New evidence of basement in the Svalbard Caledonides: Early Proterozoic zircon ages from Ny Friesland granites

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The Old Red Sandstones of Svalbard overlie a variety of folded, thrust and more or less metamorphosed successions of Early Palaeozoic and Late Proterozoic age. Some older rocks have been indicated locally by isotopic age-determination methods. In Ny Friesland, northeastern Spitsbergen, the younger sedimentary rocks of the Hecla Hoek Complex closely resemble strata of similar age (ca. 800–470 Ma) in East Greenland. They pass downwards, apparently concordantly (though contacts are reported to be faulted in some areas), into metasedimentary rocks which increase in metamorphic grade with depth; the latter, in their lower parts (Harkerbreen and Finnlandsveggen Groups of the Atomfjella Complex) include a variety of granitic gneisses. Zircons from a granite and gneissic granite of the Harkerbreen Group have been analysed by the U-Pb and $^{207}Pb/^{206}Pb$ single crystal methods and have yielded ages of ca. 1700–1800 Ma. One of these granites intrudes metasediments, indicating an Early Proterozoic age for at least part of the Harkerbreen Group. These ages imply that significant segments of pre-Caledonian crystalline basement are incorporated in the base of the Caledonian pile in northeastern Spitsbergen. They enhance comparisons of this terrane with East Greenland and contrast markedly with recent results from northwestern Spitsbergen, where Grenvillian intrusion and latest Proterozoic high P/T tectonothermal activity have been identified. These fundamental differences in the character of the pre-Devonian rocks on Svalbard indicate that terrane accretion may have involved displacements of many hundreds if not thousands of kilometres.

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Svalbard, located in the northwestern corner of the Barents Sea Shelf, provides critical evidence for understanding the Phanerozoic and Precambrian history of the Arctic. The Caledonian complexes, exposed beneath Old Red Sandstone molasse and younger Palaeozoic cover, contain a variety of rock units that were part of an Early to Mid-Proterozoic basement to the Late Proterozoic and Early Palaeozoic successions within the fold belt. Detailed analysis of these older elements is essential if we are to succeed in reconstructing the Caledonian history and distinguishing between alternative hypotheses for terrane accretion (Harland 1985).

The first comprehensive accounts of Svalbard geology (Nathorst 1910), based on the pioneering studies of Blomstrand (1864), Nordenskiöld (1863) and De Geer (1909), separated an unmetamorphosed succession of presumed Early Palaeozoic and Late Proterozic age, the 'Hecla Hoek Formation', from the underlying 'Urgebirge' (basement granitic gneisses and schists). Subsequent investigations by Kulling (1932) provided the basis of our understanding of the 'Hecla Hoek' stratigraphy, with the identification of Cambrian, Vendian and underlying Riphean strata. These early studies, however, found no unconformity separating basement from cover and closer examination showed the contact zones to be transitional (Odell 1927; Fleming & Edmunds 1931). Metamorphic grade increases downwards into the high-grade rocks and both compositional banding and penetrative foliations were found to be concordant. Migmatization of lower structural levels is widespread in some regions. These observations led to the hypothesis (Harland & Wilson 1956; Harland 1959) that a huge Late Proterozoic succession (ca. 15 km thick) underlay the Vendian strata in Ny Friesland and that any basement, if present, was Caledonized beyond recognition.

The first isotopic age-determination studies provided general support for this hypothesis (Krasil'ščikov et al. 1964; Gayer et al. 1966), though most of the ages were obtained by the K–Ar method on micas. A few K–Ar determinations of hornblendes and Rb–Sr mineral and whole-rock studies indicated the possibility of pre-Caledonian elements in the orogen (not, however, in Ny Friesland), but the data could be variously interpreted.

Soviet geologists (Sokolov et al. 1968; Krasil'ščikov 1973, 1979) have generally favoured the interpretation that the higher grade complexes are indeed basement. Comparison of the Caledonian deformed fossiliferous Late Riphean and Cambro-Ordovician successions with similar strata in the Soviet Union and Greenland provided a basis for inferring that the underlying higher grade rocks were pre-Caledonian basement. Some older isotopic ages from areas other than Ny Friesland have been obtained (Gayer et al. 1966; Gorochov et al. 1977; Turchenko 1987), but the data are difficult to interpret and in some cases have not been presented in sufficient detail to allow critical assessment. The lack, until very recently, of modern isotopic age-determination studies of the potential basement elements, has allowed a wide range of speculation and many hypotheses.

This paper presents evidence that a substantial part of northeastern Svalbard is of Early Proterozoic origin. It complements studies by Peucat et al. (1989), further west, where Grenville and latest Proterozoic tectonothermal activity have been identified. After presentation of the new data, we briefly discuss evidence for other basement units within the Caledonides on Svalbard.

Caledonian terranes

The Old Red Sandstones on Svalbard occur in a N-trending basin (Friend & Moody-Stuart 1972) delimited by major high-angle faults, the Billefjorden Fault in the east and the Raudfjorden Fault in the west (Fig. 1). A third important fault, the Breibogen–Bockfjorden Fault, defines the eastern margin of a subordinate horst of crystalline rocks in the western part of the basin. The Caledonian complexes that are separated by these structures are notably dissimilar in their stratigraphies and tectonothermal histories; these differences have been explained by hypotheses that involve variable amounts of transcurrent motion on the above-mentioned faults (Harland & Wright 1979; Birkenmayer 1981).

