fig. 2).

4.3.4. Revsneshamn Pegmatite (ck074)

At Revsneshamn (Fig. 2) on the southern side of Revsbotn an elongate pegmatite body (Revsneshamn Pegmatite), up to 2-m thick, intrudes Klubben Psammite parallel to lithological layering and the foliation. In contrast to the Litlefjord Pegmatite, earlier structures are not crosscut. Both the Revsneshamn Pegmatite and the enclosing psammite are strongly deformed by east-vergent F_3 folds (Fig. 4e).

4.4. Sørøy-Seiland nappe

4.4.1. Snøffjord migmatitic leucosome (ck003)

Orthogneisses and paragneisses within the KNC have been interpreted as basement plinths on which the Sørøy Succession was deposited (Ramsay and Sturt, 1977; Ramsay et al., 1979). These two basement lithologies are the Fagervik Complex of tonalitic orthogneiss and the Eidvågeid (Supracrustal) Sequence (herein referred to as Eidvågeid Paragneiss). It should be pointed out that there is little compelling evidence that the Eidvågeid Paragneiss represents a basement unit. Alternatively it may represent a higher metamorphic grade and more migmatized part of the Klubben Psammite.

The Eidvågeid Paragneiss is a distinctive purple lithology consisting of psammitic to pelitic, migmatitic, sillimanite-K-feldspar gneiss. The Eidvågeid Paragneiss mesosome contains biotite, muscovite, quartz, garnet and K-feldspar with accessory sillimanite, tourmaline and rutile. Granitic, often pegmatitic, leucosomes are ubiquitous. They occur widely as irregular pods and discontinuous layers varying in thickness from millimetres to several decimetres and are up to tens of metres long. They are parallel to the foliation within the mesosome and are interpreted as syn-deformational.

The leucosomes are composed of quartz, K-feldspar and garnet. Large (up to 5 cm) garnet porphyroblasts are commonly present, typically encased in quartzofeldspathic haloes. The garnets are often heavily recrystallized into polycrystalline aggregates that pseudomorph the original grains. The garnets are probably the products of the dehydration melting reaction, biotite + sillimanite + quartz = garnet + K-feldspar + melt (Spear et al., 1999). A sample of granitic leucosome (ck003) from the Eidvågeid Paragneiss was collected from the harbour at Snøffjord (Figs. 1 and 2), within the Sørøy-Seiland nappe, the uppermost nappe of the KNC.

5. U–Pb geochronology

5.1. Analytical techniques

Zircon separation was performed by standard heavy liquid and magnetic methods on sieved and washed fractions (generally 120–250 μm). Zircons were hand picked using a binocular microscope then mounted in a resin disk along with the zircon standard and polished to reveal the grain interiors. The mounts were gold-coated and imaged with a Hitachi S-4300 scanning electron microscope (SEM), using a cathodoluminescence probe (CL) to image internal structures, overgrowths and zonation. Secondary electron mode (SE) imaging was employed to detect fractures and inclusions within the grains. After U–Pb analysis, electron backscatter imaging (BSE) was used to locate the analytical spots precisely, exploiting the fact that the gold coating had been completely removed by the ion beam.

U–Th–Pb zircon analyses (Table 3) were performed on a Cameca IMS 1270 ion-microprobe following methods described by Whitehouse et al. (1997) modified after Whitehouse et al. (1999). U/Pb ratio calibration was based on analyses of the Geostandards zircon 91500, which has an age of 1065.4 ± 0.3 Ma and U and Pb concentrations of 80 and 15 ppm, respectively (Wiedenbeck

Table 3
U–Th–Pb ion-microprobe data

Sample/spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f ²⁰⁶ (%)	²³⁸ U/ ²⁰⁶ Pb	±σ%	²⁰⁷ Pb/ ²⁰⁶ Pb	±σ%	% Disc. (2σ)	²⁰⁷ Pb/ ²⁰⁶ Pb	(Ma ±σ)	²⁰⁶ Pb/ ²³⁸ U	(Ma ±σ)
Snøfjord Leucosome ck003														
Concordia age 708.8 ± 4.3 Ma (leucosome crystallization)														
[70.795722N 24.566008E]														
22-magmatic	1097	3	138	0.003	{0.03}	8.43839	1.46	0.06290	0.29	–	705	6	722	10
20-magmatic	1219	3	154	0.003	0.05	8.40967	1.49	0.06280	0.29	–	701	6	724	10
16-magmatic	1291	4	162	0.003	0.22	8.44733	1.46	0.06270	0.32	–	698	7	721	10
15-magmatic	1122	3	141	0.003	{0.03}	8.45095	1.46	0.06287	0.36	–	704	8	721	10
13-magmaticPb loss	2361	5	220	0.002	0.03	11.37559	1.57	0.06005	0.35	–6.35	605	8	543	8
10-magmatic Pb loss	3539	3	336	0.001	0.06	11.13444	1.47	0.05945	0.28	–1.32	584	6	554	8
9-magmatic Pb loss	1585	3	180	0.002	0.04	9.32267	1.46	0.06161	0.28	–	661	6	657	9
5-magmatic	1124	3	140	0.003	0.05	8.52266	1.46	0.06301	0.27	–	709	6	715	10
23-magmatic	1311	4	162	0.003	0.03	8.59193	1.46	0.06301	0.25	–	708	5	710	10
Litlefjord Granite														
Concordia age 841.1 ± 6.5 Ma (crystallization)														
7/84-7 (2) [70.73N 24.52E]														
1-magmatic	1901	286	287	0.150	0.27	7.26892	1.49	0.06729	0.41	–	847	8	831	12
2-magmatic	2577	410	386	0.159	0.17	7.39804	1.49	0.06719	0.38	–	844	8	817	11
3-core	120	72	34	0.601	{0.14}	4.43258	1.50	0.09313	0.90	–8.0	1491	17	1311	18
4-core	63	19	8	0.301	2.98	8.85066	1.49	0.07661	3.91	–15.3	1111	76	690	10
5-magmatic	1974	336	302	0.170	0.17	7.29903	1.52	0.06717	0.34	–	843	7	828	12
7/84-6b [70.73N 24.52E]														
1a-magmatic	1030	56	158	0.054	0.32	7.07012	1.64	0.06703	1.10	–	839	23	853	13
2a-magmatic	846	56	130	0.066	0.45	7.03206	1.63	0.06618	1.20	–	812	25	857	13
3a-magmatic	180	42	30	0.232	1.83	7.18385	1.64	0.06670	3.98	–	829	81	840	13
6a-magmatic	1169	91	185	0.078	0.28	6.84518	3.68	0.06747	1.33	–	852	27	879	30
Revsneshamn Granite ck077														
Concordia age 838.9 ± 9.7 Ma (crystallization)														
[70.683766N 24.3456334E]														
3-magmatic	1745	445	272	0.255	0.12	7.24716	2.16	0.06749	0.38	–	853	8	833	17
1-magmatic	235	44	35	0.188	0.17	7.54894	2.18	0.06719	1.10	–	844	23	802	16
13a-magmatic	142	105	24	0.739	{0.08}	7.31119	2.16	0.06735	1.03	–	849	21	826	17
13b-magmatic	166	101	27	0.608	{0.04}	7.43610	2.16	0.06829	0.95	–	877	20	813	17
23-magmatic	121	32	19	0.262	{0.06}	7.34870	2.16	0.06683	1.11	–	832	23	822	17
6-core	66	34	20	0.524	{0.12}	4.06185	2.17	0.09179	1.00	–	1463	19	1419	28
Litlefjord Pegmatite ck014b														
Concordia age 825.7 ± 5.4 Ma (crystallization)														
[70.711436N 24.593828E]														
11-magmatic	1506	2	221	0.001	{0.01}	7.28566	1.49	0.06677	0.36	–	831	8	829	12
16-magmatic	2188	1	328	0.001	0.78	7.19198	1.49	0.06610	0.68	–	809	14	839	12
5-magmatic	2784	1	410	0.001	{0.01}	7.24846	1.49	0.06628	0.39	–	815	8	833	12
7-magmatic	3671	1	552	0.000	{0.02}	7.09056	1.49	0.06645	0.29	–	817	6	850	12
9-magmatic	3150	1	473	0.000	{0.03}	7.09520	1.49	0.06641	0.24	–	813	5	850	12
Revsneshamn Pegmatite ck074														
Concordia age 832.8 ± 8.9 Ma (crystallization)														
[70.676154N 24.379761E]														
20-magmatic	3581	3	553	0.001	2.99	7.27397	1.66	0.06646	1.27	–	821	26	830	13
23-mix	1161	2	163	0.002	1.86	7.81142	1.64	0.06343	1.56	–	723	33	777	12
25a-magmatic	1654	3	250	0.002	0.82	7.13783	1.64	0.06604	0.46	0.05	808	10	845	13
25b-core	63	17	41	0.271	{0.05}	1.93721	1.65	0.18627	0.67	–	2710	11	2683	36
29-mix	3380	6	457	0.002	0.85	7.95913	1.64	0.06260	0.76	2.97	695	16	763	12

