Late Archean basement in the Bangenhukken Complex of the Nordbreen Nappe, western Ny-Friesland, Svalbard

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The rocks of western Ny-Friesland, northern Svalbard, are part of a tectonostratigraphy including four thrust sheets, each composed mainly of orthogneisses overlain by younger metasedimentary rocks. Previous geochronological studies have shown that the orthogneisses are dominated by ca. 1750 Mya granitoids. This study of a quartz-monzonite in one of the thrust sheets, the Nordbreen Nappe, yields a single-zircon U-Pb ion-microprobe age of 2709 ± 28 My. This is the oldest rock unit so far reported in the Svalbard Caledonides. However, age-determinations on detrital zircons in the metasediments of western Ny-Friesland have shown that Late Archean rocks were prominent sources. The new ages presented here provide the first evidence of a local source for these sedimentary rocks.

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Geological setting and previous geochronology of western Ny-Friesland

The metamorphosed succession of western Ny-Friesland—the Atomfjella Complex of Kra-
sil’shchikov (1965)—contains metasediments separated by granitic gneisses. Those authors favouring the western Ny-Friesland succession to be more or less continuous and unbroken (Harland 1997; Krasil’shchikov 1965) interpret the granitic gneisses to be metamorphosed ignimbrites (e.g. Harland 1997: 237-238). Most contacts between the sedimentary and igneous rocks are highly
strained. Quantifying the strain in the field in terms of displacement between rock units has not been possible. Decisive evidence for thrust repetition of the succession has been found in the isotope ages and provenance data summarized below.

The Caledonian tectonostratigraphy of western Ny-Friesland, includes four thrust sheets (Fig. 2) from base upwards; the Finnlandsveggen, Rekvika, Nordbreen and Dirksodden nappes (Witt-Nilsson et al. 1998). They are all metamorphosed in amphibolite facies. Each of the four thrust sheets contains granitic gneisses of ca. 1750 My age (Johansson et al. 1995; Larionov, Johansson, Tebenkov et al. 1995; Johansson & Gee 1999) and overlying cover sediments (Gee & Hellman 1996; Hellman et al. 1997) containing zircons that are both older and younger (Mesoproterozoic) than the “basement”.

The lowest thrust sheet, the Finnlandsveggen Nappe (Fig. 2), includes highly deformed gneisses and amphibolites of the Eskolabreen Complex. Granitic gneisses in this unit have been dated to 1749 ± 18, 1748 ± 21 and 1734 ± 5 Mya (Johansson & Gee 1999). One multigrain U-Pb zircon age of 2415 ± 34 My (Balashov et al. 1993) on a grey paragneiss has recently been shown to be of no geological significance due to mixing of older and younger zircons (Larionov, unpubl. data). Two samples of psammites from the Smutsbreen Formation, overlying the Eskolabreen Complex, have yielded nearly thirty detrital zircon Pb-evaporation ages dominated by three groups, 1190 - 1300 My, 1560 - 1710 My and 2560 - 2680 My, with a dominance in the Mesoproterozoic (Gee & Hellman 1996).

In the overlying Rekvika Nappe (Fig. 2), a basal granitic unit, the Instrumentberget gneiss, is overlain by conglomerates and quartzites of the Polhem Formation and metapelites with intercalated calcareous and quartzitic horizons of the Rittervatnet Formation. U-Pb zircon data on the Instrumentberget granitic gneiss yielded an age of 1735 ± 13 My and two granitic boulders in the overlying conglomerates yielded similar ages of 1739 ± 2 My and 1738 ± 5 My (Hellman et al. 1997), suggesting that some of the boulders were derived from the underlying “basement”. Additional, single-zircon, Pb-evaporation analyses from a quartzite higher up in the stratigraphy of the Polhem Formation yielded detrital zircons dominated by 1740 to 2040 My ages. Another quartzite within the same formation, collected in southern Ny-Friesland, has provided provenance ages of ca. 1320, 1510, 1870, 1970 and 2710 My (Hellman et al. 1997).