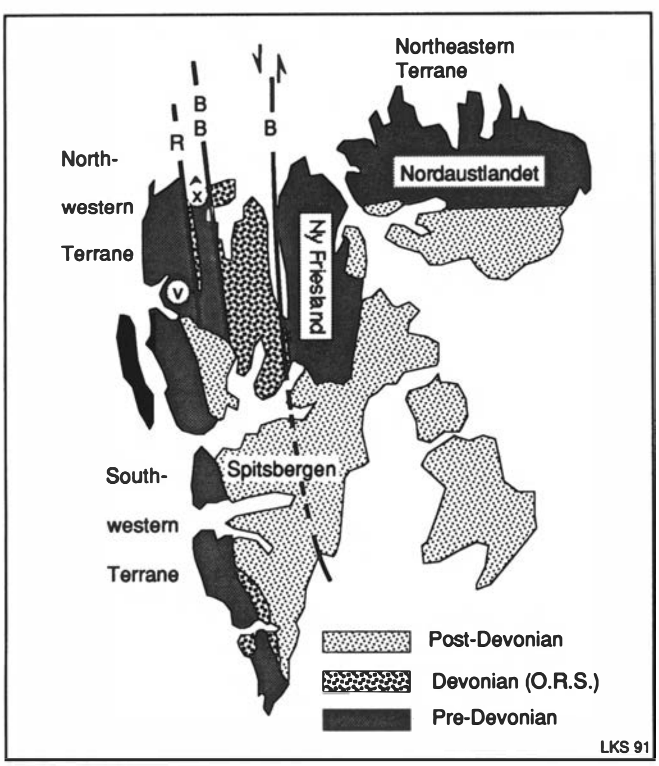

Fig. 1. Spitsbergen bedrock geology: three main terranes with contrasting stratigraphies and tectonothermal histories.

At least three Caledonian terranes are readily identifiable (Fig. 1). The largest of these, the Northeastern Terrane, is the primary concern of this paper. Lying to the east of the Billefjorden Fault and unconformably overlain by Culm sandstones, it contains well-preserved Cambro-Ordovician successions underlain by Vendian tillites, Late Proterozoic carbonates and clastics and a variety of high-grade metamorphic rocks in the lowermost structural levels. By contrast, the Caledonian rocks to the west of the Old Red Sandstone basin (composing the Northwestern Terrane) are dominated by schists and marbles, variably metamorphosed, partly migmatized and apparently unfossiliferous. A subordinate anomalous part of this terrane in Biskayerhalvøya (Fig. 1) contains a high-grade unit (the Richarddalen Complex) of eclogite-bearing gneisses, augen granites and corona gabbros (Gee 1966) that have yielded Grenvillian and Late Proterozoic U–Pb radiometric ages (Peucat et al. 1989).

South of the Northwestern Terrane, Tertiary folding and faulting influence the Caledonian rocks along the western coast of Spitsbergen. Deciphering the Caledonian and pre-Caledonian history is more difficult in this, the Southwestern Terrane, which is most probably composite. Nevertheless, it is clear that a Late Proterozoic succession more variable than in the northeast is preserved, with a substantial mafic volcanic and hypabyssal component. Most important to the discussion of the terrane relationships (Gee 1986) has been the identification of a fault-bounded blue-schist and eclogite association (Horsfield 1972; Hirajima et al. 1988), unconformably overlain by Late (perhaps Middle) Ordovician carbonates (Armstrong et al. 1986; Kanat & Morris 1988) and then turbidites, the latter probably reaching up into the Lower Silurian (Scrutton et al. 1976). Phengites in the high P rocks have yielded K–Ar ages of ca. 470 Ma (Horsfield 1972) and ^{40}Ar–^{39}Ar and Rb–Sr ages of ca. 460–470 Ma (Dallmeyer et al. 1990). These cooling ages indicate that the high P/T metamorphism must have started in the Early Ordovician or earlier, i.e. have been contemporaneous with deposition in the Northeastern Terrane.

Ny Friesland

The Caledonian rocks of Ny Friesland (Harland 1959) and Nordaustlandet (Flood et al. 1969; Ohta 1982) compose the Northeastern Terrane. A major synclinorium with N-trending axis through Hinlopenstretet dominates the central parts of the area. The youngest strata (Fortey & Bruton 1973; Fortey 1980), of early Llanvirn age, are preserved along Ny Friesland's northeastern coast. Further to the southeast on Edgeøya, a drillhole at Raddedalen (Shvartz 1985) is reported to have penetrated about 1800 m of little deformed Silurian and Ordovician strata that may also be a part of this terrane. In Ny Friesland (Harland & Wilson 1956), the succession has been divided into three supergroups, the Hinlopenstretet, Lomfjorden and Stubendorffbreen, all included within the Hecla Hoek Complex. Our new evidence indicates that at least the lower part of the Stubendorffbreen Supergroup contains a basement complex to the Caledonian successions, referred to as the Atomfjella Complex (Atomfjella Series of Krasil'ščikov 1973, 1979).