Table 3 (Continued)

Sample/spot	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f ²⁰⁶ (%)	²³⁸ U/ ²⁰⁶ Pb	±σ%	²⁰⁷ Pb/ ²⁰⁶ Pb	±σ%	% Disc. (2σ)	²⁰⁷ Pb/ ²⁰⁶ Pb	(Ma ±σ)	²⁰⁶ Pb/ ²³⁸ U	(Ma ±σ)
35-magmatic	4077	5	623	0.001	0.72	7.06098	1.67	0.06675	0.60	–	830	13	854	13
35b-magmatic	1984	3	318	0.002	3.08	7.01600	1.65	0.06621	1.76	–	813	36	859	13
45c-magmatic	1945	3	304	0.002	2.99	7.16760	1.64	0.06568	1.20	–	796	25	842	13
45a-overgrowth	3217	6	409	0.002	2.07	8.67862	1.64	0.06344	1.08	–	723	23	703	11
45b-mix	3309	5	496	0.001	5.41	7.76358	1.65	0.06110	1.99	3.87	643	42	781	12
Repvåg Granite 7/84-8 [70.82N 25.77E]	Concordia age 981.4 ± 6.9 Ma (crystallization)													
2-magmatic	304	88	58	0.290	{0.04}	6.12290	1.50	0.07185	0.68	–	982	14	975	14
20-magmatic	500	95	95	0.190	0.27	5.97990	1.50	0.07194	0.66	–	984	13	997	14
25-magmatic	397	60	74	0.150	{0.04}	6.04780	1.49	0.07178	0.67	–	980	14	986	14
23-magmatic	418	75	79	0.181	{0.05}	6.04057	1.50	0.07185	0.62	–	982	13	988	14
3-magmatic	299	54	55	0.181	{0.05}	6.11036	1.49	0.07186	0.72	–	982	15	977	14
6-magmatic	740	137	140	0.186	{0.03}	5.95908	1.51	0.07164	0.49	–	976	10	1000	14
5-magmatic	166	78	34	0.470	0.22	6.09775	1.50	0.07078	1.11	–	951	23	979	14
14-magmatic	496	139	95	0.281	0.44	6.06405	1.51	0.07036	1.15	–	939	23	984	14
Hårvika Granite ck102c [70.721338N 26.059302E]	Concordia age 977.9 ± 9.1 Ma (crystallization)													
12-mix	27	16	7	0.592	{0.32}	4.82521	1.49	0.08499	2.53	–	1315	48	1214	17
16-magmatic	868	67	155	0.077	{0.06}	6.12068	1.49	0.07132	0.53	–	954	11	975	14
2-mix	588	250	159	0.425	{0.06}	4.60429	1.52	0.08890	0.55	–5.85	1392	11	1266	18
23-mix	396	80	122	0.202	{0.08}	3.77710	1.49	0.09851	0.60	–0.90	1585	12	1513	20
3-magmatic	528	52	95	0.098	{0.15}	6.08522	1.49	0.07192	0.72	–	950	17	979	14
3b-mix	129	58	40	0.449	{0.28}	3.99044	1.50	0.09435	1.13	–	1473	24	1438	19
4-magmatic	803	139	149	0.173	{0.07}	6.09802	1.49	0.07210	0.57	–	973	12	978	14
7-magmatic	592	170	111	0.287	{0.11}	6.22430	1.50	0.07221	0.68	–	969	15	960	13
Siedgoaivi Granite ck184 [70.426054N 25.986657E]	Concordia age 973.2 ± 4.2 Ma (crystallization)													
1a-magmatic	687	103	125	0.150	0.21	6.14887	0.70	0.07156	0.48	–	973	10	971	6
2a-magmatic	554	127	103	0.229	{0.09}	6.16583	0.70	0.07181	0.44	–	980	9	969	6
2b-magmatic	292	111	56	0.381	{0.16}	6.13575	0.70	0.07166	0.78	–	976	16	973	6
3a-core	286	153	104	0.535	{0.05}	3.47304	0.70	0.10055	0.52	–	1634	10	1631	10
4a-magmatic	227	151	47	0.666	{0.20}	6.20934	0.70	0.07105	0.87	–	959	18	963	6
5a-core	259	127	171	0.489	0.06	2.00442	0.70	0.19149	0.26	–4.77	2755	4	2609	15
6a-core	118	105	45	0.883	0.15	3.60672	0.70	0.10158	0.67	–1.63	1653	12	1578	10
7a-core	198	48	39	0.242	{0.10}	5.86194	1.42	0.07254	0.74	–	1001	15	1015	13
8a-core	601	137	177	0.227	0.14	3.86206	0.70	0.09835	0.50	–4.84	1593	9	1484	9
9a-magmatic	523	141	98	0.269	{0.13}	6.09286	0.73	0.07167	0.57	–	977	12	980	7
e1-core	399	22	110	0.056	{0.10}	4.00414	0.88	0.09281	0.57	–0.12	1484	11	1437	11
e2-core	669	146	129	0.219	{0.27}	5.90469	0.87	0.07282	0.35	–	1009	7	1009	8
e3-core	46	39	18	0.834	{0.15}	3.36149	0.87	0.10311	0.85	–	1681	16	1679	13
e4-core	452	160	102	0.354	0.11	5.15777	0.87	0.08055	0.48	–2.89	1211	9	1142	9
e5-magmatic	720	160	136	0.222	{0.03}	5.98643	0.95	0.07100	0.34	1.26	957	7	996	9
e6-core	510	72	103	0.141	{0.03}	5.54974	0.89	0.07480	0.44	–	1063	9	1068	9
e7-magmatic	739	551	154	0.746	{0.04}	6.09164	0.87	0.07170	0.34	–	977	7	980	8

UTM coordinates are given in square brackets after the sample number. f²⁰⁶ (%) is the percentage of common ²⁰⁶Pb, estimated from the measured ²⁰⁴Pb. Values in parentheses indicate that no correction has been applied owing to insignificant levels of ²⁰⁴Pb. % Disc. (2σ) is the age discordance at the closest approach of the 2σ error ellipse to Concordia. All other errors are at the 1σ level. Age calculations use the routines of Ludwig (2003) and follow the decay constant recommendations of Steiger and Jäger (1977).

et al., 1995). Replicate analyses of the same domain within a single zircon were used to independently assess the validity of the calibration. Data reduction employed Excel macros developed by Whitehouse at the Swedish Natural History Museum, Stockholm. Age calculations were made using Isoplot version 3.02 (Ludwig, 2003). U–Pb data are plotted as 2σ error ellipses (Fig. 7). All age errors quoted in the text are 2σ unless specifically stated otherwise. Common lead corrections, where applied are indicated in Table 3 and assume a modern day average terrestrial common Pb composition (Stacey and Kramers, 1975), i.e., $^{207}\text{Pb}/^{206}\text{Pb} = 0.83$. A detailed rationale for choosing present day Pb as a contaminant is given by Zeck and Whitehouse (1999).

