Pb-Pb single-zircon ages of granitoid boulders from the Vendian tillite of Wahlenbergfjorden, Nordaustlandet, Svalbard

ALEXANDER N. LARIONOV, ALEXANDER M. TEBENKOV and DAVID G. GEE

Larionov A.N., Tebenkov A.M. & Gee D.G. 1998: Pb-Pb single-zircon ages of granitoid boulders from the Vendian tillite of Wahlenbergfjorden, Nordaustlandet, Svalbard. *Polar Research, 17(1)*, 71–80.

There are three areas in eastern Svalbard where Vendian tillites are exposed: eastern Ny Friesland, western Nordaustlandet (north and south of Murchisonfjorden) and further east in inner Wahlenbergfjorden, near Aldousbreen. Clasts within the massive unmetamorphosed clay-mica-carbonate matrix of the tillites include carbonates, sandstones, siltstones, metavolcanics, schists and different granitoids, the metamorphic and igneous rock types being more frequent in the upper levels of the formation. Large granite boulders, up to 1 m in diameter, are known from the easternmost outcrop at Aldousbreen. Three granitoid boulders from the Aldousbreen outcrop, differing in petrography and chemistry, have been dated by the Pb-Pb single-zircon method. They yield ages of 2830 ± 5 Ma, 1802 ± 4 Ma and 1497 ± 26 Ma. These clasts also differ in petrography, chemistry and age from all known granitic rocks on Nordaustlandet, which have recently yielded Grenvillian (950–960 Ma) and Caledonian (ca. 410 Ma) ages. The concentration of large granitic clasts in the easternmost known tillite outcrops suggests derivation from the east and/or south. Possible areas include those beneath the ice of Austfonna and below the Carboniferous strata of southeastern Nordaustlandet. The apparent lack of a significant Grenvillian overprint suggests the possibility of a more distant source.

Alexander N. Larionov, Laboratory for Isotope Geology, Museum of Natural History, P.O. Box 50007 S-104 05, Stockholm, Sweden; Alexander M. Tebenkov, Polar Marine Geological Expedition, ul. Pobedy 24, 1895 10 Lomonosov, St. Petersburg, Russia; David G. Gee, Department of Earth Sciences, Uppsala University, Villavågen 16, S-752 36 Uppsala, Sweden.

Introduction

Tillites were first discovered on Nordaustlandet by Kulling (1934), who referred to them as the Sveanor Formation. He demonstrated that these glacial deposits underlie Cambrian strata and proposed an "Eocambrian" age that was later confirmed biostratigraphically (Krasil'ščikov et al. 1965; Golovanov 1967; Knoll 1981, 1982). Summary reviews of stratigraphy, composition, origin and correlation with East Greenland tillites were given by Kulling (1934), Krasil'ščikov (1967), Flood et al. (1969) and Fairchild & Hambrey (1995) for Nordaustlandet and for the entire Svalbard region (including Ny Friesland and the western coast of Spitsbergen) by Hambrey et al. (1981) and Harland et al. (1993).

The easternmost outcrops of the Sveanor tillites were first mentioned by Winsnes (1965) from the northeastern corner of Wahlenbergfjorden, near Aldousbreen and Eltonbreen (Fig. 1). Detailed geological descriptions were given later by Edwards (1976). The basal contact of the tillites in both Nordaustlandet (Edwards 1976) and Ny Friesland (Kaufman et al. 1993) was noted to be sharp, being defined by local unconformities and conglomerate lenses. These features are amplified by the absence of Lower Vendian acritarch assemblages on Svalbard and by chemostratigraphic data (Fairchild & Hambrey 1995). In addition, a hiatus, corresponding to Ediacaran time, was proposed to occur at the top of the formation (Kaufman et al. 1993).

Two main facies are recognised in the Sveanor Formation at the Aldousbreen locality: a massive tillite with subparallel oriented clasts, a few cm in size, and composing up to 50% of the rock, and a non-laminated siltstone and mudstone with rare clasts composing less than 5% of the rock (Fig. 2A). Both, rounded and angular clasts within the unmetamorphosed clay-mica-carbonate matrix of the tillites include pebbles and boulders mainly of the immediately underlying carbonate rocks, sandstones, shales and siltstones of the Neopro-