The Vendian (including tillites), Cambrian (clastics and carbonates) and Lower Ordovician (largely carbonates, with shales at highest levels) successions of the Hinlopenstretet Supergroup and the underlying Late Proterozoic carbonates and clastics of the Lomfjorden Supergroup are closely comparable with Laurentian platform strata in East Greenland, Scotland and the northwestern Appalachians (Swett 1981; Knoll & Swett 1985; Knoll et al. 1986). Similarities also exist with the Late Riphean successions along the eastern margin of the East European platform (Golovanov & Raaben 1967). The similarities with Laurentia are so striking that it is probable that Svalbard's Northeastern Terrane formed a part of the Greenland continental margin at least during the Late Proterozoic and Early Palaeozoic. The strata in the upper two supergroups are cylindrically folded on N-trending axes with associated high-angle W-dipping cleavage. Quartzites in the base of the Lomfjorden Supergroup overlie phyllites of the Planetfjella Group, apparently concordantly (Wallis 1969). Metamorphic grade increases downwards through this ca. 4000 m thick unit to amphibolite facies at the base, where Planetfjella schists are intercalated and isoclinally folded with underlying units of the Harkerbreen Group (Gayer & Wallis 1969). The latter group in northern Ny Friesland (Gayer 1969) has yielded the new evidence of 1700–1800 Ma granitic protoliths.

The Harkerbreen Group is dominated by quartzo-feldspathic gneisses of uncertain origin and a variety of metasediments, largely psammitic, and locally including some characteristic diamictites. The quartzo-feldspathic rocks are generally penetratively foliated and have been interpreted to be mostly of volcanic or volcaniclastic origin (Harland et al. 1966). Early foliations are isoclinally folded and refolded and arched by a major structure, the Atomfjella antiform, a fold of apparently the same generation as the Hinlopenstretet synclinorium. A variety of metabasic rocks characterize the Harkerbreen Group, some concordant within the gneissosity, others obviously intrusive (Gayer 1969). Mafic rocks (Mesozoic and younger intrusions excepted) are notable for their near absence in the Planetfjella Group and overlying units (Bayly 1957; Wallis 1969). One of us (Alexander Tebenkov) has found mafic effusive units locally near the top of the Planetfjella Group, and Fairbairn (1933) reported epidiorites from the Veteranen Group (Lower Middle Hecla Hoek) in the type area. Nevertheless, the strata overlying the Atomfjella Complex clearly contain a much smaller component of mafic magmatism than the underlying units. Thus, despite the concordance of the contact between the Harkerbreen and the Planetfjella and intimate interfolding of these units, the distribution of these mafic rocks, particularly the demonstrable intrusions, suggests the hypothesis that the Harkerbreen is indeed part of an ancient basement to the Caledonian cover.

New work

Many of the quartzo-feldspathic gneisses in the Harkerbreen Group are coarse grained and of granitic appearance (Blomstrand 1864; Bayly 1957) and igneous chemistry (Manby 1990). Gayer (1969, p. 17) described one locality in the Femmilsjöen area (Fig. 2) where a 'granodiorite' intrudes psammitic metasediments and the plutonic origin is not in doubt. All the other gneisses have been interpreted as metavolcanites. This and other granitic gneisses were chosen for U–Pb zircon age-determination studies. In 1988, two of us (Alexander Krasil'ščikov and Alexānder Tebenkov), on request, collected a variety of granitic rocks from northern Ny Friesland, including the granodiorite mentioned above. Zircons have been separated from the latter and one gneissic granite (located ca. 5 km northeast of Rekvika on Verlegenhukflya) and analysed by Björn Schouenborg. Single zircons from both samples have been analysed by the $^{207}Pb/^{206}Pb$ method by Jean-Jacques Peucat in Rennes. The samples, methods and results are described below.

Sample descriptions

Sample 89141. – About 35 kg of somewhat weathered aplitic granite was sampled from Brennkollen on the south side of Femmilsjöen from the northern end of Gayer's (1969) 'granodiorite'. The main constituents are potassium feldspar, oligoclase, perthite, quartz and greenish-brown biotite; accessories include opaque phases, apatite, zircon and sphene. Myrmekitic textures and sutured quartz grain boundaries are common.

Sample 89142. – About 40 kg of unweathered reddish-grey, gneissic granite was sampled from the northern part of Mosselhalvöya, about 100 m south of Flåtan on Verlegenhuksflya. The gneiss is coarse-grained with potassium feldspar augen and albite-oligoclase, quartz and biotite; accessories include opaque minerals, apatite, zircon, sphene and fluorite.

Zircon morphology

Whole zircon grains were studied under a polarizing microscope and polished thin sections of the zircons, 25 microns thick, were examined under a scanning electron microscope (Fig. 3).