Granitic gneisses in the basal unit of the overlying Nordbreen Nappe (Fig. 2) also yield ca. 1750 My ages (data from six localities; Johansson et al. 1995). The granites contain both metaigneous and metasedimentary xenoliths, including large intercalations of the latter; together they compose the Bangenhuken Complex. The granites intrude overlying Vassfaret Formation sedi-

| Major element (wt%) | 1  | 2  | 3  | Trace element (ppm) | 1  | 2  | 3  |
|---------------------|----|----|----|---------------------|----|----|----|
| SiO₂                | 61.77 | 61.01 | 60.64 | U                  | 3  | 1  | 3  |
| Al₂O₃               | 15.80 | 15.85 | 15.66 | Th                 | 14 | 14 | 13 |
| Fe₂O₃               | 5.90  | 6.07  | 6.36  | Zn                 | 68 | 70 | 74 |
| MnO                 | 0.09  | 0.09  | 0.09  | Cu                 | 30 | 32 | 30 |
| MgO                 | 2.43  | 2.53  | 2.67  | Ni                 | 19 | 18 | 20 |
| CaO                 | 4.02  | 4.35  | 4.48  | Ba                 | 1478 | 1451 | 1450 |
| Na₂O                | 3.54  | 4.02  | 3.71  | Sc                 | 12 | 14 | 14 |
| K₂O                 | 5.22  | 5.04  | 4.95  | S                  | 188 | 238 | 194 |
| TiO₂                | 0.61  | 0.64  | 0.64  | Cr                 | 184 | 132 | 174 |
| P₂O₅                | 0.39  | 0.43  | 0.41  | V                  | 98 | 97 | 108 |
| Total               | 99.75 | 100.02 | 99.61 | La                 | 72 | 60 | 102 |
| Trace element (ppm) |     |     |     | Pb                 | 45 | 35 | 36 |
| Nb                  | 9    | 10   | 9    | Ga                 | 18 | 20 | 27 |
| Y                   | 25   | 27.6 | 26.8 | Co                 | 14 | 16 | 20 |
| Rb                  | 210  | 203  | 198  | Ce                 | 149 | 143 | 160 |
| Zr                  | 217  | 195  | 231  | Nd                 | 65 | 58 | 68 |
| Sr                  | 650  | 650  | 636  | As                 | 8  | 7  | 8  |
Late Archean basement in the Bangehuken Complex

Fig. 2. Northern Ny-Friesland, modified from Witt-Nilsson et al (1998).
ments. However, the Vassfaret Formation, from its middle to upper parts, has yielded ca. 1750 Mya detrital zircons. It has therefore been concluded (Hellman & Witt-Nilsson 1999) that the basal part of the formation, as described by Gayer & Wallis (1966), is part of an older pre-1750 Mya sedimentary succession (similar to that found in the xenoliths) and the middle to upper part is a younger sedimentary cover. Three samples collected in the middle to upper levels of the Vassfaret Formation yield 34 detrital zircon ages of 1735, 1920 - 2045 and 2540 - 2725 My (Hellman & Witt-Nilsson 1999).

At the base of the uppermost thrust sheet, the Dirksodden Nappe (Fig. 2), in the Sørbreen Formation, several horizons of a conspicuous fine-grained feldspar-megacrystic quartzofeldspathic rock have been observed. This rock has been interpreted to be either of volcanic (Gayer & Wallis 1966) or of mylonitic origin (Manby 1990; Witt-Nilsson 1999) and is dated to 1747 ± 11 My (Johansson, unpubl. U-Pb zircon age). The quartzites of the Sørbreen Formation have been sampled at three stratigraphic levels and the detrital zircons vary in age from 1720 to 2800 My (Hellman & Witt-Nilsson 1999).