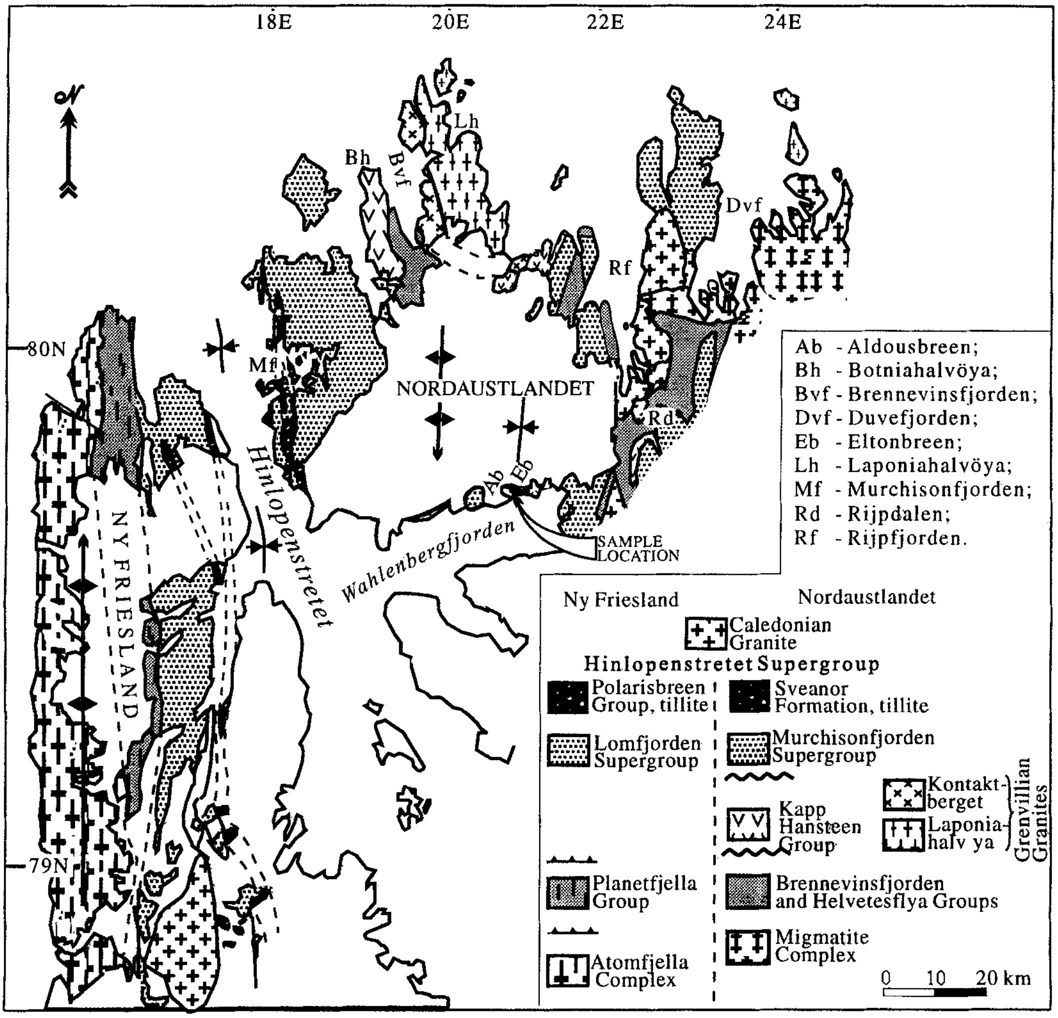

Fig. 1. Geological map of Ny Friesland and Nordaustlandet with location of samples.

terozoic Murchisonfjorden Supergroup. However, metavolcanics, schists and different types of gneisses and granitoids are also present. The tillites were interpreted by Edwards (1976) to be subglacial marine deposits, with dropstones indicating ice rafting, interbedded with two layers of wind-blown glacial loess and some fluvioglacial deposits. In their description of the tillite-bearing Polarisbreen Group of Ny Friesland (within which the Nordaustlandet Sveanor tillite is included), Fairchild & Hambrey (1984) noted the occurrence of quick facial changes. Nevertheless the thickness of the formation of ca. 160 m was shown to be uniform over a distance of 55 km along strike. From Ny Friesland, in the west via Murchisonfjorden to Aldousbreen in the east, over a distance of ca. 70 km, the tillite thickness does not vary significantly, being in the range of 150–175 m. The whole tillite group was interpreted by Fairchild & Hambrey (1995) to be dominated shallow-marine periglacial sediments, representing a lateral profile along a basin margin, with the source area supposed to be somewhere in the southeast (Fairchild & Hambrey 1984). The paleocurrent indicators observed by Edwards at Aldousbreen suggest ice-movement from east–southeast. Krasil'ščikov (1967) suggested that the source area was to the west from Ny Friesland,