Sample 89141. – The zircon concentrates were more than adequate in most size-fractions under 106 microns. Many

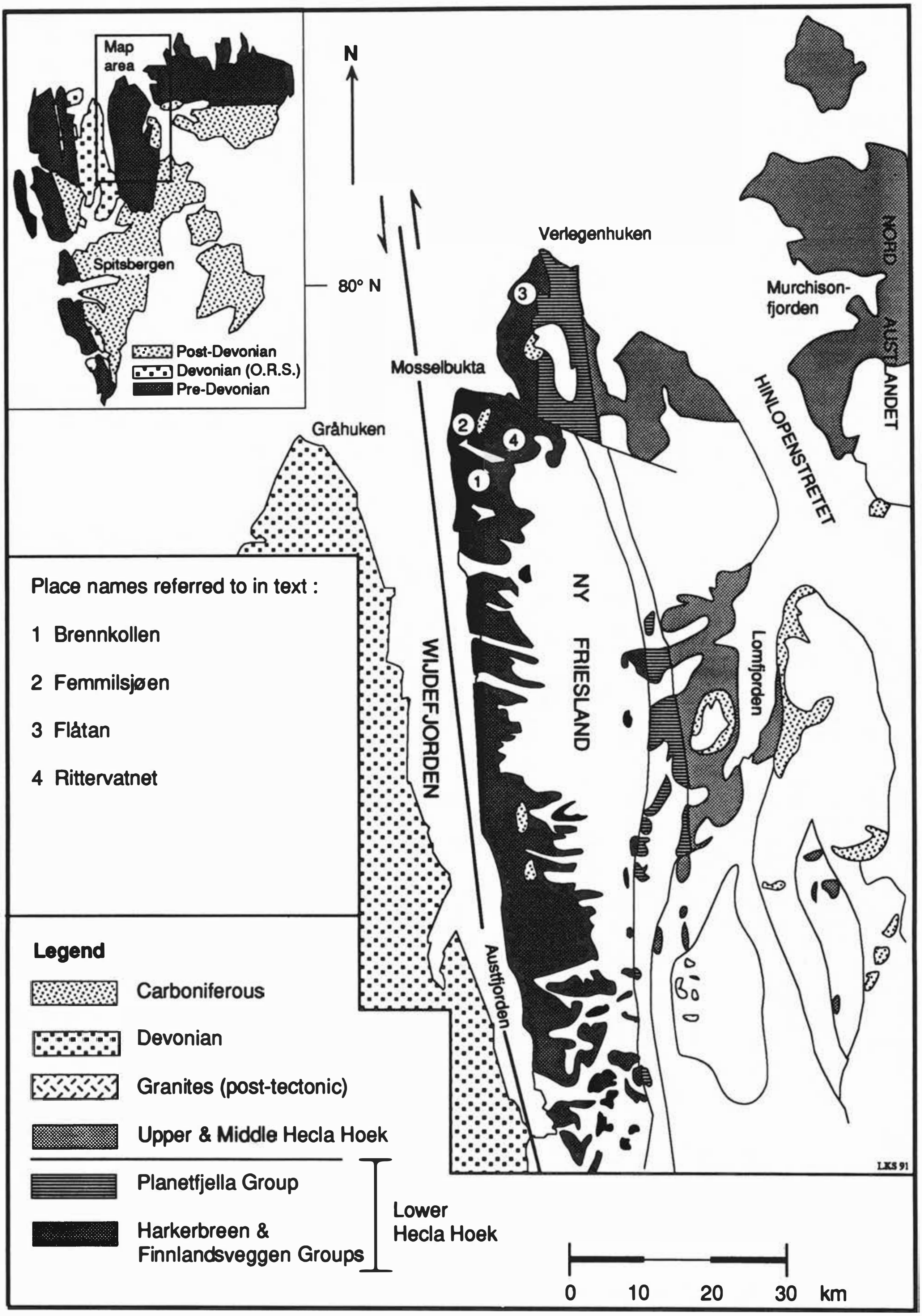

Fig. 2. Ny Friesland geology (from Harland 1959).

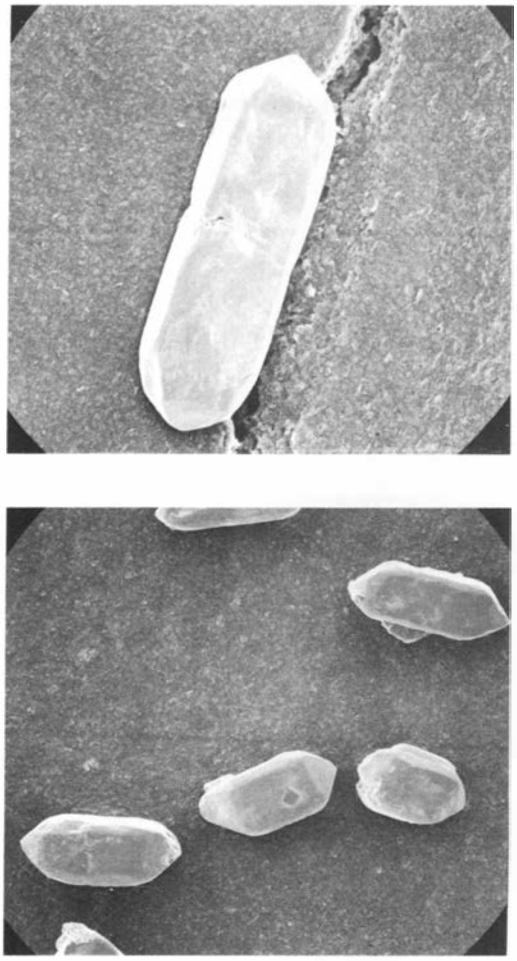

Fig. 3. A–B. Scanning electron microphotographs of the analysed zircons (A, above) from sample 89141 and (B, below) from 89142. The length of the zircons is approximately 200 μm.