Sample locality and geochemistry

During the 1994 field season, a previously unknown unit of magmatic rock was discovered in Ny-Friesland. It is located in a klippe ca. 500 m north-east of Femmilsjøen (Fig. 2), apparently at the same structural level as the base of the Bangenhukken Complex in the Nordbreen Nappe. The contact relationships between the “normal” ca. 1750 Mya granitic-gneisses of the Bangenhukken Complex and the new rock type are not exposed. However, it is clear that the rocks are exposed in a synform (Fig. 2) and the lower contact to the Rittervatnet Formation (Fig. 2) is deformed to a banded mylonite (Fig. 3b). The latter becomes more quartz-rich downwards and goes over to fine-banded (0.5 - 5 cm thick) feldspar-quartz, psammites and amphibolites of the Rittervatnet Formation (Fig. 3c). Below the contact these sediments are better preserved but extensively folded.
Late Archean basement in the Bangehuken Complex

Fig. 4. Thin-section of the quartz-monzonite. (a) Showing a reaction rim of hornblende (Hbl) around pyroxene (Px); also a zircon (Zr), and (b) showing a phenocryst of perthitic K-feldspar (Kfsp) in a K-feldspar dominated matrix with some plagioclase and quartz.

Analyse

| No. of | Size (10 - 6 m) | 12 | 19 | 22 | 47 | 2 | 6 |
|-------|----------------|----|----|----|----|---|---|
| crystals | (mg) | 100 - 120 | 70 - 80 | 100 - 150 | 60 - 80 | 150 | 100 |
| Weight (ppm) | 0.034 | 0.016 | 0.066 | 0.064 | 0.0052 | 0.0084 |
| 545 | 492 | 565 | 500 | 1448 | 693 |
| 304 | 266 | 310 | 269 | 795 | 370 |
| 0.98 | 0.89 | 0.33 | 3.2 | 8.4 | 7.6 |
| 15300 | 14400 | 44700 | 4000 | 5400 | 2800 |
| 7.170 | 7.672 | 7.036 | 7.179 | 7.631 | 6.831 |
| 12.37 | 12.08 | 12.23 | 12.05 | 12.51 | 11.90 |
| ±2σ | 12.37 | 12.08 | 12.23 | 12.05 | 12.51 | 11.90 |

Table 2. Conventional U-Pb zircon data from the quartz-monzonite. (Table continued next page.)

Norrish & Chappel (1977) with the trace elements analysed using pressed powder pellets. The samples were analysed by X-ray fluorescence spectrometry using a Philips PW1404 and X-unique spectrometer. Instrument calibration was controlled using international standards, internal synthetic standards and blanks.

The results are reported in Table 1. Total alkali contents (K₂O+Na₂O) are plotted versus silica (SiO₂) in discrimination diagrams by Cox et al. (1979), used for plutonic rocks by Wilson (1989). The data fall in the syeno-diorite field (Fig. 5a). In a P-Q diagram (Fig. 5b; Debon & Le Fort 1983) the data fall in the quartz-monzonite field which is approximately equivalent to syeno-diorite using the nomenclature by Streckeisen (1976). We have chosen here to refer to the rock as quartz-monzonite.

The best preserved part of the quartz-monzonite was sampled for both the chemical analyses and an U/Pb zircon study; xenoliths were avoided.

Three samples were chosen for geochemical analysis at the School of Geological and Computer Sciences, University of Natal, Durban, South Africa. Major and minor elements were analysed using the lithium tetraborate fusion method of Cox et al. (1979), used for plutonic rocks by Wilson (1989). The data fall in the syeno-diorite field (Fig. 5a). In a P-Q diagram (Fig. 5b; Debon & Le Fort 1983) the data fall in the quartz-monzonite field which is approximately equivalent to syeno-diorite using the nomenclature by Streckeisen (1976). We have chosen here to refer to the rock as quartz-monzonite.

The best preserved part of the quartz-monzonite was sampled for both the chemical analyses and an U/Pb zircon study; xenoliths were avoided.

*Corrected for mass fractionation (0.10 ± 0.04% per AMU).

*Corrected for common lead, blank and mass fractionation.
Zircon geochronology and results

The zircons were separated at the Department of Geology, Lund University, using standard procedures, involving crushing, Wilfley table and Franz magnetic separator. Zircons were selected for analysis by handpicking in alcohol under a microscope. The chemical preparation and mass spectrometer (TIMS) analyses were made at the Laboratory for Isotope Geology at the Swedish Museum of Natural History. Ion-microprobe analyses were made at the NORDSIM laboratory at the Swedish Museum of Natural History.

