Caledonian migmatization in central Nordaustlandet, Svalbard

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On the island of Nordaustlandet, northeastern Svalbard, a Grenvillian-age basement complex is overlain by Neoproterozoic to Cambrian sedimentary rocks. Both early Neoproterozoic (c. 950 Ma) and Caledonian (c. 410 Ma) granites have been recognised in the area. Migmatites, spatially associated with the granites, have been variously interpreted to be of Precambrian or Caledonian age. New studies of the stratigraphy, structure, metamorphism and migmatization show that the intensity of Caledonian tectonothermal activity increases from west to east across Nordaustlandet. Migmatization of the lowermost metasedimentary units of the Neoproterozoic Murchisonfjorden Supergroup occurred in the vicinity of Innvika and was followed shortly thereafter by intrusion of Caledonian granites. Ion-microprobe (NORDSIM) analyses of zircons in two neosome samples of the migmatites indicate Caledonian migmatization.

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Introduction

The Caledonian rocks of Svalbard, deformed and metamorphosed in the early Palaeozoic, are exposed around the western and northern coasts of Spitsbergen, in Ny Friesland and the northern parts of Nordaustlandet (Fig. 1). According to most tectonic interpretations, the Svalbard Caledonides can be subdivided into at least three independent provinces with different pre-Caledonian histories and locations (Harland 1972; Harland & Gayer 1972; Harland et al. 1974; Harland & Wright 1979; Harland 1985 & 1997). The boundaries between the terranes are much disputed; we follow Gee & Page, (1994) and refer to the Southwestern, Northwestern and Eastern terranes. The Eastern Terrane has been inferred to be composite and subdivided into the West Ny Friesland and Nordaustlandet terranes (Gee et al. 1995; Witt-Nilsson et al. 1998).

The Nordaustlandet Terrane (including eastern Ny Friesland) consists of a Neoproterozoic and Cambro-Ordovician sedimentary cover, resting on a basement complex of Mesoproterozoic phyllites and c. 950 Ma volcanic and granitic rocks (Gee et al. 1995; Johansson et al. 2000). The Caledonian deformation of eastern Ny Friesland and western Nordaustlandet is dominated by upright to W-vergent folds and near vertical cleavage. Caledonian low greenschist facies metamorphism characterises the lower stratigraphical units of the Neoproterozoic succession. However, in central Nordaustlandet, the metamorphic grade of the lower parts of these Neoproterozoic successions increases, and is associated with migmatization; these relationships provide the focus of this paper.

The timing of high-grade metamorphism and anatexis in Nordaustlandet has long been uncertain. The crystalline complexes of granites, augen gneisses and associated migmatites, both in Nordaustlandet and northwestern Spitsbergen were originally interpreted to be part of an Archaean basement, on which the younger Precambrian and Lower Palaeozoic sediments (Hecla Hoek Formation) were deposited (Nordenskiöld 1864, 1875; Nathorst 1910). Later, Holtedahl (1914, 1926) reinterpreted the origin of Spitsbergen's northwestern complex to be the result of mobilisation and intrusion during the Caledonian orogeny. Sandford (1926) originally favoured this interpretation for Nordaustlandet. However, he later (1950, 1956) suggested that the metamorphic rocks were part of a gneissic core, older than the Hecla Hoek sediments and possibly of Archaean age. Krasil'scikov (1965) inferred that old crystalline rocks are not exposed in Nordaustlandet, but later (Krasil'scikov 1973) proposed that pre-Riphean basement existed east from Duvefjorden. Flood et al. (1969) presented the results of a wide-ranging reconnaissance of Nordaustlandet in which they favoured the existence of a basement complex, but did not recognise a major

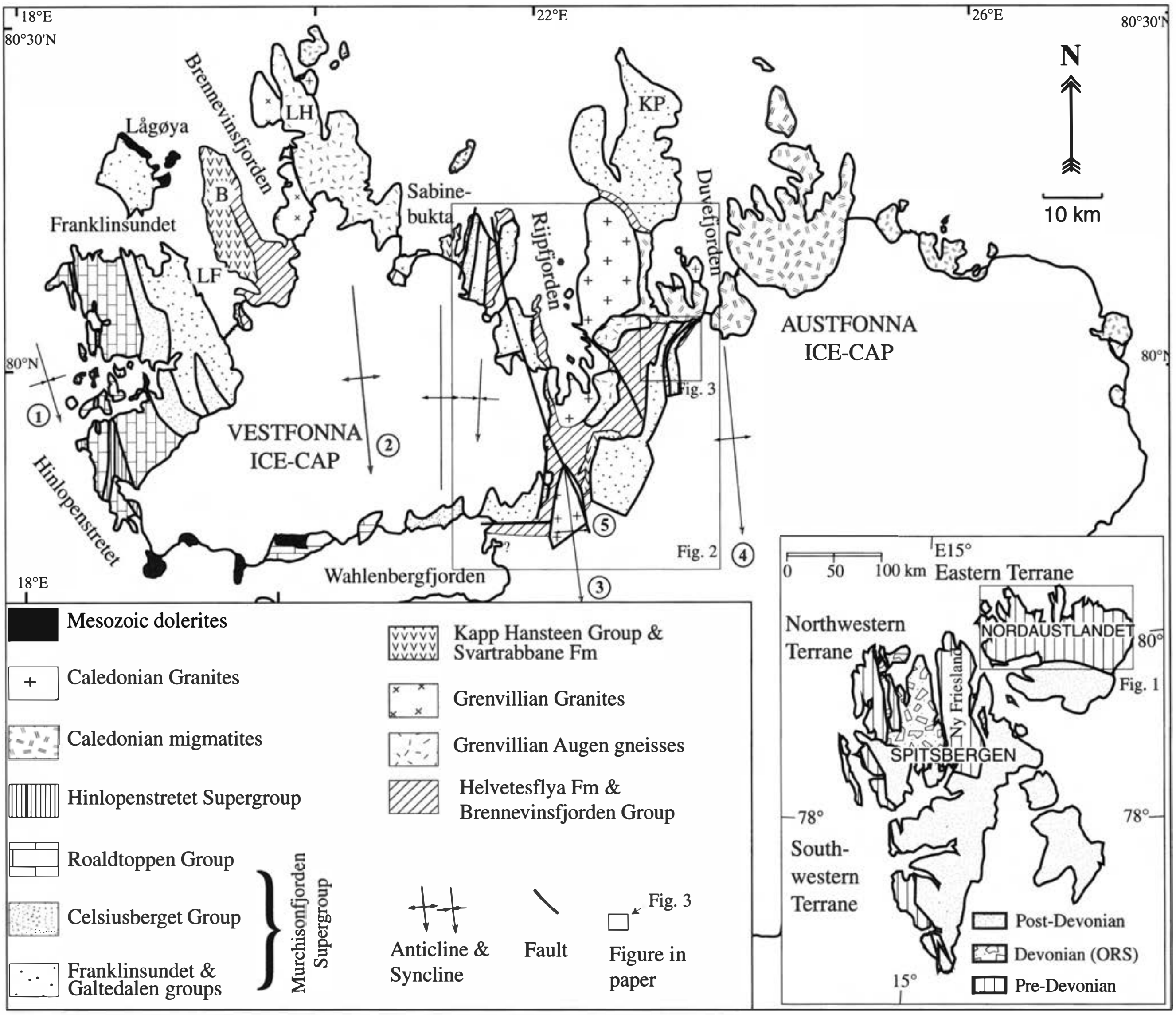

Fig. 1. Simplified geological map of Nordaustlandet (from Sandelin et al. 2001). Squares refers to figures in this paper. Numbers in circles are: 1–Hinlopenstretet Syncline, 2–Vestfonna Anticline, 3–Rijpdalen Anticline, 4–Austfonna Anticline, 5–Bengtssenbukta fault zone. Inset map shows the setting of Nordaustlandet in the Svalbard archipelago and the distribution of pre- and post- Devonian rocks. B – Botniahalvøya, L – Lågøya, LF – Lady Franklinfjorden, LH – Laponiahalvøya, KP – Kapp Platen.

unconformity, and considered the granites to be Caledonian syn- and post-orogenic intrusions.