5.2. Results

5.2.1. Hårvika Granite (ck102c)

Zircons from sample ck102c are euhedral and either clear inclusion free crystals or brown more turbid grains that are generally larger. Under CL the grains display idiomorphically zoned regions that may surround cores (Fig. 6A). Most grains have narrow rims of CL-bright material similar to the sample from the Repvåg Granite (see below). In contrast to the Repvåg sample, all grains have additional CL-dark homogenous overgrowths that surround the CL-bright rims. These may represent metamorphic overgrowths though none were large enough for ion-probe analysis (Fig. 6A). Four spots on four

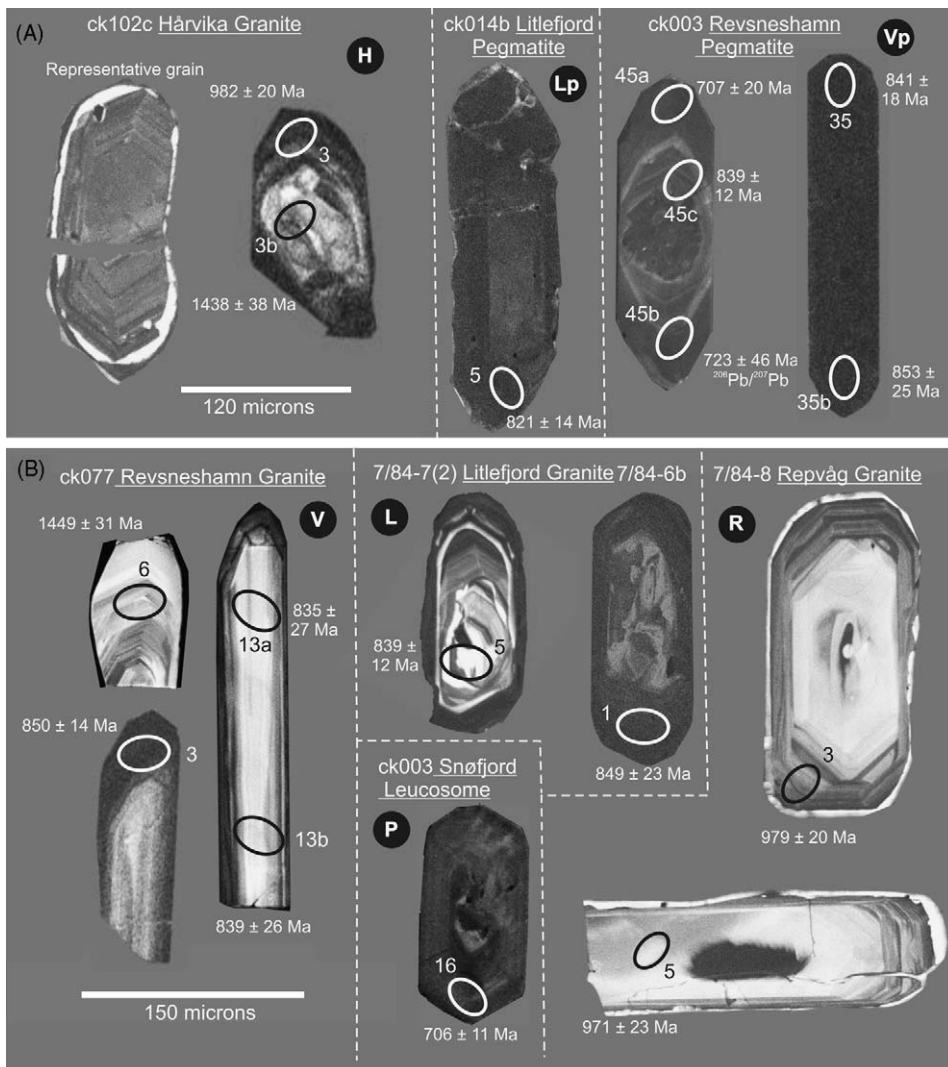


Fig. 6. Representative zircon petrography: SEM-CL images from (A) Hårvika Granite, Litlefjord Pegmatite and Revsneshamn Pegmatite; (B) Revsneshamn Granite, Snøfjord leucosome, Litlefjord Granite and Repvåg Granite. Ellipses show ion microprobe analyses, numbered as in Table 3. U–Pb dates are Concordia ages unless stated otherwise and are quoted with 2σ uncertainties. Sample identification corresponds to Fig. 1.

different grains carefully sited within idiomorphically zoned regions have a Concordia age (Ludwig, 1998) of 978 ± 9 Ma (Fig. 7A). Spots on core regions define a mixing line with upper intercept of c. 1670 Ma and a lower intercept that passes through the age of the magmatic zircon (Fig. 7A).

5.2.2. Siedgoaivi Granite (ck184)

Zircon grains from the Siedgoaivi granite are dominantly euhedral crystals around $150 \mu\text{m}$ long, that are clear in transmitted light. A minority of grains have an orange colouration and are larger, up to $300 \mu\text{m}$ long. Under CL all grains show idiomorphically zoned regions. Some display rounded cores, which are themselves idiomorphically zoned. Seven spots sited on idiomorphically zoned rims on six grains yield a Concordia age of 973 ± 4 Ma (Fig. 7B). Two spots sited on idiomorphically zoned core regions yield a Concordia age of 1009 ± 9 Ma. A further three cores have Concordia ages of 1066 ± 12 Ma, 1680 ± 20 Ma and 1633 ± 14 Ma. Four grains are discordant but yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of between 1210 and 1653 Ma. One crystal has an Archaean core, which is 6% discordant, and a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2755 ± 9 Ma (Fig. 7B).

5.2.3. Repvåg Granite (7/84-8)

The zircon population consists dominantly of well-faceted grains approximately $120 \mu\text{m}$ long. The majority of grains have a yellow colouration although a proportion of the population is clear, with no systematic difference in morphology between the different grain colourations. Under CL the grains display idiomorphically zoned regions that may surround cores of either CL-bright or CL-dark material. All grains have rims of CL-bright material, which appears to show its greatest development at the terminations of the zircon. Eight spots were sited in the main body of eight different zircon grains, carefully positioned not to sample core regions or CL-bright rim material. The data define a Concordia age of 981 ± 7 Ma (Figs. 6B and 7C).

5.2.4. Litlefjord Granite (7/84-7(2) and 7/84-7b)

Zircons from both samples are colourless to yellowish and are typically free of inclusions and major fractures, although occasional fractures occur in the core regions. The majority are elongate prisms (l:w ~5) usually around $150 \mu\text{m}$ in length with somewhat rounded tips. Larger stubby grains (l:w ~4) are less frequent, while occasional heavily rounded zircons are also present. The zircons show CL-dark idiomorphic zoning, sometimes developed around CL-bright cores (Fig. 6B),

which together with the high aspect ratio is taken to indicate that these grains are magmatic, possibly with inherited cores.

Five analyses from five grains of sample 7/84-7b and four analyses of four grains from sample 7/84-6b are presented in Table 3. Of these, seven are concordant and define a Concordia age of 841 ± 7 Ma (Fig. 7E). Most are from CL-dark idiomorphically zoned rim regions, although some are from CL-brighter idiomorphically zoned centres both are interpreted as magmatic. Thus, a new more precise age constraint is placed on the crystallization of the Litlefjord Granite. The rims are relatively high in U (>846 ppm) with Th/U ratios between 0.05 and 0.17.

Spots 3 and 4 (Table 3) from sample 7/84-7b, both from CL-bright cores, lie on a discordia with an upper intercept on Concordia at $1546 + 58/-53$ Ma, interpreted as the age of an inherited component. The lower intercept at c. 420 Ma possibly reflects Scandian Pb-loss.

5.2.5. Revsneshamn Granite (ck077)

Zircons from sample ck077 are similar to those from the Litlefjord Granite, being dominantly euhedral with sharp terminations. All grains show CL-dark idiomorphically zoned regions, sometimes surrounding CL-bright oscillatory-zoned cores. Approximately 25% of the population shows inherited core regions. Five spots from CL-dark idiomorphically zoned regions on four grains yield a Concordia age of 839 ± 10 Ma (Figs. 6B and 7F), interpreted as a magmatic age. Two of the spots have been corrected for common Pb (Table 3). Exclusion of these yields an indistinguishable Concordia age of 834 ± 15 Ma. An oscillatory-zoned CL-bright rounded core region has a Concordia age of 1449 ± 31 Ma (Figs. 6B and 7F), interpreted to represent the age of an inherited component.

5.2.6. Litlefjord Pegmatite (ck014b)

Zircons from the Litlefjord Pegmatite (sample ck014b) are golden-brown, euhedral, doubly-terminated, elongate prisms (l:w > 0.7), generally free of inclusions and fractures, usually between 200 and $250 \mu\text{m}$, less commonly up to $500 \mu\text{m}$ in length. All grains are CL-dark, weakly zoned (Fig. 6A) and apparently lack cores.