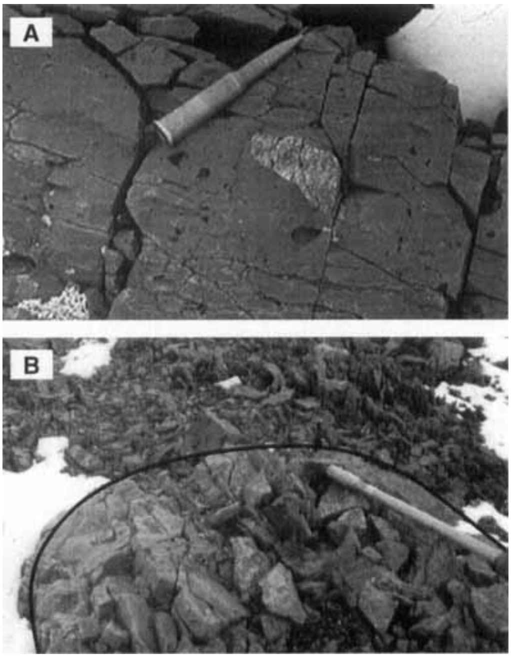

Fig. 2. Outcrops at Aldousbreen, inner Wahlenbergfjorden: A. Typical tillite. Bullet size ca. 70 mm; B. Large granite boulder, sample g50-1, marked with line.

but he also noted a decrease of the clastic component and an increase of the carbonate content within the tillites from south to north, which could imply derivation from a southerly source. Proximity to land (Harland et al. 1993) was proposed by the angular shape of silt particles. Comparison of carbonate and clastic debris with the transgressive Neoproterozoic carbonate sequence, underlying the tillite, allowed Hambrey et al. (1981) to estimate a maximum depth of erosion in the source area of about 2.5 km, while Krasil'ščikov (1967) proposed a figure of less than 1.2 km. These estimates took no account of the source of the igneous and metamorphic clasts.

Similarity of the red Aldousbreen granitic boulders to the Rijpfjorden granite exposed ca. 20 km to the northeast was commented on by Hjelle (in Edwards & Taylor 1976). Edwards and Taylor tried to date the granite clasts by analysing six samples from large boulders by the whole rock Rb-Sr method. A three point line, corresponding to age of 1275 ± 45 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.72172 ± 0.00056, was obtained. Three other points were scattered off the line. This result suggested the possibility of Grenvillian-age rocks in the source area and also that they were derived from a crustal precursor.

In recent years, Grenvillian-age granites, intruding the older migmatites, have been found in northwestern Nordaustlandet (Gee et al. 1995). Caledonian granites have also been identified (Johansson & Larionov 1996). Metasedimentary and metavolcanic clasts in the tillites are probably derived from Grenvillian and older formations, similar to those now exposed in northwestern and central Nordaustlandet. The granitoid boulders from the tillite of inner Wahlenbergfjorden were sampled in order to further constrain the age of the Vendian source terrains.

Sample description

Three different granitoid boulders were sampled by one of the authors (AMT) during a two-day visit to Aldousbreen in May 1995.

Sample g50-1 is a red coarse-grained massive angular granite boulder, 1.0 × 1.5 m in diameter (Fig. 2B). A weakly developed cataclastic texture is present. The main minerals are quartz (35%), albite (35%) and potassium feldspar (25%). A small amount of chlorite (3%), sericite (less then 1%) and opaque ore minerals (1%) are present. Zircon, apatite and sphene occur as accessory minerals. Two generations of quartz occur: coarse grains (the same size as feldspars) and finer elongated grains which form a few parallel thin cataclastic zones. For both varieties, sutured boundaries are typical. The plagioclase is coarsely twinned and altered to dusty aggregates. The potassium feldspar is perthitic and fresher than the plagioclase.

Sample g50-2 is a coarse grained grey granite with equal amounts (35%) of potassium feldspar and plagioclase (albite), quartz (15%), secondary chlorite (10%) and carbonate (5%). Opaque ore minerals, apatite and small prismatic zircon grains occur in accessory amounts. Potassium feldspar is often perthitic. The finely twinned plagioclase is more fresh than the potassium feldspar. Chlorite and carbonate occur as secondary phases, the latter being mainly concentrated in cross-cutting small veins.

Sample g50-3 is a medium grained grey granitic gneiss, with 40% quartz, 35% potassium feldspar and 20% plagioclase (albite) as the main minerals. Subparallel orientation of chlorite flakes (3–5%) and elongation of cataclastic quartz grains with suture boundaries mark the gneissosity of the

Table 1. Bulk chemistry composition for granitoids of Nordaustlandet and tillite boulders of Wahlenbergfjorden.