The first radiometric-age data from Nordaustlandet, obtained mainly by K-Ar and Rb-Sr methods (Gayer et al. 1966; Ohta 1994 & references therein) showed evidence of widespread Caledonian tectonothermal activity. Recently, U/Pb zircon studies (Gee et al. 1995; Johansson et al. 2000) have provided clear evidence of a Grenville age for some of the granites; others were confirmed to be Caledonian in age (Gee et al. 1999).

Neoproterozoic and Early Palaeozoic, little metamorphosed sedimentary rocks occur on both sides of Hinlopenstretet (Fig. 1). They were first distinguished by Nordenskiöld (1864, 1866) as the "Hecla Hoek Formation" in northern Ny Friesland and later described in northern Nordaustlandet by Kulling (1932, 1934) in more detail, particularly the "Murchison Bay Formation". In the latter, he included c. 3000 m of limestones, dolomites, shales and quartzites between a section of Cambrian sandstones and tillites (the latter correlated with Varanger tillites on Greenland and in Scandinavia) and volcanites and sedimentary rocks of his Cape Hansteen Formation. Flood et al. (1969) described the structure and stratigraphy of the Murchisonfjorden area, upgraded Kulling's Murchison Bay Formation to Murchisonfjorden Supergroup and divided it into three groups. In western Nordaustlandet, the contact between the strata of Murchisonfjorden Supergroup and the volcanites of the underlying Kapp Hansteen Group is apparently not exposed (beneath Lady Franklinfjorden).

The major unconformity at the base of the Murchisonfjorden Supergroup, suggested to exist by some previous authors (Sandford 1956; Flood et al. 1969; Krasil'scikov 1973), was first recognised by Gee & Tebenkov (1996) in central Nordaustlandet. They found that the Neoproterozoic succession was deposited on a folded Grenvillian basement, consisting of phyllites and quartzites of the Helvetesflya Formation (Brennevinsfjorden Group of western Nordaustlandet) and volcanics and quartz porphyries of the Svartrabbane Formation (Kapp Hansteen Group in the west). Gee & Tebenkov (1996) also showed that another major unconformity, similar to that documented on Botniahalvøya (Flood et al. 1969; Ohta 1982b; Gee et al. 1995), separated the Helvetesflya metasediments from the overlying volcanic rocks.

During the 1994-1998 field seasons, mapping of the basal units of the Neoproterozoic succession of central Nordaustlandet (Tebenkov et al. 1999; Sandelin et al. 2001) established correlation between central and western Nordaustlandet. The new work around Innvikhøgda (Fig. 2) showed the lowermost parts of the Murchisonfjorden Supergroup to be migmatized. This is the only area on Svalbard that is known today where sediments, inferred to be of Neoproterozoic age, are influenced by Caledonian migmatization. The various lines of evidence for this interpretation – stratigraphical, structural, metamorphic and isotopic, are presented below.

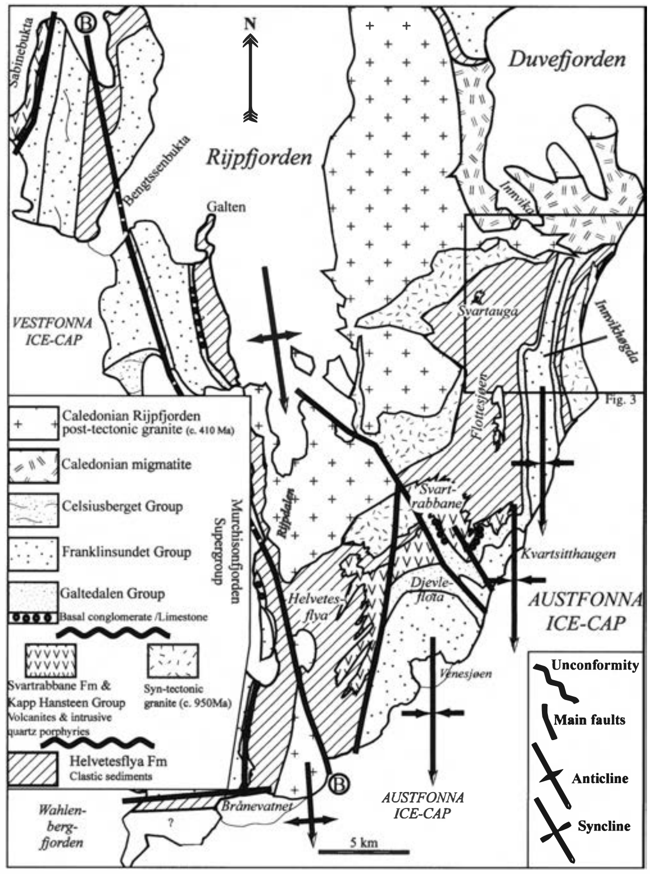

Fig. 2. Geological map of the ice-free area in central Nordaustlandet (from Sandelin et al. 2001). B-Bengtssenbukta Fault

Geology of central Nordaustlandet

An ice-free corridor in central Nordaustlandet separates the two major ice-caps Vestfonna and Austfonna. In this area, the structures are dominated by the Rijpdalen Anticline, with subordinate synclines and anticlines in the eastern and western limbs (Fig. 2). A major NNW-trending fracture-zone (the Bengtssenbukta Fault) and a few other parallel normal faults further to the northeast are developed, with downthrow to the northeast.

Three main stratigraphical units, the Helvetesflya Formation, the Svartrabbane Formation and the Murchisonfjorden Supergroup, separated by major unconformities, are well developed in the area. In the northeastern part of central Nordaustlandet, south of Innvika, the Helvetesflya Formation is intruded by c. 950 Ma granites (now deformed to augen gneiss). Both these rocks and the overlying Neoproterozoic Murchisonfjorden Supergroup are reworked by Caledonian migmatization and intruded by Caledonian post-tectonic granites.

Lithology and Stratigraphy

Helvetesflya Formation. – The Helvetesflya Formation, outcropping in the core of the Rijpdalen Anticline (Fig. 2), is the oldest rock unit known in the area. Gee & Tebenkov (1996) and most previous authors correlated the Helvetesflya Formation with the Brennevinsfjorden Group of western Nordaustlandet (Ohta 1982a; Gee et al. 1995). The Helvetesflya Formation is dominated by dark grey and black phyllites (meta-argillites) and subordinate, fine-grained psammites in the western limb of the Rijpdalen Anticline. In the southwest, around Brånevatnet, psammites become more frequent and massive, with up to 1m thick graded beds, although phyllites still dominate.

To the south from Ringgåsvatnet (Fig. 3), above a gently SE-dipping intrusive contact with gneissic augen granites, previously described also by Flood et al. (1969, fig.46, p.91), the lower part of Helvetesflya Formation consists of phyllites (meta-argillites) interbedded with thin, rare, fine-grained psammites. These strata are isoclinally folded and their thickness is difficult to estimate; at least 1000 m is suggested. About 2 km to the southeast from the contact with the augen gneisses, thicker, fine-grained, graded sandstones (turbidites) appear in the phyllites (Gee & Tebenkov 1996). Light grey, sandy units grade upwards into dark phyllites. The succession youngs southeastwards and the rhythm-thickness increases upwards, changing from a cm in the northwest to up to 1 m in the southeast, close to Svartrabbane, where sandstone dominates.