Five spots from homogenous CL-dark regions (Fig. 6A) in five grains yield a Concordia age of 826 ± 5 Ma (Fig. 7D). One of these, spot 16, required common lead correction. If this analysis is excluded, the Concordia age remains unchanged at 826 ± 6 Ma.

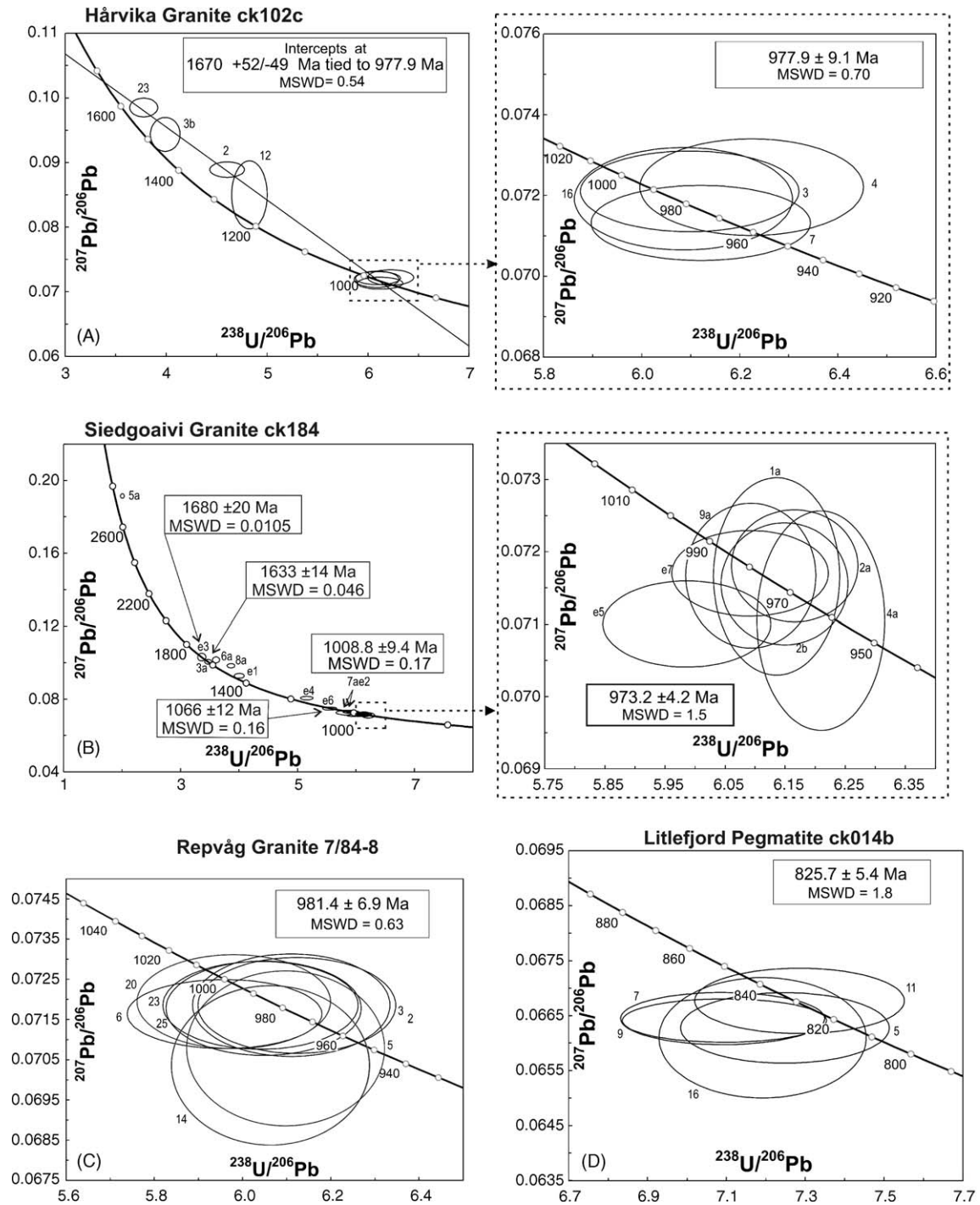


Fig. 7. Tera–Wasserburg Concordia diagrams ($^{207}\text{Pb}/^{206}\text{Pb}$ vs. $^{238}\text{U}/^{206}\text{Pb}$) showing zircon ages for Hårvika Granite (A), Siedgoaivi Granite (B), Repvåg Granite (C), Litlefjord Pegmatite (D), Litlefjord Granite (E), Revsneshamn Granite (F), Revsneshamn Pegmatite (G) and Snøfjord leucosome (H). Spot numbers indicated are those given in Table 3. Errors are 2σ .

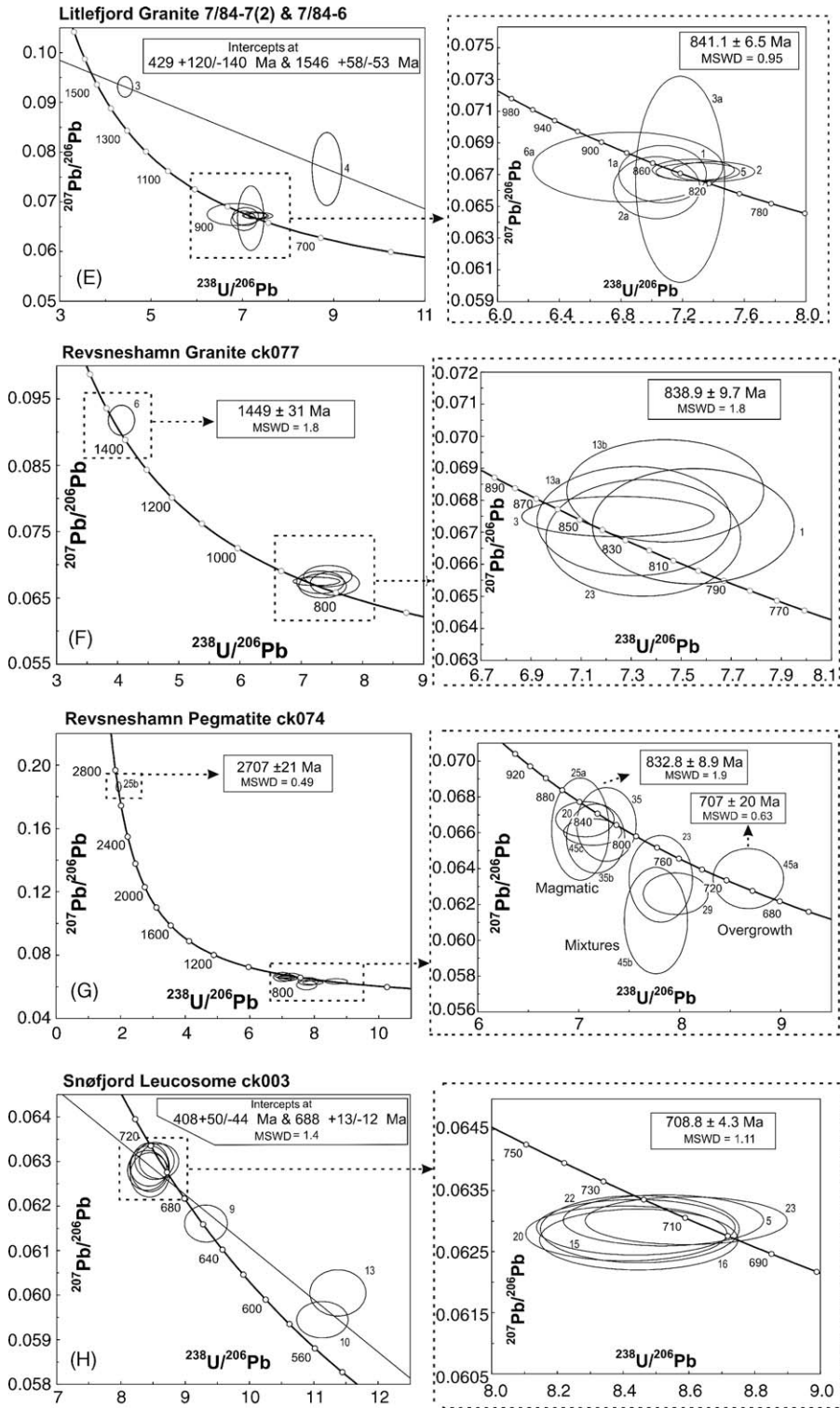


Fig. 7. (Continued).