Table 1. The Hecla Hoek succession in Ny Friesland (after Harland 1985).

Hinlopenstretet Supergroup (Upper Hecla Hoek)

Oslobreen Group (1.2 km)
Valhallfonna Fm (Limestone) Arenig-Llanvirn
Kirtonryggen Fm (limestone and dolomite) Arenig
Tokommane Fm (dolomite and sandstone) Caerfai

Polarisbreen Group (0.8 km)
Drakoisen Fm (shale)
Wilsonbreen Fm (tillite) Late Varangian
Elbobreen Fm (shale) Early Varangian

Lomfjorden Supergroup (Middle Hecla Hoek)

Akademikerbreen Group (2 km)
Backlundtoppen Fm (dolomite and shale)
Draken Conglomerate Fm (Early Sturtian)
Svanbergfjellet Fm (limestone and dolomite)
Grusdievbreen Fm (limestone)

Veteranen Group (3.8 km)
Oxfordbreen Fm (shales)
Glasgowbreen Fm (greywacke and quartzite)
Kingbreen Fm (quartzite and shale with greywacke and carbonate)
Kortbreen Fm (quartzite and limestone)

Stubendorffbreen Supergroup (Lower Hecla Hoek)

Planetfjella Group (4.8 km)
Vildalen Fm (semipelite, psammite and quartzite)
Flåen Fm (semipelite, psammite and quartzite with acid pyroclastics)

Harkerbreen Group (4.1 km)
Sørbreen Fm (quartzite and psammite)
Vassfaret Fm (semipelite, psammite and amphibolite)
Bangenhuk Fm (feldspathite, psammite and amphibolite)
Rittervatnet Fm (psammite, semipelite and amphibolite)
Polhem Fm (quartzite and amphibolite)

Finnlandsveggen Group (2.7 km)
Smutsbreen Fm (semipelite and marble)
Eskolabreen Fm (feldspathite, semipelite and amphibolite)

zircons are fragmented. Most grains are brown and bipyramidal prismatic in form. Length/width ratios are between 1 and 2, but a few light-coloured to clear crystals have a greater ratio. Cracks and opaque inclusions are common in all types and the crystals frequently contain optically distinct cores.

Sample 89142. – The zircon concentrates were more than adequate in all fractions except <45 microns. The grains are light brown in colour and bipyramidal prismatic in form. Length/width ratios are around 2 to 3. Inclusions and optically distinct cores are common.

Analytical methods

Conventional U–Pb analyses. – The sample preparation and the U–Pb analyses were carried out at the Laboratory of Isotope Geology at the Museum of Natural

Table 2. U–Pb analyses for sample 89141 (Brennkollen aplitic granite).

No. on Fig. 4	Zircon fraction	Concentrations in ppm U	Pb_{rad}	^{204}Pb	Atomic ratios and $^{207}Pb/^{206}Pb$ model age $^{206}Pb/^{204}Pb$ a)	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$ Age (Ma)
a	<45	2690	447	0.120	2930	0.1392	0.15628 ± 38	2.1188 ± 78	0.09833 ± 25	1593
b	45–74	2480	416	0.150	2900	0.1487	0.15667 ± 56	2.0911 ± 102	0.09680 ± 30	1563
c	74–106	2815	480	0.135	3150	0.1351	0.16076 ± 48	2.1817 ± 89	0.09843 ± 25	1596
d	106–150	1700	328	0.065	3400	0.1225	0.18337 ± 44	2.5614 ± 146	0.10131 ± 47	1648
e	>150	2485	449	0.125	2910	0.1257	0.17182 ± 41	2.3421 ± 136	0.09886 ± 49	1603
f	45–74 ab	3855	651	0.140	3780	0.1378	0.15915 ± 38	2.1236 ± 66	0.09677 ± 18	1563
g	74–106 ab	2815	491	0.120	3250	0.1349	0.16499 ± 38	2.2197 ± 60	0.09758 ± 14	1578

a) $^{206}Pb/^{204}Pb$ corrected for blank and mass discrimination; all other atomic ratios have been corrected for initial lead. Errors are given as least significant digits at the 95% confidence level.
ab) abraded, as described by Krogh (1982).

History in Stockholm, Sweden. The zircon separation followed standard procedures, including the use of heavy liquids and magnetic separator. The zircons were divided into five size-fractions (Tables 2 and 3). Two of these were air-abraded in attempts to improve their concordancy. Clear and unfractured zircon grains were then handpicked under the microscope from each of the seven fractions for further analysis.

Chemical procedures mainly followed those described by Corfu & Stott (1986). Uranium and lead isotope ratios were measured on a Finnigan MAT 261 mass spectrometer. Calculation of the ages is based on a procedure similar to that of Ludwig (1980). The analytical errors are given in Tables 2 and 3. The decay constants recommended by Steiger and Jäger (1977) were used. Corrections for mass fractionation were 0.12% AMU for lead and uranium. The total lead blank was 0.6 ng lead for both samples. Common lead corrections according to the model of Stacey and Kramers (1975) were $^{206}Pb/^{204}Pb = 15.96$, $^{207}Pb/^{204}Pb = 15.36$ and $^{208}Pb/^{204}Pb = 35.60$ for sample 89141 and $^{206}Pb/^{204}Pb = 15.81$, $^{207}Pb/^{204}Pb = 15.33$ and $^{208}Pb/^{204}Pb = 35.45$ for sample 89142.