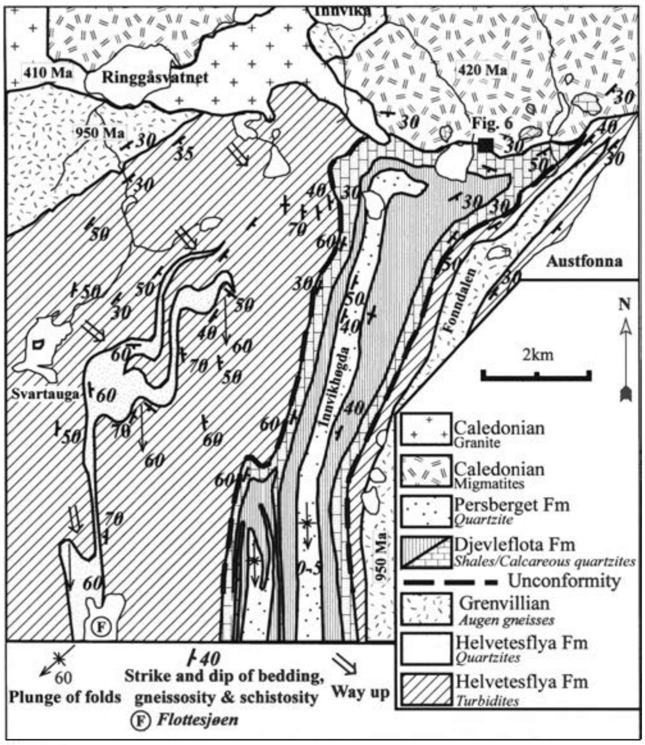

Fig. 3. Geological map of the area to the south of Innvika and Ringgåsvatnet.

In the area northeast of Svartauga (Fig. 2, 3), the turbidites pass up abruptly into light quartzites. Cross-bedding was observed in a few places, clearly showing the strata to young southeastwards. Conglomerates are found locally at the base of the quartzite unit, c. 500 m east of lake Svartauga. They contain round quartzitic clasts, 5-10 cm in diameter (rarely up to 20-50 cm) in a coarse-grained quartzitic matrix. The thickness of the conglomerate unit varies up to c. 50 m. It passes upwards and laterally into massive quartzites. To the northeast, the thickness gently decreases and, after 2.5-3 km, they pass transitionally into turbidites which also overlie the quartzitic unit. Southwards, the quartzites have been mapped 10 km from the conglomerate locality, their thickness varying up to 500 m. Here they are also overlain by phyllites and turbidites. Thus, these quartzites are an integral part of the Helvetesflya Formation and not a lower part of the Murchisonfjorden Supergroup (cf. Ohta 1982a).

To the northeast and east from Svartrabbane (Fig. 2, 3), more massive turbidites dominate in the Helvetesflya Formation. The thickness of fine-grained sandstones in the base of the rhythms reaches up to 1m. Southeast of Svartrabbane, in the type area of the Helvetesflya Formation, dark, thin- to medium-bedded strata, with equal sandy and phyllitic parts, are observed.

Summarising the stratigraphy of Helvetesflya Formation, we can roughly subdivide it into five units, from the base to the top: phyllites (meta-argillites) up to 1000 m thick with no lower contact exposed (intruded by c. 950 Ma granites); c. 500 m of coarsening upwards turbidites; up to 500 m of quartzites, locally with conglomerates at the base; phyllites interbedded with fine-grained turbidites c. 1000 m thick, and finally c. 500 m with dominating black phyllites. Way-up evidence suggests that this is the order of deposition, although isoclinal folding on the scale of an outcrop is frequent, and there may be significant fold repetition.

Svartrabbane Formation. – To the north of Kvartsitthaugen (Fig. 2), the Helvetesflya turbidites are unconformably overlain by basal conglomerates of the Svartrabbane Formation (Gee & Tebenkov 1996). This unconformity has been mapped along the northeastern side of Svartrabbane and also in eastern Helvetesflya. The turbidites are inverted directly beneath the unconformity and the conglomerates rest on different lithologies of the Helvetesflya Formation. Thus, north of Svartrabbane, they overlie massive turbidites, whilst east of Svartrabbane and in eastern Helvetesflya, they rest on black phyllites.

The basal conglomerates of the Svartrabbane Formation vary in thickness from a few cm up to c. 5 m. The subangular clasts are compositionally similar to the directly underlying rocks and occur in a sandy volcaniclastic (rhyolitic) matrix. In the northern outcrops of the Svartrabbane hills, where massive Helvetesflya turbidites dominate, the pebbles (with rare boulders up to 60cm in diameter) are represented mainly by fine-grained sandstones, whereas fragments of meta-argillites are typical to the east of Svartrabbane and on Helvetesflya.

Above the conglomerates, interbedded rhyolites and andesites are exposed (Tebenkov 1983; Ohta 1985). Whether or not the acid volcanites were originally massive quartz porphyries or rhyolitic lava flows with fluidal texture is often difficult to distinguish, due to a superimposed penetrative schistosity. However, some vertical massive quartz porphyry dikes do occur, a few metres thick, with sharp intrusive contacts to surrounding volcanics. Likewise, more mafic units can locally be shown to be intrusions. The estimated thickness of the Svartrabbane Formation is c. 1000 m according to our observations, i.e. about half that estimated by Ohta (1985).

Basal part of Murchisonfjorden Supergroup. – The stratigraphy of the lower part of the Neoproterozoic Murchisonfjorden Supergroup has been described recently by Sandelin et al. (2001). A new basal unit, the Galtedalen Group, has been defined, composed of conglomerates and sandstones overlain by limestones, dolomites and shales, in all c. 230 m thick. This group is well exposed in the western limb of the Rijpdalen Anticline. The Djevleflota Formation, outcropping in the eastern limb of the anticline (Gee & Tebenkov 1996) in central Nordaustlandet, can be correlated with the newly introduced Galtedalen Group.

The basal conglomerates of the Galtedalen Group in central Nordaustlandet were deposited unconformably on different units of the eroded Grenvillian basement, transgressing across the folded turbidites of the Helvetesflya and volcanites of the Svartrabbane formations.

The basal member of the Djevleflota Formation on Svartrabbane and to the northwest from Kvartsitthaugen is represented by massive, brown, quartzitic sandstones and conglomerates with mainly quartzitic clasts, up to 5 cm in diameter. The matrix is medium- to coarse-grained quartzite and the conglomerates are interbedded with and pass up into similar sandstones, commonly cross-bedded (Ohta 1982c; Gee & Tebenkov 1996). The general thickness of this conglomerate-quartzitic sandstone unit is about 100 m, including a more calcareous upper part. In the eastern limb of the Rijpdalen Anticline, it is conformably overlain by c. 100 m of dark grey-green and sometimes yellowish, calcareous shales.

The sandstone and shale units of the Djevleflota Formation are recognisable throughout the eastern limb of the Rijpdalen Anticline, beneath the massive white and pink quartzites of the Persberget Formation (Franklinsundet Group) in the Venesjøen, Kvartsitthaugen and Innvikhøgda synclines (Fig. 2). Carbonates, so prominent in the upper part of the Galtedalen Group in the type area, have not been recognised in the Djevleflota Formation of central and eastern Rijpdalen (Sandelin et al. 2001).

In both limbs of the tight Innvikhøgda Syncline (Fig. 3), the Djevleflota calcareous shales change into biotite-phyllites and then garnet-biotite schists towards the north. Likewise the Djevleflota basal quartzites, brown and massive in the south, change transitionally through light brownish thin-bedded varieties into greenish, calcareous, epidote-rich quartzites in the north. South of Innvika, all rocks below the Persberget quartzites are affected by the migmatization. Within the migmatites, somewhat rotated rafts of quartzites are preserved, up to 100 m long and few metres to tens of metres thick.