Conventional U-Pb method

The zircons are translucent, colourless to light yellow and short-prismatic, mostly with rounded surfaces; a few are long-prismatic and have a length to width ratio of more than 4:1. The most clear and pristine zircons were separated into six different size fractions by handpicking. One fraction (3) consists of long-prismatic zircons. Fraction 1, 2, 4, 5 and 6 were air-abraded using the method described by Krogh (1982).

The chemical preparation follows Krogh (1973) with dissolution of the zircons in HF+HNO₃ (10:1) in microcapsules (Parrish 1987) placed in stainless steel bombs at 205 °C. Fractions 1 to 4 were spiked with a $^{208}\text{Pb}/^{233}\text{U}/^{235}\text{U}$ tracer, whereas fraction 5 and 6 where spiked with a $^{205}\text{Pb}/^{233}\text{U}/^{235}\text{U}$ tracer. U and Pb were extracted using ion exchange in HCl and analysed on a Finnigan MAT 261 mass spectrometer. The common lead correction follows Stacey & Kramers (1975). The Pb analyses are corrected for fractionation by $0.10 \pm 0.04 \%$/mass unit and U according to measured $^{233}\text{U}/^{235}\text{U}$ ratios.

The age and error calculations are made using PBDAT (Ludwig 1991) and Isoplot (Ludwig 1998). The six analysed fractions (Table 2) are ca. 6 - 10 % discordant and a combined regression line through the six analyses yields an upper intercept age of 2764 ± 33 My and a lower intercept of 1207 ± 290 (2 sigma) My with a MSWD of 5.2 in Fig. 6a.

U-Pb ion-microprobe method

Handpicked zircons were cast in epoxy and then polished until a cross-section was obtained

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Table 2: U-Pb ages and errors

| Fraction | $^{206}\text{Pb}/^{238}\text{U}$ ratio | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | Error corr. |
|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-------------|
| 1        | 0.4843           | 0.315           | 0.1852          | 0.083           | 2700 ± 1       | 0.967       |
| 2        | 0.4770           | 0.433           | 0.1836          | 0.091           | 2691 ± 1       | 0.979       |
| 3        | 0.4813           | 0.358           | 0.1843          | 0.067           | 2692 ± 1       | 0.983       |
| 4        | 0.4758           | 0.185           | 0.1837          | 0.074           | 2687 ± 1       | 0.929       |
| 5        | 0.4881           | 0.114           | 0.1859          | 0.044           | 2706 ± 1       | 0.933       |
| 6        | 0.4710           | 0.187           | 0.1832          | 0.056           | 2682 ± 1       | 0.959       |

* Error correlation.
The analyses were made on a Cameca IMS 1270 ion-microprobe with high sensitivity and high mass-resolution. The analytical procedure follows Whitehouse, Cleasson et al. (1997) and Whitehouse, Kamber et al. (1999). Data were calibrated using Geostandards 91500 (Wiedenbeck et al. 1995) and if necessary corrected for initial lead using the Stacey & Kramers (1975) model. An external error, based upon the standard measurements during a specific analytical session, was propagated onto the observed errors from the unknowns. Errors in $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are observed errors, which generally exceed counting statistical errors. The errors are given at the 1 sigma confidence level (Table 3) and the calculated intercept ages are at the 2 sigma level (Fig. 6b).