Single zircon analyses. – Analyses of single zircons were performed on a Cameca TSN 206 mass spectrometer following the procedure proposed by Kober (1986, 1987). Correction for mass fractionation was 0.10% AMU. The common lead used for corrections had an isotopic composition from 1700 Ma, following the Stacey and Kramers (1975) model. We have selected several typical grains from each sample, none with rounded cores, but some with possible euhedral cores.

Results of U–Pb studies

Sample 89141. – The data points from this sample scatter somewhat and do not define a true 'isochron'. The points are discordant (Fig. 3) and the abrasion did not give any major change in the discordancy. The MSWD calculated with the Ludwig (1980) model is 58. This indicates that the scatter of the data points cannot be caused entirely by analytical errors. A line of regression for all the data points calculated according to the Ludwig model gives an upper intercept age of 1809^{+165}_{-122} Ma.

Sample 89142. – The data are slightly less discordant than those for sample 89141 and the discordancy is notably decreased by the abrasion. A modified Ludwig model is therefore used for the regression of all the data and yields an upper intercept age of 1778^{+53}_{-45} Ma.

Lower intercept ages for both samples are in the interval of 300 to 330 Ma with an error of about 50 Ma.

Samples 89141 and 89142 together: All the data from both samples are plotted on Fig. 4. A common regression line for the granites defines an age of 1778 ± 30 Ma.

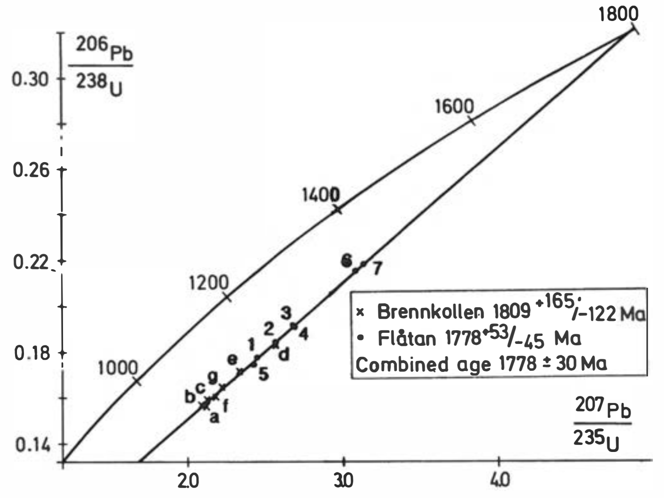

Fig. 4. Concordia diagram for zircons, from both the Brennkollen (89141) and Flåtan (89142) granitic rocks. The discordia line is calculated for fourteen zircon fractions. Analytical data are given in Tables 2 & 3.

Results of single zircon studies

Seven single zircons were analysed from both samples 89141 and 89142. Several grains from 89141 provided the oldest $^{207}Pb/^{206}Pb$ ages, around 1670 Ma and 89142 at around 1695 Ma (see Table 4 and Fig. 5). All seven zircon grains yield $^{207}Pb/^{206}Pb$ ages that are about 100 Ma younger than U–Pb ones.

Interpretation

Two main alternatives can be entertained to explain the differences between the ages obtained by the U–Pb and Pb–Pb methods. The first hypothesis considers the Pb–Pb results to be minimum ages from which we have not obtained the oldest values for the time of intrusion. This is consistent with the existence of lower intercepts around 300 Ma, defined by the U–Pb data.

The second hypothesis is suggested by the occurrence of cores in the zircons. A few crystals in sample 89141 contain rounded cores (probably inherited) and a large number of subeuhedral cores which probably crystallized early from the granitic magma. Similarly, 89142 contains a very few crystals with rounded or irregularly shaped cores and a lot of euhedral cores; the zoning strongly suggests a response to variations in the contents of some trace elements during crystal growth. The presence of inherited cores in zircons generally is demonstrable in the U–Pb system by complex models; for example by the existence of two more or less meaningful intercepts, or by some scattering of data in the concordia diagram, with an upper intercept older than the true age of the magma. This second hypothesis is favoured by the fact that the data in the U–Pb diagram scatter somewhat for sample 89141. In addition, the ages appear to be older by ca. 50 Ma for both samples when abraded fractions are taken into account, favouring the possibility of inherited cores. If this is the case, the single zircons would provide