5.2.7. Revsneshamn Pegmatite (ck074)

Zircons from the Revsneshamn Pegmatite (sample ck074) are similar to those of the Litlefjord Pegmatite, being golden-brown euhedral, doubly terminated, variably elongate prisms. The grain size is dominantly around 300 μm although occasional grains are up to 600 μm in length. The more elongate prisms are CL-dark, rarely with weak oscillatory zoning. The more squat prisms have CL-dark rims overgrowing complexly zoned generally CL-brighter interiors. Only 1 grain out of 50 displayed a rounded CL-bright core.

Ten analyses from six grains are presented in Table 3, all of which have been corrected for common lead. One analysis (spot 25b), from a distinct CL-bright core, plots well away from the main population (Fig. 7G) and has a much higher Th/U ratio and lower U content (Table 3). This is interpreted as an inherited component and has a Concordia age of 2707 ± 21 Ma. Five spots (20, 25a, 35, 35b and 45c) from four grains define a Concordia age of 833 ± 9 Ma, interpreted as the crystallization age of the pegmatite. This is indistinguishable from the age obtained from the Litlefjord Pegmatite. Four spots from the rims of three grains have younger ages. Three of these (spots 23, 29 and 45b) are interpreted as mixtures. However, the youngest (spot 45a), from a clearly defined overgrowth (Figs. 6A and 7G) has a Concordia age of 707 ± 20 Ma, identical to the age obtained from the Snøfjord leucosome (Fig. 7H, see below).

5.2.8. Snøfjord migmatitic leucosome (ck003)

The zircon population in sample ck003 consists of sharply-terminated, elongate (l:w=3) euhedral bi-prisms with sharp terminations commonly between 200 and 250 μm in length. They are generally CL-dark with faint idiomorphic zoning and occasional CL-bright cores (Fig. 6B). The zircons are translucent, colourless to pink and dominantly inclusion- and fracture-free.

Nine spots from nine grains have a high U content but contain some common lead, for which a correction has been made (Table 3). Six analyses define a Concordia age of 709 ± 4 Ma (Fig. 7H), interpreted as the crystallization age of the leucosome. Three grains, 9, 10 and 13, plot separately from the others and lie on a poorly defined discordia, with intercepts at 688 ± 12 Ma and $408 + 49/-45$ Ma. The disposition of these data may be due to lead loss during the Scandian orogeny.

6. Discussion

The results reveal a distinct spatial and temporal pattern in which the age of magmatic crystallization decreases towards the top of the nappe pile. In the low-

ermost nappe (Kolvik nappe) and in the overlying Oldarfjord nappe, magmatism is dated at c. 980 Ma. Above these nappes, in the Havvatnet Imbricate Stack, magmatism is dated at c. 840 Ma, whereas in the uppermost nappe (Sørøy-Seiland nappe) migmatization is recorded at c. 710 Ma.

Although the Porsanger Orogeny was originally proposed to have affected the entire KNC, based on regional correlation of structural style (Daly et al., 1991), it now seems more likely that events were spatially limited. This is in keeping with the younging age of magmatism upwards within the nappe pile and is consistent with the earliest deformation also decreasing in age upwards within the nappe stack (Fig. 8). Moreover, anatexis events in higher nappes are recorded within adjacent lower nappes by new mineral (zircon) growth and resetting of susceptible isotopic systems (discussed below). This suggests that juxtaposition and deformation accompanied anatexis during accretion. The events affecting each nappe are considered in turn below commencing with the lowest nappe.

6.1. Kolvik and Oldarfjord nappes

6.1.1. Grenville (Sveconorwegian) events: the Hårvika, Siedgoaivi and Repvåg granites

The Hårvika, Siedgoaivi and Repvåg granites have identical ages within error, yielding a weighted mean age of 976 ± 3 Ma (MSWD = 2.2), which is interpreted as their intrusion age. This result invites comparison with late- to post-tectonic magmatism in the Sveconorwegian Province of SW Sweden and southern Norway. Partial melting, associated metamorphism and penetrative ductile deformation along the Mylonite Zone have been recorded between 980 ± 13 Ma and 968 ± 13 Ma (Andersson et al., 2002). Banded migmatites to the east of the Sveconorwegian Frontal Deformation Zone have been dated between 990 and 960 Ma (Andersson et al., 1999). Identical ages of zircon growth in other high-grade rocks within the Sveconorwegian Domain in southern Norway and SW Sweden (Åhäll and Schöberg, 1999; Eliasson and Schöberg, 1991; Johansson et al., 1998; Scherstén et al., 2000) have been interpreted to date late orogenic extension during the final stage of the Sveconorwegian orogeny (Romer and Smeds, 1996; Möller and Söderlund, 1997).

The structural relationship of the Repvåg Granite to the enclosing Klubben Psammite indicates deformation of the metasediments before c. 980 Ma (Fig. 4). The age of this event is not known but it could represent Sveconorwegian deformation, at least within the Oldarfjord and Kolvik nappes. If the older zircon cores within

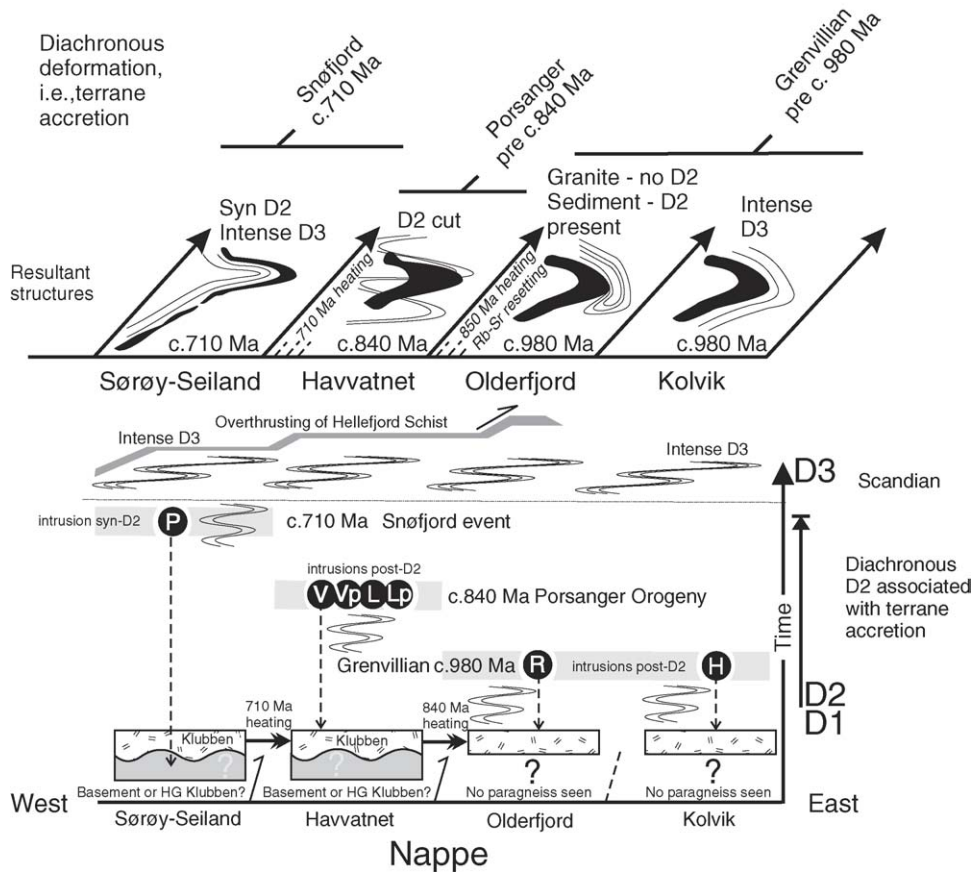


Fig. 8. Space vs. time diagram for the development of Neoproterozoic deformation within the KNC. Diagram shows deformation reflecting episodic terrane accretion at c. 980, c. 840 and c. 710 Ma. Samples are shown within the tectonostratigraphy and are linked to the formation they reside within. Upper half of figure shows structural evidence for deformation within each nappe and indicates diachronous D2 deformation. Note that the age of deformation and intrusion youngs upwards within the nappe pile, including thermal events associated with terrane docking affecting previously accreted blocks. HG Klubben = high grade metasediment.

these granites reflect an inherited component from the metasedimentary country rocks then the maximum constraint on the age of this event is provided by the youngest inherited grain, i.e., 1009 ± 9 Ma within the Siedgoaivi granite. The folds resulting from this event are similar in style and kinematics to the regional F_2 fold phase. If this structural correlation is extended to other nappes, the D2 event could represent Sveconorwegian deformation throughout the entire KNC. This is discussed further below and the more conservative view that the early deformation is characteristic of individual nappes is preferred.