Structure

The N-trending Rijpdalen Anticline and associated Venesjøen, Kvartsitthaugen and Innvikhøgda synclines are apparently the only regionally developed fold-phase

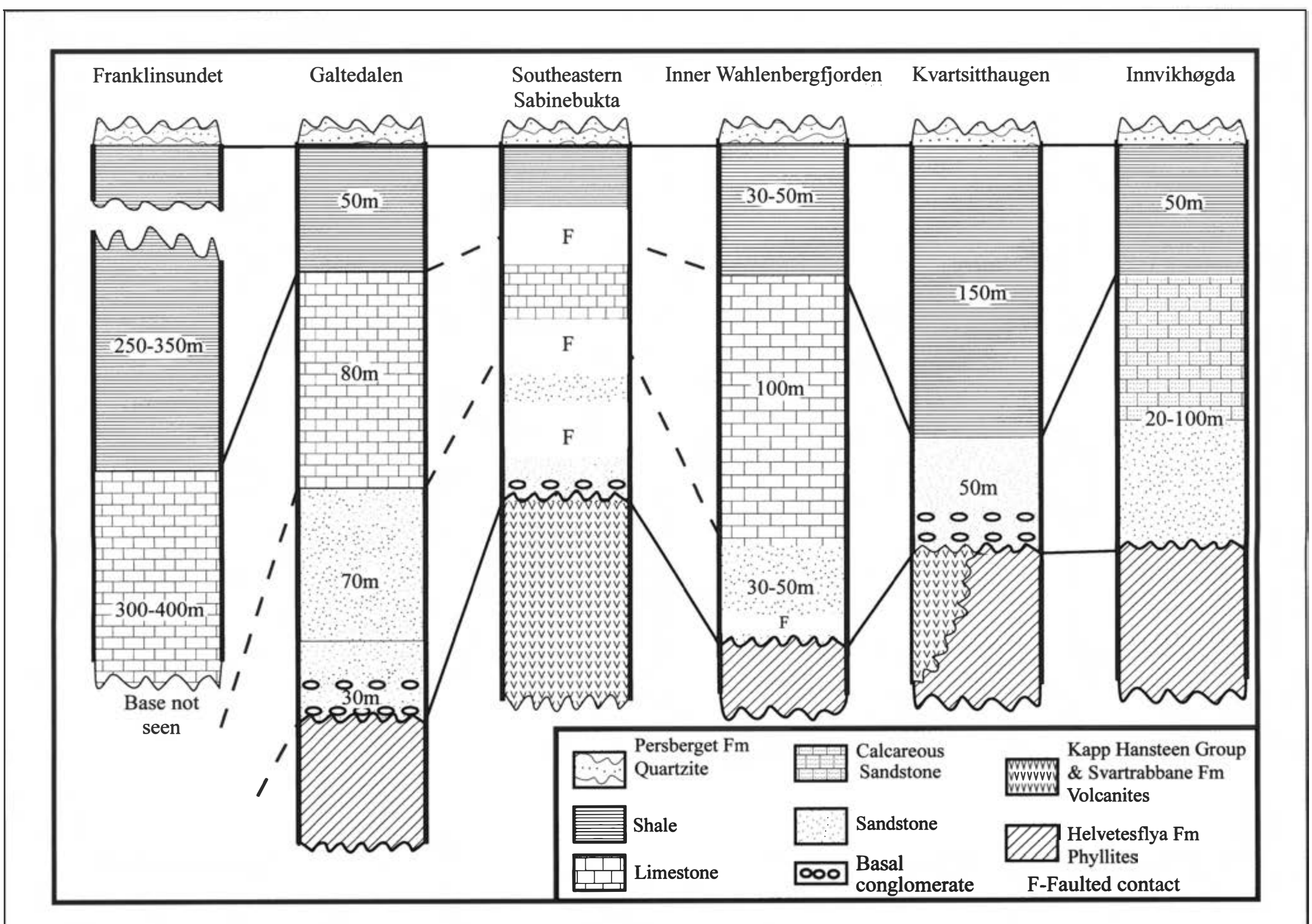

Fig. 4. Correlation of the basal part of Murchisonfjorden Supergroup (from Sandelin et al. 2001).

influencing the Neoproterozoic strata. The hinges of the anticlines, separating these synclines, are partly truncated by faults. A high-angle cleavage is associated with these open cylindrical folds, the axes of which have a gentle (up to 10-20°) plunge to the south. In the northwestern parts of the Innvikhøgda Syncline, calcareous quartzites of the Djevleflota Formation are folded disharmonically as a result of deformation connected with migmatization. The hinge of the Innvikhøgda Syncline is refolded in this northern area.

The rocks below the Murchisonfjorden Supergroup were shown by Flood et al. (1969) to be isoclinally folded prior to development of the Rijpdalen Anticline. The Helvetesflya and Svartrabbane formations are tight to isoclinally folded together, with the development of a schistosity parallel to the axial surfaces of the folds. The folds generally plunge SE in the eastern limb of the Rijpdalen Anticline and NW in the western limb. The internal parts of the massive volcanic units of the Svartrabbane Formation are less intensively folded, but the regional schistosity is generally present. Within the Helvetesflya phyllites a late crenulation is typical, with a mineral lineation (large flakes of muscovite parallel to the axis of small, cm size, commonly chevron-type folds) plunging 40-60° to SSE.

Previous work in the Ringgåsvatnet area, south of Innvika (Flood et al. 1969 p. 91 & 109), has shown that the Ringgåsvatnet augen granite (dated to c. 950 Ma by Johansson et al. 2000) intruded the Helvetesflya phyllites syn-tectonically. The contact is tight to isoclinally folded and an axial surface gneissosity in the granitic rocks was generated together with the dominating schistosity in the Helvetesflya meta-argillites. These folds are inferred to be of the same generation as those described above that fold the Svartrabbane Formation.

Mapping of the basal contact between the Svartrabbane Formation and the underlying Helvetesflya Formation has shown that the latter was inverted, at least locally, prior to deposition of the volcaniclastic rocks. The character of this early deformation of the Helvetesflya Formation is not fully established. Nevertheless, facing directions in the Helvetesflya turbidites (Fig. 3) indicates that both major and minor, tight folds existed in the Helvetesflya Formation prior to deposition of the Svartrabbane basal conglomerates. Judging by the structures in the clasts of the basal Svartrabbane conglomerates, the Helvetesflya meta-argillites were not penetratively deformed prior to erosion.

In summary (Fig. 5), it can be concluded that at least three generations of deformation can be distinguished in central Nordaustlandet. Early folding of the Helvetesflya Formation was followed by uplift and erosion prior to deposition of basal conglomerates and eruption of volcanic rocks of the Svartrabbane Formation.