Electron backscatter images (Fig. 7) were used to select domains to be analysed by the ca. 30 µm diameter spot of the ion-microprobe. Different domains of the zircons were analysed (Fig. 7) and

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**Table 3.** Ion-micriprobe zircon data from the quartz-monzonite. Errors on ages and ratios are at the 1 sigma confidence level and corrected for common lead (Stacey & Kramers 1975) if necessary. The data is calibrated using Geostandard 91500 (Wiedenbeck et al. 1995). Analyses written in italics have not been calibrated for Geostandard 91500 (see text). (Table continued next page.)

| Grain* (spot) | U (ppm) | Pb (ppm) | Th (ppm) | Th/U (means) | fU (% Total) | $^{207}\text{Pb}/^{206}\text{Pb}$ | ± σ (%) | $^{207}\text{Pb}/^{235}\text{U}$ | ± σ (%) | $^{208}\text{Pb}/^{235}\text{U}$ | ± σ (%) |
|---------------|---------|----------|----------|--------------|-------------|----------------|--------|----------------|--------|----------------|--------|
| 02a*          | 506     | 381      | 493      | 0.975        | 0.00        | 0.18530        | 0.72   | 13.885         | 5.21   | 0.54345        |
| 02b           | 431     | 295      | 416      | 0.965        | 0.00        | 0.19190        | 1.26   | 12.867         | 7.17   | 0.48613        |
| 03a*          | 2272    | 1289     | 220      | 0.097        | 0.00        | 0.18480        | 0.45   | 11.996         | 5.83   | 0.47079        |
| 25a           | 489     | 297      | 337      | 0.689        | 0.01        | 0.18680        | 0.25   | 11.155         | 2.89   | 0.43311        |
| 25b           | 789     | 447      | 360      | 0.457        | 0.02        | 0.18339        | 0.66   | 10.918         | 1.91   | 0.43181        |
| 26a           | 280     | 182      | 244      | 0.868        | 0.01        | 0.18830        | 0.30   | 11.550         | 2.89   | 0.44846        |
| 26b           | 556     | 302      | 217      | 0.390        | 0.13        | 0.17560        | 0.33   | 10.138         | 2.87   | 0.41872        |
| 26c*          | 802     | 462      | 308      | 0.384        | 0.22        | 0.17787        | 0.66   | 11.115         | 4.02   | 0.45321        |
| 27a           | 325     | 176      | 209      | 0.644        | 0.02        | 0.17930        | 0.41   | 9.8336         | 1.50   | 0.39777        |
| 28a           | 518     | 307      | 285      | 0.549        | 0.01        | 0.18520        | 0.29   | 11.244         | 2.87   | 0.44032        |
| 29a           | 246     | 150      | 185      | 0.752        | 0.01        | 0.18560        | 0.53   | 10.975         | 2.90   | 0.42887        |
| 29b           | 285     | 189      | 156      | 0.548        | 0.01        | 0.18840        | 0.48   | 12.772         | 2.98   | 0.49167        |
| 30a           | 431     | 260      | 286      | 0.663        | 0.03        | 0.19058        | 0.60   | 11.561         | 1.56   | 0.43996        |
| 30b*          | 284     | 177      | 173      | 0.610        | 0.02        | 0.18210        | 0.44   | 11.557         | 1.53   | 0.45949        |
| 31a           | 232     | 145      | 184      | 0.730        | 0.00        | 0.17640        | 0.34   | 9.9969         | 2.87   | 0.41102        |
| 31b*          | 282     | 192      | 223      | 0.791        | 0.01        | 0.18490        | 0.30   | 12.308         | 1.56   | 0.48279        |
| 31c*          | 265     | 177      | 159      | 0.599        | 0.02        | 0.18760        | 0.32   | 12.800         | 1.48   | 0.49484        |
| 32a           | 340     | 262      | 295      | 0.866        | 0.06        | 0.18817        | 0.58   | 14.630         | 5.75   | 0.56387        |
| 32b           | 217     | 164      | 202      | 0.931        | 0.06        | 0.18056        | 0.79   | 13.811         | 6.41   | 0.55478        |