Hitherto, the effects of the Sveconorwegian have been recognised in Norway only as far north as Molde in the Western Gneiss Region (Tucker et al., 1990). However, the new data from the Olderfjord and Kolvik nappes indicate that late Sveconorwegian magmatism and deformation affected the northernmost Norwegian

Caledonides, supporting the notion of a segment of the Sveconorwegian-Grenvillian orogenic belt extending between Baltica and Greenland (Karlstrom et al., 2001).

The Hårvika, Siedgoaivi and Repvåg granites represent crustal anatexis and crystallization at c. 980 Ma of a source that includes the inherited zircons dated at c. 1.6–1.7 Ga. This inheritance age closely matches the Sm–Nd t_{DM} model ages of the enclosing metasediments. Thus, melting of these units, into which the granites intrude, is possible (Kirkland and Daly, 2004).

6.2. Havvatnet Imbricate Stack

6.2.1. Porsanger event; Litlefjord–Revsneshamn granites

Due to the similarity in petrography, fabrics, crystallization age and outcrop occurrence we consider the

Litlefjord Granite and the Revsneshamn Granite to be parts of a single body. Together they yield a weighted mean age of 840 ± 6 Ma (MSWD = 0.12), which is interpreted as the time of intrusion.

The new data are a significant improvement on the discordia intercept age of *Daly et al. (1991)*, which was based on TIMS analyses of multi-grain zircon fractions. The disposition of these data suggests mixing between inherited cores and magmatic rims, with the effects of lead loss superimposed. If the smallest grain size fraction analysed by *Daly et al. (1991)*, which likely suffered the greatest degree of lead loss, is discarded, the remaining data yield a lower discordia intercept age of 822 ± 14 Ma, within error of the SIMS result presented here.

Based on clear field evidence (Fig. 4a and b), and geochronology from the Litlefjord Granite, the amphibolite-facies metasediments of the Klubben Psammite within the Havvatnet Imbricate Stack underwent D1 and D2 penetrative deformation before c. 840 Ma. This deformation corresponds to the Porsanger Orogeny (*Daly et al., 1991*) or Porsangerhalvøyen event (*Roberts, 2003b*). The older age constraint on the Porsanger Orogeny is placed by the youngest Sm–Nd t_{DM} model age for the Klubben Psammite of c. 1.6 Ga (*Kirkland and Daly, 2004*). This permits correlation of the D2 deformation between the Havvatnet Imbricate Stack and lower nappes where it occurred before 980 Ma. Thus, the D2 deformation affecting the Havvatnet Imbricate Stack could also be of Sveconorwegian (Grenville) age as suggested by *Daly et al. (1991)*. However, the validity of correlating D2 structures between different nappes based solely on structural style is questionable. Diachronous deformation is preferred in view of the younging trend of granite intrusion ages from lower to higher nappes, which impose progressively younger age constraints, and because the c. 710 Ma leucosome in the Sørøy-Seiland nappe is syn-deformational (see below).

The Rb–Sr age of c. 836 Ma for the Repvåg Granite, though poorly constrained, was considered to date the emplacement of this body (recalculated from *Daly et al., 1991*). However, this age is significantly younger than the true crystallization age revealed by the new U–Pb data. Interestingly, the Rb–Sr age is indistinguishable from the c. 840 Ma crystallization ages of the Litlefjord and Revsneshamn granites within the overlying Havvatnet Imbricate Stack. This suggests that the Rb–Sr isotopic system of the Repvåg Granite may have been reset during the intrusive event in the overlying nappe implying that the Olderfjord nappe and the Havvatnet Imbricate Stack were juxtaposed at this time.

Daly et al. (1991) also pointed out that the Porsanger Orogeny could correlate with the Knoydartian Orogeny that affected the Moine Supergroup of the Scottish Highlands. The Knoydartian involved compressional deformation and high-grade metamorphism associated with crustal thickening and is now dated as having occurred in several stages between 870 and 670 Ma (*Vance et al., 1998; Kinny et al., 2003; Tanner and Evans, 2003; Cawood et al., 2004; Storey et al., 2004*).

Inherited cores within the zircon grains from the Litlefjord and Revsneshamn granites have crystallization ages of $1546 + 58/-53$ Ma and 1449 ± 31 , respectively. *Daly et al. (1991)* presented a poorly defined U–Pb zircon upper intercept age of 1730 ± 216 Ma from the Litlefjord Granite and a Sm–Nd t_{DM} model age of 1760 Ma. A c. 1500 Ma crystallization age likely reflects the age of an inherited component within both granites.

The data suggest the Litlefjord Granite has a Proterozoic source. At 840 Ma, the Nd isotopic composition of the Litlefjord Granite is similar to that of the ‘basement’ Eidvågeid Paragneiss and more pelitic parts of the Klubben Psammite (*Kirkland, unpublished*). It is possible that melting of the Eidvågeid Paragneiss was the source for the Litlefjord Granite although a mixture between the paragneiss and the Klubben Psammite also fits with the available data.

The younger age limit on the Klubben Psammite is 1663 Ma based on Sm–Nd model ages (*Kirkland and Daly, 2004*). Alternatively, if the inherited zircons in the Revsneshamn Granite were derived from the Klubben Psammite, the younger age limit is 1449 ± 31 Ma. Hence, an age bracket for the Porsanger Orogeny in the KNC is placed between c. 840 Ma and the Calymmian (Early Mesoproterozoic; 1400–1600). This revises both the upper and lower age bounds reported by *Daly et al. (1991)* for D2 deformation in the Havvatnet Imbricate Stack.

6.2.2. Litlefjord and Revsneshamn pegmatites

The Litlefjord and Revsneshamn pegmatites represent coeval intrusions. Their mean intrusion age of 828 ± 5 Ma (MSWD = 1.8) reflects a later event after the emplacement of the Litlefjord and Revsneshamn granite bodies at c. 840 Ma.

The inherited component of 2.7 Ga within the Revsneshamn Pegmatite provides evidence for an Archaean component in the KNC. The Fagervik Orthogneiss has a Sm–Nd t_{DM} model age of 2.8 Ga and an unradiogenic Pb isotope signature consistent with old low U/Pb crust (*Aitchison, 1989*). The inherited component in the pegmatite may reflect the incorporation of zircon grains from the orthogneiss or ancient detritus within the Klubben

Psammite. A similar Archaean age was also recorded in an inherited zircon core from the Siedgoaivi granite in the Kolvik nappe.

The Litlefjord Pegmatite clearly demonstrates that F_2 folds are cut within the Havvatnet Imbricate Stack, whereas the Revsneshamn Pegmatite confirms that D3 deformation affected the region after c. 830 Ma. The D3 deformation produced folds similar in style to those formed during D2.

A thin overgrowth on a c. 830 Ma old magmatic zircon in the Revsneshamn Pegmatite has been dated at 707 ± 20 Ma (Figs. 6A and 7E). This zircon growth within the Havvatnet Imbricate Stack was synchronous with syn-deformational migmatization within the Eidvågeid Paragneiss of the overlying Sørøy-Seiland nappe, which yields leucosome ages of 709 ± 4 Ma (discussed below). Hence, juxtaposition of these two nappe units clearly pre-dates Scandian transport.