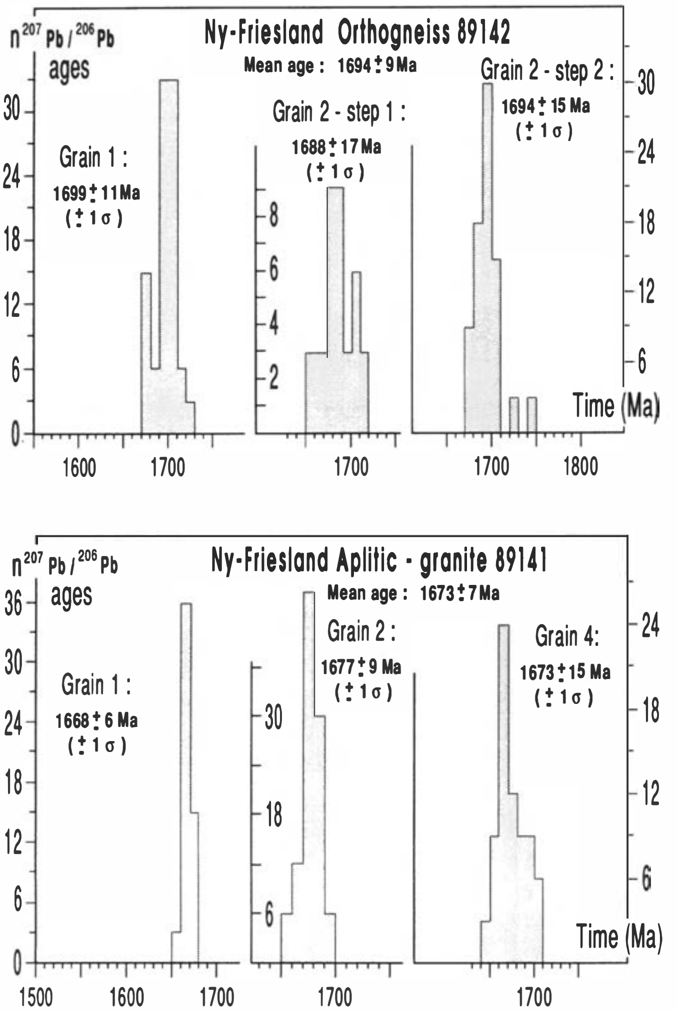

Fig. 5. Frequency histograms of oldest $^{207}Pb/^{206}Pb$ ages determined for single grains of zircon by the evaporation method (Kober 1986, 1987).

the more confident ages, because they have been obtained from crystals without optically visible cores or with only euhedral cores.

Independent of which interpretation is preferred, a 1700–1800 Ma old intrusion age is indicated by both methods. Furthermore, this conclusion is supported by a third dating of a gneiss from near Femmilsjöen, reported to be of metavolcanic origin (Gayer 1969), which provided a $^{207}Pb/^{206}Pb$ age of 1707 ± 5 Ma from a single zircon, the latter containing no visible core (work in progress, J.J.P.)

Implications

The data presented above, indicating an age of ca. 1700–1800 Ma for the Ny Friesland granitic rocks, provides compelling evidence that a significant part of the Harkerbreen protolith is of Early Proterozoic age. Less-deformed specimens will be necessary if the precision in the age of the intrusions is to be improved. The possibility that the Harkerbreen quartzo-feldspathic gneisses are of dominantly volcanic origin (Harland et al. 1966) and derived from a single homogeneous source can be discounted. The intense penetrative foliation in the gneisses may be either of younger Proterozoic or Caledonian origin, probably the latter. Of potential importance in this context is the interpretation (Gayer 1969) that the dated 'granodiorite' and some of the metabasic rocks were intruded after an early phase of folding of the metasediments, but prior to the subsequent phases. The evidence deserves closer analysis, and might suggest that the crystalline basement to the Caledonian cover was subject to Early Proterozoic or earlier orogenic deformation prior to the ca. 1750 Ma granite intrusion. The age of the metasediments intruded by these granites remains unconstrained. However, within the Harkerbreen Group, one of the units, the Rittervatnet Formation, contains diamictites, with large (up to 2 m in diameter) granitic clasts, suggesting the possibility for dating the source of the sediments and, thus, bracketing the age of sedimentation.

Basement elsewhere in the Svalbard Caledonides

A wide range of granitic gneisses and associated metasediments have been reported from the Atomfjella Complex of Ny Friesland (Bayly 1957; Harland et al. 1966) and a

Table 3. U–Pb analyses for sample 89142 (Flåtan granite gneiss).

No. on Fig. 4	Zircon fraction	Concentrations in ppm			Atomic ratios and $^{207}Pb/^{206}Pb$ model age					
	Fraction[b]	U	Pb_{rad}	^{204}Pb	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$ Age (Ma)
1	<45	666	122	0.0680	1500	0.0965	0.17799 ± 39	2.4511 ± 71	0.09987 ± 17	1622
2	45–74	642	122	0.1095	935	0.0986	0.18490 ± 41	2.5684 ± 72	0.10074 ± 16	1638
3	74–106	643	126	0.1630	660	0.0970	0.19224 ± 44	2.6732 ± 88	0.10085 ± 21	1640
4	106–150	578	113	0.1595	605	0.0937	0.19130 ± 42	2.6887 ± 89	0.10194 ± 23	1660
5	>150	545	97	0.0990	570	0.0992	0.17481 ± 38	2.4279 ± 104	0.10073 ± 33	1638
6	45–74 ab	552	123	0.1550	670	0.1045	0.21558 ± 47	3.0812 ± 120	0.10366 ± 30	1691
7	74–106 ab	507	115	0.1045	1140	0.1046	0.21852 ± 48	3.1322 ± 78	0.10396 ± 11	1696

[a)] $^{206}Pb/^{204}Pb$ corrected for blank and mass discrimination, all other atomic ratios have been corrected for initial lead. Errors are given as least significant digits at the 95% confidence level.

[ab)] abraded, as described by Krogh (1982).

Table 4. Lead isotope ratios determined for single grains of zircon by the evaporation method.