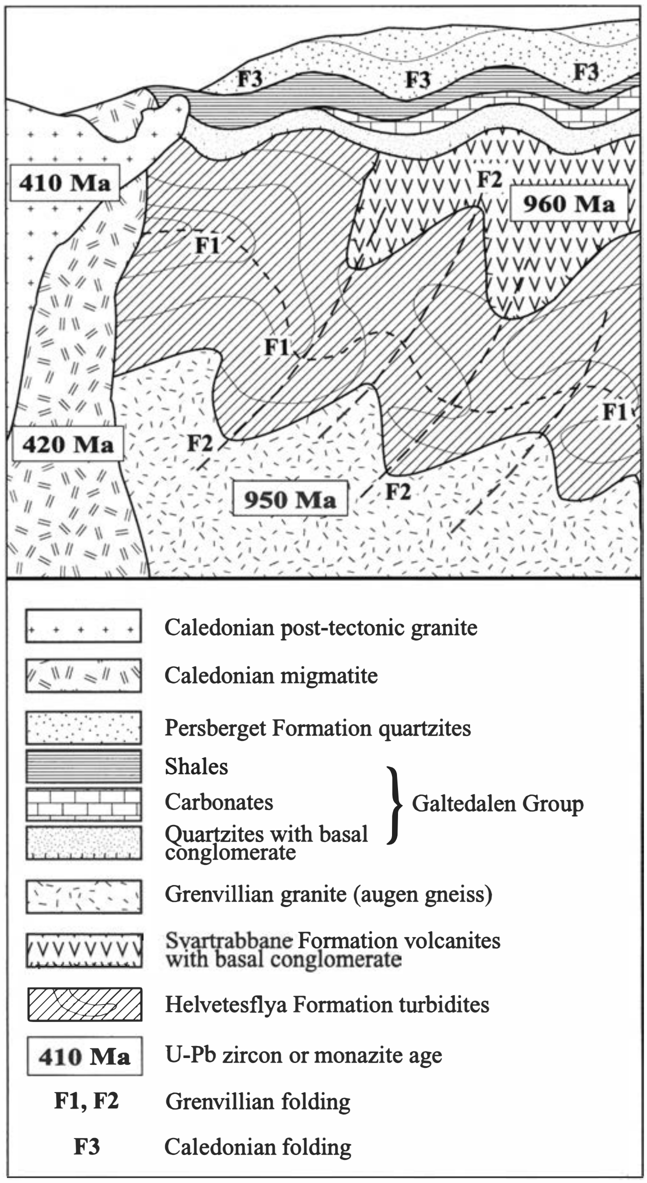

Fig. 5. Diagrammatic synthesis of the Grenvillian and Caledonian tectono-thermal history of central Nordaustlandet

The volcanites were subsequently folded together with the Helvetesflya metasedimentary rocks and penetratively deformed during intrusion of the syn-tectonic augen granites. Cooling of the latter, uplift and erosion established the basement on which the Neoproterozoic successions of the Murchisonfjorden Supergroup were deposited. Finally, the entire complex of basement and cover was subject to Caledonian folding, metamorphism and post-tectonic granite intrusion.

Metamorphism and migmatization

As mentioned earlier, the widespread occurrence of migmatites in northern and eastern Nordaustlandet has been interpreted previously to be either of Caledonian or Precambrian origin; it may well be both. The eastern areas of migmatites, in the vicinity of Duvefjorden (Fig.

1) and further east, have been described previously as the 'Duvefjorden Migmatite Complex' (Tebenkov, in Gramberg et al. 1990).

South of Duvefjorden, the migmatites are overlain by metasediments of the Helvetesflya and Djevleflota formations and intruded by Caledonian granites. Regional greenschist facies metamorphism occurred, both during the Grenvillian intrusion of the 950 Ma granites and after deposition of the Neoproterozoic Murchisonfjorden Supergroup. Contact metamorphism has been recognised, both in relation to the Grenville-age and the Caledonian granites.

The pre-Caledonian metamorphism, influencing the Helvetesflya and Svartrabbane formations, was associated with the development of a regional fine-grained schistosity and crystallisation of muscovite, chlorite and sometimes biotite. Towards the contact with the syn-tectonic Ringgåsvatnet and related granites (c. 950 Ma), biotite appears more widely and then garnet-biotite; staurolite-andalusite-garnet-biotite parageneses occur along the contact (also in Flood et al. (1969, pp. 106-108)). The discordant intrusive contact is folded by minor tight folds, similar to those in the phyllites. Parallel oriented flakes of biotite, muscovite and layers of fine grained quartz mark the foliation in the meta-argillites. A well-developed axial surface schistosity-gneissosity penetrates the contact itself. Parallel to this foliation, idioblastic staurolite and andalusite overgrow the foliation in the metasediments to a distance of up to 10 m from the contact. The presence of folded aplitic dikes and pegmatite veins in the metasediments, close to the contact, sharing the same axial surface schistosity, indicates syntectonic intrusion of the magmas.

Contact-metamorphic phenomena are also observed near the western margin of Austfonna in Fonndalen, where coarse-grained granites, deformed to augen gneisses, intrude the Helvetesflya Formation. The sedimentary rocks have been transformed, due to contact metamorphism, into biotite- and garnet-biotite schists. This high greenschist facies metamorphism stops sharply c. 400 m to the west of the Helvetesflya contact with the augen gneisses, against the overlying basal quartzites and phyllites of the Murchisonfjorden Supergroup, in the eastern limb of the Innvikhøgda Syncline. The overlying phyllites of the Djevleflota Formation (equivalent to Galtedalen Group), located between these basal Djevleflota quartzites and overlying Persberget quartzites, have low greenschist facies metamorphic assemblages. This evidence supports the interpretation that deposition of the basal quartzites occurred after the syn-tectonic intrusion of the megacrystic granites and the associated contact metamorphism of the Helvetesflya Formation.

Caledonian regional metamorphism in the western and southern parts of Nordaustlandet is associated with a

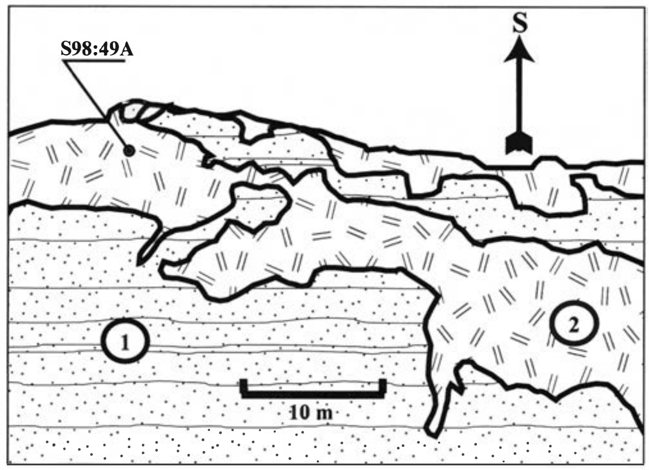

Fig. 6. Caledonian migmatization of Neoproterozoic metasediments. Northern slope of the hill, c. 3 km to the southeast of Innvika (drawn from a photo by Sandelin, 1998). 1 – Palaeosome of quartzites of Murchisonfjorden Supergroup; 2 – Granitic neosome of Caledonian migmatite.

new generation of sericite, growing parallel to the cleavage in the Neoproterozoic shales and slates. This lowermost stage of greenschist facies metamorphism is seen in the Westmanbukta and Djevleflota shales, in the hinge of the Venesjøen and Kvartsitthaugen synclines. Further to the north in the limbs of the Innvikhøgda Syncline, the metamorphic grade increases. Biotite and then garnet appear in the meta-argillites of the Djevleflota Formation, which south of Innvika are migmatized (Fig. 6). The migmatites of the Duvefjorden Complex are represented, as shown previously also by Flood et al. (1969), by foliated, banded gneisses with inclusions of metasediments (palaeosome) and more homogeneous varieties of grey granitic gneisses (neosome).

Within the migmatites, the fragments of reworked metasedimentary rocks are represented by lenses of garnet-biotite schists, epidotic and calcareous quartzites and marbles. The pelitic and quartzitic rocks are similar to those described above in the Helvetesflya Formation and basal units of the Murchisonfjorden Supergroup. The marbles may be fragments of metamorphosed limestones and dolomites of the Galtedalen Group, although they have not been seen by us further to the south, in the Djevleflota type area.

The contact metamorphic influence of the Caledonian post-tectonic intrusions on the phyllites of the Helvetesflya Formation is possible to observe everywhere in the vicinity of the Rijpfjorden and Winsnesbreen granites (c. 410 Ma, Johansson et al. 2002) in the hinge of Rijpdalen Anticline. The intrusive contacts are generally sharp and there is little associated deformation in the surrounding rocks. Andalusite and biotite overgrow the original sericite-quartz-feldspar association in the phyllites up to 50 m from the contact and the rocks are transformed into fine-grained hornfels. A few

Fig. 7. Combined SEM-CL (Scanning Electron Microscope – Cathodeluminescence) images of the analysed zircons, with analysed spots and $^{207}Pb/^{206}Pb$ ages in million years indicated. Ages in brackets are more than 20 % discordant or have high common lead contents.