6.3. Tectonic setting of the c. 840 Ma magmatism

Paulsson and Andréasson (2002) envisaged magmatism at c. 845 Ma to reflect rifting in the Scottish Highlands, Central Taimyr Belt and the Seve-Kalak Superterrane. They reached this conclusion by associating granites with gabbroic intrusions of similar age. Correlations between Neoproterozoic magmatism in the Scandinavian Caledonides have been made with magmatism in the Scottish Highlands where the Ardgour granite gneiss yields a U–Pb age of 870 ± 48 Ma (Friend et al., 1997) and an associated metagabbro gives a similar 873 ± 6 Ma age (Millar, 1999). In Central Taimyr, plagiogranites have been dated between 785 and 850 Ma and gabbroic rocks at c. 740 Ma (Vernikovskiy and Vernikovskaya, 2001). In the Seve Nappe Complex, the Vistas Granite intruded at 845 ± 14 Ma (Paulsson and Andréasson, 2002).

Ryan and Soper (2001) presented numerical models outlining the possibility of granitic melting by the intrusion of rift-related mafic dykes within the basement of the Moine Supergroup, although significant volumes of mafic material are required to provide the necessary heat. A similar mechanism could explain the c. 840 Ma granitic magmatism on Porsangerhalvøya. Although large volumes of mafic igneous rocks are not known at this time, the Litlefjord Granite cuts a small gabbroic body near its hanging wall contact (Fig. 4f).

However, this gabbro plots within the calc-alkali field of Pearce and Cann (1973) and in the within plate tholeiite/volcanic-arc basalt field in the Th–Hf–Ta diagram of Meschede (1986) and thus its chemistry is compatible with a volcanic arc setting. At 840 Ma it has a

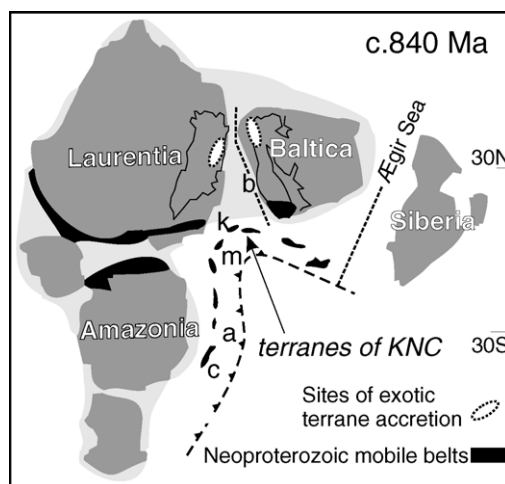


Fig. 9. Neoproterozoic c. 840 Ma palaeogeographic cartoon of Rodinia based on palaeomagnetic data, reconstructions and interpretations of Hartz and Torsvik (2002), revised to show Baltica in the conventional orientation. Continental fragments and magmatic arcs: Avalonian (a), Cadomian (c), terranes of the Greenland Krummedal Supercrustal Succession (k), Scottish Moine (m), and the KNC. These reside along the southeastern margin of Rodinia and were subsequently sutured on to West Africa, Amazonia, Baltica and Laurentia during the Late Precambrian or welded into distinct mobile belts only later accreted onto the continental landmasses. b = Baltica margin.

strongly depleted (i.e., mantle-like) initial Nd isotopic composition (sample ck002, $\epsilon_{Nd_{840}} = 5.4$, Table 2). It is possible that the gabbro represents a coeval mantle-derived magma that may have been thermally responsible for crustal anatexis that produced the Litlefjord body. However, without age constraint on the gabbro, this link is tenuous. The gabbro may be a cognate mafic enclave within the granite.

A volcanic arc setting is also compatible with the calc-alkaline peraluminous chemistry and trace-element ratios of the c. 840 Ma granites (e.g., Pearce et al., 1984). Moreover, the c. 840 Ma magmatism did not necessarily occur on the margin of Baltica since it is recorded in allochthonous units. This permits a palaeogeographic setting in which accretion of volcanic arc terranes constructed a distinct mobile belt that resided outboard of Baltica (Fig. 9). We thus consider a volcanic arc setting more plausible for the c. 840 Ma granitic magmatism within the Havvatnet Imbricate Stack.

6.4. Sørøy-Seiland nappe

6.4.1. Snøfjord event: Snøfjord migmatitic leucosome

The pegmatitic leucosome from the Eidvågeid Paragneiss within the Sørøy-Seiland nappe has a

crystallization age of 709 ± 4 Ma. Magmatism at this time also occurs elsewhere within the Sørøy-Seiland nappe. On Stjernøya, 90 km south west of Snøfjord, the Sandøra Granite was intruded at 706 ± 3 Ma (Corfu et al., 2004). The leucosomes within the Eidvågeid Paragneiss are parallel to the foliation and are syntectonic. Hence, the D2 deformation in the Sørøy-Seiland nappe occurred at c. 710 Ma and thus cannot be correlated with the deformation in the underlying Havvatnet Imbricate Stack. This demonstrates that a hitherto unrecognised tectonometamorphic event has affected the KNC.

7. Tectonic model for the KNC

Arising from the data presented in this paper, a radical revision of the structural evolution of the KNC is presented in Fig. 8, which depicts a polyorogenic history reflecting episodic amalgamation of terranes. This model associates episodic Neoproterozoic deformation events throughout the North Atlantic region and provides a unified model for their evolution. Within the Olderfjord and Kolvik nappes, the D2 deformation took place before c. 980 Ma and may be an expression of the Grenville (Sveconorwegian) Orogeny. Grenville (Sveconorwegian) deformation has hitherto only been recognised in south-western Scandinavia. This supports a palaeogeography that has a Grenville segment between Baltica and Greenland. D2 deformation took place within the Havvatnet Imbricate Stack before or at c. 840 Ma. Syn-deformational leucosomes within the Eidvågeid Paragneiss formed in the c. 710 Ma Snøfjord event, which also affected the underlying Havvatnet Imbricate Stack. Still younger deformation may yet be found within higher thrust sheets grouped into the Sørøy-Seiland nappe.

The terrane accretionary model is difficult to reconcile with the traditional view that the KNC metasediments were deposited on the Baltoscandian margin. Although this remains a possibility, the allochthonous nature of the KNC and its atypical structural and magmatic evolution when compared to the autochthonous Baltic basement invites correlation outside Baltica, with, for example, the Moine Supergroup of the Scottish highlands. Within the Moines a range of Neoproterozoic events (c. 820, 740 and 670 Ma) (Storey et al., 2004) has been identified that are believed to have affected a basin sequence of Laurentian provenance (Cawood et al., 2004 and references therein). These ages of deformation are similar to those in the Sørøy-Seiland nappe and Havvatnet Imbricate Stack.

A similarity also exists between the two lower nappes of the KNC (Olderfjord and Kolvik nappes)

and the Krummedal sequence in Greenland and the Brennevinsfjorden group on Eastern Svalbard both of which consist of early Neoproterozoic sediments and late Grenville (960–970 Ma) intrusives (Watt and Thrane, 2001; Johansson et al., 2005). The Taimyr region of northern Russia also experienced similar magmatism in the Neoproterozoic. The Mamont-Shrenk and Faddey gneissic terranes in Taimyr were intruded by granites, containing mainly Mesoproterozoic inherited zircons, between 880 and 940 Ma (Pease, 2001) while the Chelyuskin and Stanovoy ophiolites are dated at c. 755 Ma (Vernikovskiy et al., 2004). The accretion of these terranes in the late Neoproterozoic invites comparison with the KNC and supports the idea that Baltica and Laurentia were connected by an active margin in the Neoproterozoic (Fig. 9).

Baltica is typically envisaged as facing Greenland, its Tornquist margin looking onto west Gondwana. However, much of Neoproterozoic palaeogeography is uncertain. Some reconstructions show Baltica geographically inverted in comparison to Laurentia (Torsvik et al., 1991; Hartz and Torsvik, 2002). However, adopting a conventional orientation for Baltica relative to Laurentia (Dewey, 1969; Karlstrom et al., 2001) during most of the Neoproterozoic, the Timanian, Avalonian and Cadomian arcs can be linked to both Baltica and Laurentia in a Pacific rim-type scenario with a broad sweep of outboard volcanic arcs (Fig. 9). This palaeogeography allows a similar depositional setting for the Moines and the KNC terranes and is consistent with an accretionary mechanism to explain the compressional deformation in both regions (Fig. 9).