Sample 89141		$^{207}Pb/^{206}Pb$ measured	n $^{207}Pb/^{206}Pb$ ratios measured	$^{206}Pb/^{204}Pb$ measured	$^{207}Pb/^{206}Pb$ corrected	$^{207}Pb/^{206}Pb$ Ages (Ma)
grain 1		0.10512 ± 15	54	5042 ± 209	0.10241	1668 ± 6
grain 2		0.10740 ± 10	96	3052 ± 150	0.10289	1677 ± 9
grain 3	step 1	0.1113 ± 11	27	1173 ± 78	0.09947	1614 ± 23
	step 2	0.10867 ± 20	15	1629 ± 78	0.10013	1626 ± 4
	step 3	0.11500 ± 27	9	1012 ± 55	0.10131	1648 ± 6
grain 4		0.10498 ± 22	69	5711 ± 560	0.10270	1673 ± 15
Sample 89142						
grain 1		0.10643 ± 15	71	6155 ± 359	0.10412	1699 ± 11
grain 2	step 1	0.10741 ± 38	33	3615 ± 365	0.10349	1688 ± 17
	step 2	0.11265 ± 14	78	1538 ± 35	0.10386	1694 ± 15
grain 3		0.10896 ± 51	45	2084 ± 66	0.10269	1673 ± 23

complicated Precambrian history can be expected to emerge. Present evidence suggests that the Biskayerhalvöya area of the Northwestern Terrane contains Precambrian metamorphic units (the Richarddalen Complex) of very different history to those in Ny Friesland. Grenville age intrusions and tectonothermal activity may be present in the latter area; as yet there is no evidence. Latest Proterozoic (ca. 600 Ma) high P/T metamorphism can hardly be represented in Ny Friesland unless a major fault (terrane boundary) separates the Lomfjorden Supergroup from the underlying Harkerbreen (and Planetfjella?) Groups of the Stubendorffbreen Supergroup (cf. Manby 1990).

In southwestern Spitsbergen, several unconformities have been described by Birkenmayer (1981) and co-authors. More recent work (Craddock et al. 1985; Bjørnerud et al. 1991) has demonstrated the presence of at least one major unconformity separating presumed Vendian conglomerates, carbonates and phyllites from underlying polydeformed schists. We can anticipate that, with the application of more sophisticated age-determination methods, a fascinating, albeit fragmentary, Precambrian record will emerge on Svalbard.

Caledonian Terrane accretion

The different stratigraphies and tectonothermal histories of the Caledonian terranes on Svalbard persuaded Harland (1971), Harland et al. (1974) and Harland & Wright (1979) that the major Billefjorden fault (Harland et al. 1974), defining the eastern margin of the Old Red Sandstone basin, was a terrane boundary involving substantial (in the order of 1000 km) strike-slip movement, mainly of Svalbardian (Late Devonian) age. Subsequent investigations (Torsvik et al. 1985; Lamar et al. 1986), refuted the evidence for significant post-Old Red Sandstone transcurrent movement, but their studies had otherwise little relevance for the fundamental question of the nature of Caledonian terrane accretion. Studies of the Northwestern Terrane (Gee 1966, 1972) provided evidence that similar N–S faults (e.g. the Breibogen–Bockfjorden and Raudfjorden Faults) probably initiated as transcurrent (sinistral) structures, prior to Devonian deposition; thereafter they acted as essentially extensional structures, in the former case down-throwing first to the east in the Devonian and subsequently, during or after the Carboniferous, to the west. That the Breibogen fault is a major structure penetrating the deep lithosphere is supported by the location in Bockfjord, along its southerly trace, of a Quaternary volcanic centre, the lavas carrying deep crustal and mantle xenoliths (Amundsen et al. 1988).

Perhaps the strongest evidence in favour of Harland's transcurrent hypothesis for Caledonian terrane accretion on Svalbard is to be found in the Vestgötabreen subduction complex. The remarkable similarities between the Late Proterozoic and Cambro-Ordovician stratigraphies of the Northeastern Terrane and East Greenland (Caby & Bertrand-Sarfati 1988) suggest that these shallow marine environments must have been part of the same Laurentian margin during the Late Proterozoic, Cambrian and at least part of the Ordovician. By contrast, the Late Proterozoic and Early Palaeozoic stratigraphies of western Spitsbergen clearly represent a more mobile continental margin, dissimilar from East Greenland and perhaps comparable with Ellesmere Land (Harland 1985; Ohta et al. 1989). Nevertheless, the stratigraphic correlations in western Spitsbergen are uncertain (Harland et al. 1979; Hjelle et al. 1979; Kanat & Morris 1988), and they can hardly be used as support for major terrane separation prior to Caledonian accretion (Birkenmayer 1981). However, evidence for the latter is to be found in the Vestgötabreen Complex, where the cooling history (Dallmeyer et al. 1990) of the high P, blue-schist and eclogite parageneses (Ohta et al. 1986) imply Early–Mid-Ordovician subduction. This complex must have separated Svalbard's Northeastern Terrane from the Laurentian margin of Greenland, unless the former was assembled by considerable transcurrent displacement on the N–S faults. Of particular interest is the evidence that these displacements, however large, occurred during Scandian collisional orogeny (Gee 1975) further south in the orogen in Scandinavia.

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