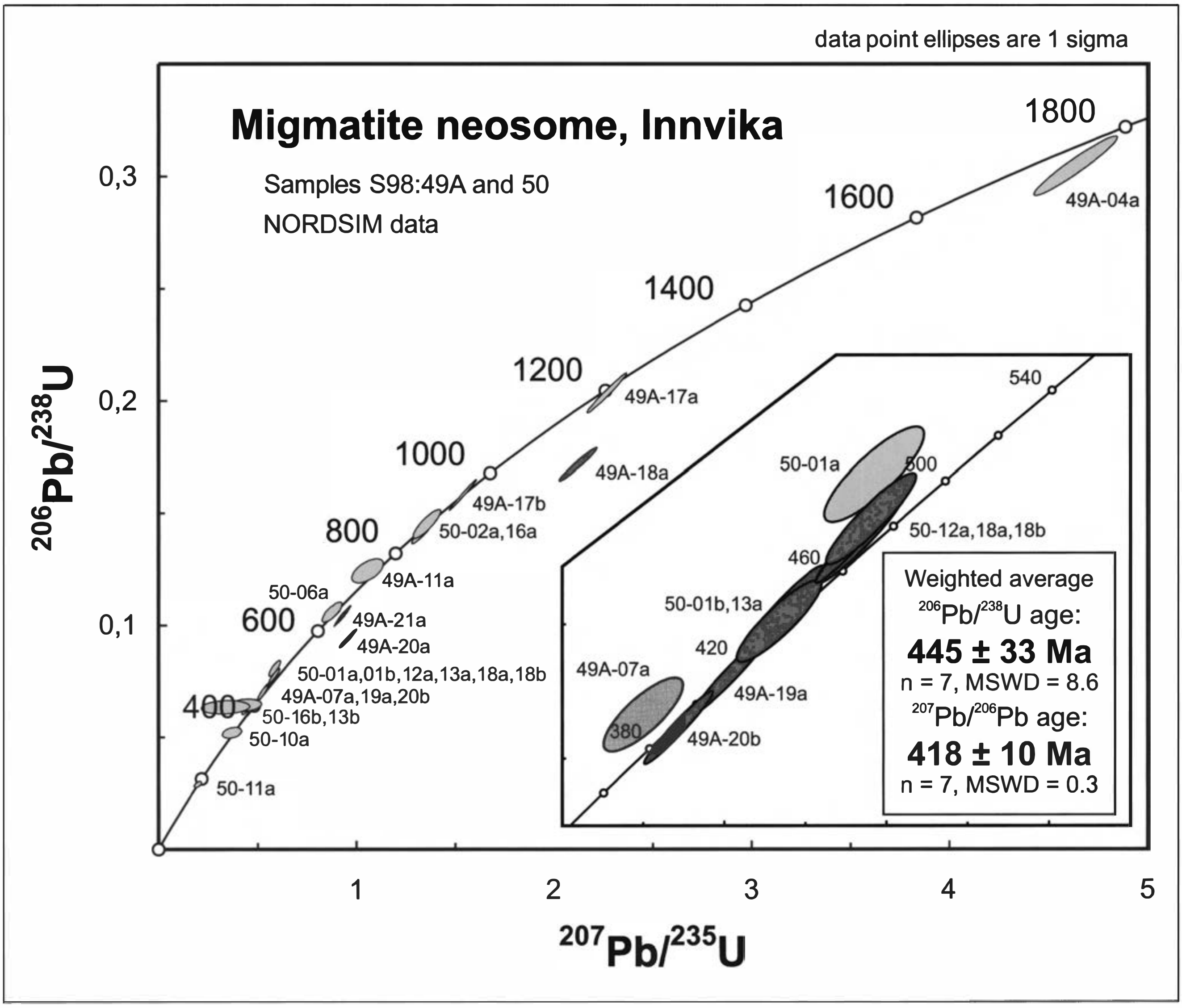

Fig. 8. Concordia diagram for zircons from Innvika migmatite sample S98:49A and S98:50, with inset showing enlargement of the concordia segment from 360 to 540 Ma. Size of symbols corresponds to 1σ error; numbering as in Table 1.

aplites, up to 1 m thick, and a few tens of metres long, occur in Helvetesflya phyllites up to a distance of 50 m from the main intrusions.

In a few places, the post-tectonic Caledonian granites cut the basal formations of the Murchisonfjorden Supergroup (Fig. 2); no significant changes in the mineral assemblage of the metasediments have been observed in the contacts; likewise, intrusion of these young granites into the migmatites has little influence on the mineral parageneses of the latter in the contact zone.

U-Pb zircon dating of the Innvika migmatite neosome

Although the early K-Ar and Rb-Sr work on Nordaustlandet (ages summarized by Gayer et al. (1966), and recalculated by Ohta (1994), using decay constants of Steiger & Jäger (1977)) indicated the widespread influence of Caledonian thermal events, it provided no indication of the early Neoproterozoic history (taking the lower boundary of the Neoproterozoic at 1000 Ma; Harland et al. 1989; Plumb 1991; Remane et al. 1997).

The subsequent demonstration of widespread intrusions of S-type granites of both Grenvillian and Caledonian age (Johansson et al. 2000, 2002) established the importance of two tectonothermal episodes. The published isotope-dating has concentrated on the igneous rocks (both granites and Kapp Hansten/Svartrabbane volcanic rocks); migmatites are being investigated and the first results are reported here.

In order to date the age of migmatization, two neosome samples were collected, one (sample S98:49A) from a granitic neosome impregnating the basal quartzites of

Table 1. NORDSIM ion microprobe U-Pb data on zircons from two neosomes in the Duvefjorden Migmatite Complex at Innvika, central Nordaustlandet, Svalbard.