The Corrovarre mafic dyke swarm within the Sørøy-Seiland nappe has been dated by Sm–Nd mineral isochrons at c. 580 Ma (Zwann and Van Roermund, 1990). These intrusives cut tectonic foliations and have a similar age to the U–Pb dates of gabbros, felsic differentiates and carbonatites of the SIP at c. 560 Ma (Roberts et al., 2004). The Corrovarre dykes have been considered as belonging to Baltoscandian rift magmatism that is recorded in a 1000 Km long NNE–SSW trending belt parallel to the Caledonian orogenic trend (Andréasson, 1987). This material was inferred to have been intruded along the continental–oceanic interface at this time (Andréasson, 1987). If the magmatism occurred on the Baltoscandian margin then the upper nappes of the KNC must already have been accreted to Baltica by this time. However, there is no firm reason to link the SIP to the Baltica margin. The SIP has also been considered to form a microcontinental sliver that was detached from Baltica, eventually reunited with its parent continent during later Caledonian tectonism (Siedlecka et al., 2004).

The SIP has been envisaged as being located in the vicinity of a triple junction between Baltica, Siberia and the Ran Sea, the inferred Balto-Timanian triple junction of Siedlecka et al. (2004) and Rice and Reiz (1994) (Fig. 9).

Siedlecka et al. (2004) considered the sediments of the entire KNC as a single succession and proposed that they represented the outermost parts of the Baltoscandian margin. These authors along with Andréasson et al. (1998) linked the spatial association of KNC sedimentation and SIP magmatism implying that the sediments represented a rift sequence. The new dating results show that the KNC sediments cannot be related to the opening Iapetus basin associated with the SIP because they were deposited substantially before its inception. They were deposited before c. 710 Ma in the case of the uppermost nappe, before c. 840 Ma in the Havvatnet Imbricate Stack and before c. 980 Ma in the case of the Kolvik and Olderfjord nappes.

Furthermore these rocks were unequivocally subject to compression during the Neoproterozoic. Given the stark difference in the age of Neoproterozoic deformation and its distinct spatial pattern we consider that the various nappes of the KNC comprise individual terrane slivers juxtaposed during episodic accretion and only later sutured onto Baltica. SIP magmatism associated with Vendian rifting is located mainly within the highest nappe of the KNC. Allowing for shortening later in the Caledonian, the locus of rifting must have been outboard (present west) of the Neoproterozoic accreted belt.

8. Implications for the Finnmarkian Orogeny and the effect of overprinting deformations

We find no evidence for major structures or large-scale kinematic reorganization during a Finnmarkian event *sensu stricto*. Members of the c. 560–570 Ma SIP (Roberts et al., 2006) truncate folds and a well-developed foliation (Sturt et al., 1978) that developed earlier and were themselves deformed during the Scandian Orogeny (Sturt et al., 1978; Andersen et al., 1982; Dallmeyer, 1988a; Dallmeyer et al., 1989), which strongly overprinted the Neoproterozoic structures from c. 438 Ma to before or at c. 428 Ma (Kirkland et al., 2005a).

Intense Scandian reworking of the nappes has resulted in parallelism of early and late fabrics in most localities within the KNC. Scandian D3 structures, including eastward-verging F₃ folds with a penetrative axial planar S₃ foliation, display top to the east kinematics and clearly post-date all the igneous bodies described here. D3 structures are assigned a Scandian age because similar structures affect the early Silurian Hellefjord Schist and discordia lines suggest lead loss during

the Scandian Orogeny. Moreover, Ar–Ar mineral ages (Dallmeyer, 1988a) demonstrate widespread Caledonian thermal effects.

D2 structures are rarely preserved and are therefore difficult to recognise because of intense Scandian overprinting. Because of this, most of the post-D2 granite bodies appear conformable. Evidence that they cross-cut F₂ folds is only preserved in a few critical localities. Preservation of early deformation would appear to depend on the orientation of the intrusive body. A simple mechanistic model to explain this may be related to the degree of simple shear as opposed to stress accommodation by bulk rotation. Where granite sheets have been rotated into the direction of thrusting (i.e., ENE–WNW, as in the case of the Litlefjord Granite and Litlefjord Pegmatite), cross-cutting relationships relative to early folds and fabrics are preserved. However, in the normal situation where the intrusive body is parallel to the strike of the thrusts, i.e., orthogonal to the transport direction (as in the case of the Revsneshamn Granite), simple shear has deformed all fabrics into parallelism.

9. Conclusions

Granitic and pegmatitic intrusives cutting the Sørøy Succession become progressively younger upwards within the Kalak Nappe Complex of Finnmark, Arctic Norway (Fig. 8). The Hårvika and Siedgoaivi Granites within the Kolvik nappe and the Repvåg Granite within the Olderfjord nappe yield identical ages of 976 ± 3 Ma. Following D2 deformation within the Havvatnet Imbricate Stack, the Litlefjord and Revsneshamn granites were emplaced at 840 ± 5 Ma, while the Litlefjord and Revsneshamn pegmatites intruded at 828 ± 5 Ma. Syn-tectonic migmatization occurred within the Sørøy-Seiland nappe at 709 ± 4 Ma.

The tectonometamorphic evolution of the KNC is considerably more complex than existing models for the region have suggested (Roberts and Gee, 1985; Roberts, 1985; Gayer et al., 1984; Sturt et al., 1978). Although the early (D2) deformation within the KNC has traditionally been correlated regionally, it is more likely that diachronous deformation occurred at different times within each nappe, consistent with episodic terrane accretion (Fig. 8). Early deformation within the Olderfjord and Kolvik nappes likely occurred at c. 980 Ma permitting correlation with the Sveconorwegian (Grenville) deformation of SW Scandinavia. The D2 deformation within the overlying Havvatnet Imbricate Stack definitely took place at or before c. 840 Ma (Porsanger Orogeny), while the succeeding Sørøy-Seiland nappe was deformed at c. 710 Ma (Snøfjord event).

The change in the age of magmatic activity from c. 980 Ma through c. 840 Ma to c. 710 Ma on progressing upwards through the tectonostratigraphy indicates that the nappes experienced different thermal histories before they were juxtaposed. However, certain events are shared between adjacent nappes. Contemporaneous intrusion of the Hårvika and Siedgoaivi granites with the Repvåg Granite at c. 980 Ma suggests that the Kolvik nappe and Olderfjord nappes were in contact by this time. Granite intrusion at c. 840 Ma within the Havvatnet Imbricate Stack (Litlefjord and Revsneshamn granites) corresponds to resetting of the Rb–Sr system within the c. 980 Ma Repvåg Granite in the underlying Olderfjord nappe and suggests that the two nappes were juxtaposed by c. 840 Ma. Similarly, metamorphic zircon overgrowths within the Havvatnet Imbricate Stack (Revsneshamn Pegmatite) at the same time as leucosome formation in the overriding Sørøy-Seiland nappe suggests that these two nappes were juxtaposed at c. 710 Ma (Fig. 8). Later Caledonian transport reactivated these Neoproterozoic terrane boundaries.

The spatial and temporal pattern of deformation and intrusion provides a key to understanding the style of orogenesis. Systematic spatial change in the age of intrusion and associated deformation within the KNC are consistent with an accretionary orogen. In particular, geochronological evidence for coeval thermal events close to the contacts between adjacent terranes constrains their time of juxtaposition. The results show that the KNC sediments do not represent a single contiguous sequence deposited on the rift margin of Baltica. Instead, they are a product of an accretionary orogen most likely constructed from disparate terrane fragments bound together during the Neoproterozoic. These fragments are exotic to the margin of the Baltica craton. Intriguingly, their time and mode of docking with Baltica is as yet unknown.

The region of Finnmark including the KNC and Magerøy nappe represents two lithotectonic assemblages—Precambrian metasediments accreted episodically in the Neoproterozoic, and early Silurian rocks juxtaposed with them during the Scandian orogeny (c. 438–428 Ma). Extreme care is required when investigating polyphase and polyorogenic belts because the earlier history may only be preserved where the overprinting strain is low. Such localities are critical to understanding the early evolution of these belts. We note that it is impossible to characterize the early deformation of such regions without a sophisticated understanding of the later overprinting deformation.

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