*a Asterisks denote that the analyse point is used in the combined age calculation (Fig 5b) and fulfill the criteria of being less than ± 10 % discordant and have U/Pb ages with less than 6 % error.
the results of all nineteen spots are given in Table 3. A discordant standard zircon (91500) was used during one of the analytical sessions, and it was therefore not possible to calibrate some of the data. These data are written in italics (Table 3) and not used in the age calculations. However, the observed $^{207}\text{Pb}/^{206}\text{Pb}$ ages are not significantly different from the calibrated ratios. If all calibrated data (Table 3) are used, an upper intercept age is calculated to be $2705 \pm 31\text{ My}$ with a MSWD of 8.0. In this paper we prefer to put more confidence in the data that are less than 10% discordant at the 2 sigma level and have U/Pb ratios with less than 6% errors (Table 3). These data are marked with asterisks in Table 3 and yield an upper intercept of $2709 \pm 28\text{ My}$ with a MSWD of 1.7 (Fig. 6b).
**Interpretation of isotope data**

The conventional (TIMS) method yields high analytical precision for each data point. However, if the obtained results are discordant, it is hard to make a confident interpretation of the data because they may represent multiple zircon growth phases in single crystals or even different zircon age populations. On the other hand, ion-microprobe data have generally poorer analytical precision, but the results represent a small domain (ca. 30 µm) of the zircons. This makes it possible not only to date different zircon populations in one sample, but also to date different domains of one zircon separately. The chances of mixing different age domains and zircon populations are less likely with an ion-microprobe; therefore, each analysis has greater geological significance.

In the analysed rock some of the zircons are prismatic, with typical magmatic morphology; many have rounded surfaces. The consistent age data from cores and rims suggest that the zircons were formed during a single magmatic event, but many of the crystals have probably been subject to different degrees of resorption perhaps due to the Caledonian amphibolite facies metamorphism.

The two methods yield the results of 2764 ± 33 Mya (Fig. 6a) for the conventional (TIMS) and 2709 ± 28 Mya (Fig. 6b) for the ion-microprobe. A high MSWD of 5.2 of the regression lines indicates a large scatter around the best-fit line for the conventional (TIMS) method. Mixing of two zircon populations in combination with Pb-loss could explain the observed data scatter, but the ion-microprobe data were not able to identify different zircon populations. The most likely explanation for the scatter of the conventional (TIMS) data and the discordancy of the zircons is a complex history of Pb-loss (more than two stages). In western Ny-Friesland two tectonostratigraphic events are known: one associated with the intrusion of the ca. 1750 Mya granitic gneisses and a second in Caledonian time associated with transgression under high amphibolite facies conditions. It is possible that both these events and probably also a recent Pb-loss have effected the zircons. The ion-microprobe data are less discordant and scatter less (MSWD of 1.7; Fig. 6a, b). Therefore, we regard the ion-microprobe data to be more reliable than the conventional (TIMS) data. Consequently, we consider 2709 ± 28 My (Fig. 6b) to be the best estimate of the age of the quartz-monzonite.

**Summary and discussion**

The tectonostratigraphy in western Ny-Friesland includes four thrust sheets, each composed of a “basement” complex overlain by younger metasedimentary rocks. The “basement” has previously been shown to be fairly homogenous, dominated by ca. 1750 My old granitic gneisses (Johansson et al. 1995) and some minor sedimentary lenses including xenoliths (Gayer & Wallis 1966; Witt-Nilsson et al. 1998). This study shows that the basement, at least in the Nordbreen Nappe, also includes Late Archean quartz-monzonites of ca. 2710 My age.

Geochronological studies of detrital zircons in the metasediments from each of the thrust sheets (Hellman et al 1997; Hellman & Witt-Nilsson 1999) has shown that the provenance for these sediments was dominated by Palaeoproterozoic bedrock of 1700 - 1750 My, 1850 - 2050 My and late Archean 2500 - 2800 My ages. In the Rekvika Nappe, conglomerate boulders in the basal parts of the formation have been dated to 1740 Mya and the same age was obtained from the underlying basement. Apparently, ca. 1750 Mya basement contributed directly to the cover sediments; similarly, it is probable that some of the late Archean detrital zircons found in the metasediments were derived from the Late Archean basement reported here from the Nordbreen Nappe. It seems likely that further analyses of the western Ny-Friesland basement may yield evidence of 1850 - 2050 Mya bedrock, into which the younger Palaeoproterozoic granitoids were intruded.

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