		Measured ratios [2]										
Sample/spot	Description [1]	$^{207}Pb/^{206}Pb$	±1σ %	$^{207}Pb/^{235}U$	±1σ %	$^{206}Pb/^{238}U$	±1σ %	Error [3] corr.	$^{208}Pb/^{232}Th$	±1σ %	Disc. % [4] conv.	f_{206} [5]
S98:49A. Migmatite neosome, Innvika												
S98:49A-04a	Centre, clear, Cl-bright/zoned	0,1105	0,88	4,642	3,00	0,3046	2,86	0,96	0,0923	9,79	-5,9	0.05
S98:49A-07a	Long, centre, clear, Cl-zoned	0,0516	2,18	0,451	3,60	0,0633	2,86	0,80	0,0198	9,79	48,0	0.18
S98:49A-11a	Centre, clear, Cl-zoned	0,0620	3,98	1,065	4,90	0,1246	2,86	0,58	0,0204	21,14	13,0	1,26
S98:49A-17a	Centre, core?, CL-patchy	0,0811	0,53	2,277	2,92	0,2036	2,87	0,98	0,0753	9,69	-2,6	0.03
S98:49A-17b	Outer, clear, CL-zoned/dark	0,0708	0,39	1,546	2,89	0,1585	2,86	0,99	0,0340	10,54	-0,2	0,14
S98:49A-18a	Outer, clear, CL-zoned	0,0899	0,70	2,131	2,95	0,1720	2,86	0,97	0,0704	9,72	-30,3	0.05
S98:49A-19a	Centre, clear, CL-zoned/dark	0,0552	0,72	0,504	2,95	0,0663	2,86	0,97	0,0231	10,27	-1,4	0.00
S98:49A-20a	Centre, core?, CL-zoned	0,0742	0,61	0,968	2,93	0,0946	2,87	0,98	0,0540	10,31	-46,3	0.03
S98:49A-20b	Outer, clear, CL-dark	0,0550	0,70	0,472	2,95	0,0623	2,87	0,97	0,0172	11,57	-5,1	0,07
S98:49A-21a	Long, tip, fractured, CL-dark	0,0649	0,51	0,935	2,91	0,1045	2,87	0,98	0,0443	9,93	-17,7	0,12
S98:50. Migmatite neosome, Innvika												
S98:50-01a	Huge, centre, clear, CL-grey	0,0530	1,84	0,593	3,41	0,0811	2,86	0,84	0,0230	10,61	55,4	0,19
S98:50-01b	Huge, outer, zoned, CL-dark	0,0547	0,85	0,538	2,99	0,0713	2,87	0,96	0,0149	29,94	11,6	0,70
S98:50-02a	Centre, s-turbid, CL-zoned	0,0687	1,06	1,355	3,16	0,1431	2,98	0,94	0,0478	10,67	-3,2	0.00
S98:50-06a	Centre, clear, CL-bright	0,0604	2,45	0,885	3,77	0,1062	2,86	0,76	0,0240	12,37	5,5	0,25
S98:50-10a	Rim, clear/zoned, CL-dark	0,0523	8,58	0,379	9,05	0,0525	2,88	0,32	0,0035	517,15	10,3	10,85
S98:50-11a	Rim, clear, CL-dark	0,0509	5,22	0,207	5,95	0,0295	2,86	0,48	0,0025	362,87	-21,4	9,42
S98:50-12a	Outer, clear, CL-zoned	0,0554	0,94	0,584	3,01	0,0764	2,86	0,95	0,0229	10,52	10,6	0.00
S98:50-13a	Centre, clear, CL-zoned	0,0552	1,46	0,534	3,22	0,0702	2,86	0,89	0,0207	9,78	4,7	0,25
S98:50-13b	Outer, s-turbid, CL-dark	0,0493	12,55	0,440	12,88	0,0647	2,89	0,22	0,0123	17,20	151,4	51,00
S98:50-16a	Centre, clear, CL-bright	0,0680	1,63	1,364	3,36	0,1455	2,94	0,87	0,0417	10,24	0,9	0,62
S98:50-16b	Outer, zoned, CL-grey/dark	0,0392	23,23	0,345	23,42	0,0638	2,96	0,13	0,0053	35,54	205,5	65,12
S98:50-18a	Centre, clear core, CL-grey	0,0553	0,63	0,583	2,96	0,0764	2,90	0,98	0,0242	9,78	12,1	0.0
S98:50-18b	Outer, zoned, CL-dark	0,0550	1,19	0,591	3,10	0,0779	2,86	0,92	0,0229	10,92	17,5	0,71

1) *Description: position of spot, appearance of spot area in transmitted light, appearance of spot area in cathodoluminescence.*

2) *Corrected for common lead at 400 Ma according to Stacey & Kramers (1975) model:* $^{206}Pb/^{204}Pb = 18.080$, $^{207}Pb/^{204}Pb = 15.595$, $^{208}Pb/^{204}Pb = 37.894$.

3) *Error correlation* $^{207}Pb/^{235}U$ - $^{206}Pb/^{238}U$.

4) *Percent discordance; negative value = normal discordant; positive value = reverse discordant.*

5) *Fraction of* ^{206}Pb *derived from common lead.*

the Murchisonfjorden Supergroup in the northernmost end of the Innvikhøgda Syncline, south of Innvika (Fig. 6), and the other (sample S98:50) c. 200 m further north, inside the main field of the Duvefjorden Migmatite Complex. In hand specimen both rocks have the character of relatively homogeneous, fine- to medium-grained, grey granites, being composed of quartz, K-feldspar, plagioclase, muscovite and biotite.

Zircons were mounted and analysed on the NORDSIM ion microprobe using standard methods as described in Whitehouse et al. (1997) and Zeck & Whitehouse (1999), with the 91500 zircon standard (1065 Ma, Wiedenbeck et al. 1995) as a reference. Data reduction was done with software developed by M. Whitehouse, and concordia diagrams generated with the Isoplot/Ex program (Ludwig 2000). The results are reported in Table 1 and illustrated in Figs. 7 and 8.

Sample S98:49A is apparently dominated by inherited zircons, ranging in $^{207}Pb/^{206}Pb$ age from c. 670 Ma to c. 1800 Ma. For example, grain 17 consists of a concordant c. 1200 Ma old core with a concordant 950 Ma old overgrowth; thus it is probably derived from the Grenvillian granites or volcanites of central Nordaustlandet (Johansson et al. 2000). Two analytical spots (19a, 20b) plot almost concordantly at c. 400 Ma (Fig. 8), suggesting crystallization during Caledonian migmatization. These show CL-dark characteristics (Fig. 7), which is typical for Caledonian zircons from Nordaustlandet granites.

Sample/spot	Concentrations U ppm	Th ppm	Pb ppm	Th/U meas	Calculated ages in million years $^{207}Pb/^{206}Pb$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ
S98:49A. Migmatite neosome, Innvika										
S98:49A-04a	146	50	54	0,343	1808	16	1757	25	1714	43
S98:49A-07a	255	211	21	0,827	270	49	378	11	396	11
S98:49A-11a	734	133	100	0,181	675	83	736	26	757	20
S98:49A-17a	450	332	124	0,737	1224	10	1205	21	1195	31
S98:49A-17b	1440	59	246	0,041	950	8	949	18	948	25
S98:49A-18a	272	73	56	0,268	1423	13	1159	21	1023	27
S98:49A-19a	825	9	58	0,011	420	16	415	10	414	11
S98:49A-20a	702	39	74	0,056	1047	12	687	15	583	16
S98:49A-20b	1197	32	79	0,027	410	16	393	10	390	11
S98:49A-21a	1466	64	166	0,044	770	11	670	14	641	18
S98:50. Migmatite neosome, Innvika										
S98:50-01a	524	68	46	0,129	328	41	473	13	503	14
S98:50-01b	4458	63	336	0,014	399	19	437	11	444	12
S98:50-02a	291	16	45	0,055	889	22	870	19	862	24
S98:50-06a	198	27	23	0,137	618	52	644	18	651	18
S98:50-10a	3259	107	180	0,033	300	185	326	26	330	9
S98:50-11a	9689	229	300	0,024	237	116	191	10	187	5
S98:50-12a	658	60	54	0,092	430	21	467	11	474	13
S98:50-13a	314	132	26	0,422	419	32	435	11	438	12
S98:50-13b	2128	1207	159	0,567	164	270	370	41	404	11
S98:50-16a	223	58	37	0,258	868	33	874	20	876	24
S98:50-16b	2179	1813	154	0,832	-402	518	301	63	399	11
S98:50-18a	2045	248	171	0,121	425	14	466	11	475	13
S98:50-18b	3783	366	319	0,097	414	26	471	12	483	13

In sample S98:50, two zircons yield ages of c. 870 Ma (02a, 16a; possibly Grenvillian zircons with some superimposed lead loss), one yields an age around 620 Ma (06a), whereas the remaining data points are essentially Caledonian. These are mainly CL-dark whole crystals or overgrowths, including the huge, CL-grey to CL-dark zircon 01 (Fig. 7), although two of them are from CL-zoned material (12a, 13a). Four of them have large common lead contents (10a, 11a, 13b and 16b), and yield large analytical errors or ages far below 400 Ma, after correction for common lead (Stacey & Kramers 1975, at 400 Ma). However, five analyses (01b, 12a, 13a, 18a, 18b) plot with a slight reverse discordance between 400 and 500 Ma (Fig. 8), and together with analyses 19a and 20b from sample S98:49A, they yield a weighted average $^{207}Pb/^{206}Pb$ age of 418 ± 10 Ma (2σ, MSWD 0.3). The $^{206}Pb/^{238}U$ age for the same seven points is 445 ± 33 Ma (2σ, MSWD 8.6), the somewhat higher age reflecting the reverse discordancy for most of the points. Although the $^{207}Pb/^{206}Pb$ age is more precise, both in terms of age uncertainty and MSWD value, the larger uncertainty of the $^{206}Pb/^{238}U$ age (± 33 Ma) is more realistic in reflecting the spread of data points along the concordia from 400 to 500 Ma, and the somewhat higher age (445 Ma) is in good agreement with U-Pb and Pb-Pb ages on migmatites from easternmost Svalbard (Kvitøya; Johansson et al. in prep.). The U, Th and Pb contents and Th/U ratios are highly variable, both in the inherited and the new-formed zircon components (Table 1), and not conclusive for the origin of the zircons (magmatic vs. metamorphic).

Whereas some of the cores of the zircons are close in age to the time of early Neoproterozoic magmatism (c. 950 Ma) of the Nordaustlandet basement, a few yield younger Neoproterozoic ages (eg. 620 Ma for S98:50 zr 06). In view of the stratigraphic record of more or less continuous sedimentation throughout the Neoproterozoic, it is likely that these ages are disturbed and lack geological significance.

Four monazite grains mistakenly handpicked and mounted as zircons, were also analysed during the same session. Since no monazite standard was used, their U, Th and Pb contents and U/Pb ratios could not be properly evaluated, and the results are thus not reported in Table 1 or plotted in Fig. 8. However, their $^{207}Pb/^{206}Pb$ age (412 ± 53 Ma, 2σ, MSWD 25), also provides support for a Caledonian age of migmatization.

Summary and conclusions

In their paper on the Early Neoproterozoic unconformities in central Nordaustlandet, Gee & Tebenkov (1996, p.81) commented on the problems of defining the extent and degree of Caledonian regional metamorphism in the central and eastern parts of the island. "The evidence allows the possibility that the pre-Devonian basement, to the east of Nordaustlandet, beneath the northern Barents Sea (Barentsia), may be composed of Grenvillian complexes little influenced by Caledonian tectonothermal activity. Alternatively, Barentsia is dominated by Caledonian hinterland tectonics, with extensive middle Palaeozoic tectono-thermal reworking of a Precambrian basement". In this paper, four main lines of evidence (stratigraphic, structural, metamorphic and isotopic) have been presented that, in combination, provide compelling evidence for Caledonian, high T, moderate P, regional metamorphism of eastern Nordaustlandet.

Stratigraphy

The new mapping of central Nordaustlandet (Sandelin et al. 2001 and this study) has demonstrated that the Djevleflota Formation of eastern Rijpdalen can be readily correlated with the Galtedalen Group of western Rijpdalen, only the carbonate component being apparently absent in the eastern areas. Interestingly, the presence of marbles in association with quartzites as rafts in the Innvika migmatites suggests that the carbonate component may not be completely absent; indeed, it suggests that the carbonates may increase towards the north, in the eastern limb of the Rijpdalen Anticline, in a way similar to that in the western limb.

The underlying Helvetesflya Formation can be subdivided into at least five units, dominated by turbidites, but includes both meta-argillites and at least one cross-bedded quartzite. The lithologies are similar to those described from western Nordaustlandet's Brennevinsfjorden Group (Gee et al. 1995; Nilsson 1997, unpublished undergraduate thesis) and it would seem reasonable to treat the Helvetesflya unit as a group. We have chosen not to do so, leaving the detailed stratigraphy of the pre-Murchisonfjorden formations to those who map central Nordaustlandet in more detail in the years to come. Likewise the Svartrabbane Formation, dated to c. 960 Ma (Johansson et al. 2000) may be subdivided into at least a couple of mappable units (the basal conglomerates and overlying volcanites).

Structure

Mapping of the Innvikhøgda Syncline has shown that this fold tightens northwards and is refolded in the northernmost areas, close to the migmatites. Whereas further to the south and west, all related Caledonian structures are upright to inclined a little to the west (axial surface cleavages dipping c. 70° E), in the case of the Innvikhøgda Syncline, the axial surface changes in orientation from near vertical in the south to moderately E-dipping in Innvikhøgda and low angle SE-dipping near the migmatites. Here, it is truncated by the latter. The metasedimentary rocks below the massive Persberg- et quartzites were disharmonically folded in the vicinity of the migmatite front. Thus, the refolding can be related to the migmatization.

Tight to isoclinal folding of the Svartrabbane and Helvetesflya formations, before the deposition of the Murchisonfjorden Supergroup, occurred during intrusion of the Ringgåsvatnet augen granite (c. 950 Ma, Johansson et al. 2000). A related axial-surface foliation (gneissosity in the granites and schistosity in the metasedimentary and metavolcanic rocks) can be mapped in the area south of Ringgåsvatnet and Svartrabbane. Thus, it can be shown that this folding and granite intrusion occurred only a few million years after the Svartrabbane volcanicity. Folding of the Helvetesflya Formation prior the Svartrabbane volcanicity, as described by Gee & Tebenkov (1996), was apparently not associated with development of penetrative schistosities. This conclusion is supported by the lack of a penetrative foliation in the clasts of Helvetesflya metasediments that occur in the basal Svartrabbane conglomerates. The regional geometry of this folding remains to be established.

Metamorphism

The observed increase in metamorphic grade of the Djevleflota Formation quartzites and meta-argillites towards the contact with the Duvefjorden Migmatite Complex may be related either to the regional heating during Caledonian metamorphism or to the later intrusion of granites. In view of the limited influence of contact metamorphism (andalusite and garnet-bearing hornfels near the contact), recognized further south in central Nordaustlandet, we interpret this metamorphism to be related to migmatization.

Early Neoproterozoic regional metamorphism of the Helvetesflya and Svartrabbane formations is generally of somewhat higher (chlorite, muscovite and sometimes biotite) greenschist facies than the regional Caledonian metamorphism seen in the Neoproterozoic meta-argillites. This Grenville-age tectonothermal activity reached high amphibolite facies in the contact of the 950 Ma granites, suggesting the possibility that the Duvefjorden Migmatite Complex may have been generated partly during the Grenvillian orogeny and then reworked in Caledonian times.

Isotope age data

The ion microprobe analyses provide evidence for a Caledonian migmatization event in the form of overgrowths and newly formed zircon crystals yielding a weighted average $^{207}Pb/^{206}Pb$ age of 418 ± 10 Ma and a $^{206}Pb/^{238}U$ age of 445 ± 33 Ma. Monazites provide a similar, but imprecise, $^{207}Pb/^{206}Pb$ age. The proportion of inherited zircon is larger in sample S98:49A, collected from the migmatite neosome impregnating the basal part of the Murchisonfjorden Supergroup, than in sample S98:50 derived from the more massive neosome inside the main migmatite complex. The zircon $^{207}Pb/^{206}Pb$ age of the migmatite neosome is, within error, identical to the U-Pb age of the major Rijpfjorden granite massif (conventional U-Pb monazite age 412 ± 1, single zircon Pb-evaporation age 423 ± 6 Ma, single monazite Pb-evaporation age 427 ± 14 Ma, ion microprobe zircon age 410 ± 15 Ma, Johansson et al., 2002), as well as that of the smaller Djupkilsodden pluton (conventional U-Pb zircon age 417 +18 / -7 Ma, single zircon Pb-evaporation age c. 410 Ma, Gee et al. 1999), suggesting a close relationship between migmatization and granite intrusion.

The four lines of evidence, summarised above, lead to the conclusion that Caledonian tectonothermal activity increased from west to east across Nordaustlandet and that Caledonian migmatization occurred in central Nordaustlandet. Along with the structural evidence of W-vergent folding, this suggests that the Caledonian hinterland lay further to the east on the Barents Shelf. Recent work (Johansson & Larionov 1999) in areas further to the east, provide additional evidence of the increasing influence of Caledonian metamorphism in that direction. The location of the Caledonian suture (s) in the Barents Sea (Gee & Ziegler 1996) remains to be clearly defined.

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