No.	Sample	Rock Type	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
						Wahlenbergfjorden[1]								
1	g50-1	red granite	69.50	0.23	16.08	3.02	–	0.00	0.75	0.87	4.51	4.88	0.09	0.20
2	g50-2	grey granite	58.71	0.32	16.12	5.03	–	0.07	2.19	7.46	4.73	4.38	0.08	0.10
3	g50-3	grey granite-gneiss	72.82	0.13	12.64	2.23	–	0.00	0.39	3.52	3.75	3.99	0.05	0.30
						Rijpfjorden[2]								
4	17-3T77	Granite	73.25	0.13	15.01	0.05	1.02	0.03	0.28	0.72	3.90	4.63	0.18	0.60
5	21-1T77	Granite	71.99	0.34	15.08	0.64	1.25	0.03	0.42	0.85	3.60	4.32	0.24	1.20
6	73-1T88	Granite	69.02	0.48	14.17	3.29	–	0.05	0.92	2.30	3.13	4.70	0.31	2.50
7	75-1T88	Granite	72.03	0.31	14.73	2.19	–	0.02	0.56	0.88	3.60	4.76	0.41	0.96
8	77-3T88	Granite	72.58	0.30	14.64	2.13	–	0.00	0.53	1.01	4.04	4.90	0.26	0.96
9	g28-1	Granite	71.36	0.30	14.96	0.62	1.67	0.34	0.40	1.32	3.81	5.37	0.20	0.94
10	g28-2	Granite	71.42	0.43	14.43	0.20	2.03	0.44	0.65	1.73	3.18	5.21	0.17	1.02
11	g28-3	Granite	72.21	0.26	15.31	0.10	1.43	0.21	0.39	1.07	3.33	5.29	0.28	0.82
						Kontaktberget[3]								
12	g23-1	Granite	75.95	0.04	13.82	0.31	1.07	0.03	0.05	0.31	3.62	4.70	0.05	0.00
13	g23-2	Granite	75.87	0.10	13.23	0.22	1.79	0.05	0.05	0.30	3.57	4.69	0.08	0.00
14	g23-3	Granite	71.84	0.40	14.84	0.21	2.89	0.04	0.45	1.29	3.17	4.75	0.12	0.00
15	g23-4	Granite	75.00	0.22	12.98	0.38	1.91	0.04	0.15	0.41	3.81	4.66	0.09	0.00
16	g23-5	Granite	73.13	0.30	14.14	0.11	1.79	0.03	0.20	0.97	3.53	5.66	0.14	0.00
						Djupkilsodden[4]								
17	59-3T95	Q-Monzonite	60.12	1.52	15.79	1.42	4.68	0.08	2.03	2.90	2.61	5.59	0.88	1.42
18	60-1T95	Q-Monzonite	60.29	1.32	14.66	2.47	3.51	0.10	2.59	3.34	2.66	5.89	0.91	1.29
19	60-2T95	Granite	72.82	0.17	13.91	1.09	1.18	0.00	0.12	0.56	2.92	6.09	0.06	0.23
20	60-3T95	Granite	67.90	0.34	15.25	2.10	1.59	0.08	0.21	0.58	3.49	6.62	0.06	0.58
21	60-4T95	Q-Monzonite	64.16	1.15	14.56	1.93	3.05	0.07	1.22	2.63	2.84	5.83	0.66	1.04
22	61-1T95	Granite	70.95	0.32	14.04	0.82	2.08	0.02	0.19	0.97	2.95	6.27	0.13	0.43
23	61-3T95	Granite	67.17	0.68	14.89	1.22	2.74	0.05	0.51	1.64	2.77	6.67	0.29	1.00
24	61-4T95	Q-Monzonite	64.00	1.18	15.45	1.48	3.96	0.08	1.08	2.83	3.12	5.37	0.56	0.64
25	61-5T95	Q-Monzonite	61.23	1.34	14.98	1.79	4.14	0.10	2.35	2.94	2.64	5.83	0.87	0.86
26	61-6T95	Q-Monzonite	60.62	1.29	15.59	2.05	3.66	0.10	2.34	3.42	2.56	5.93	0.89	1.01

[1] this paper; [2] Tebenkov, unpublished data; [3] Gee et al. 1995; [4] Gee et al. in prep.
If FeO is absent, Fe_2O_3* is total.

rock. Secondary carbonate (1–2%) is concentrated in thin cracks within the feldspar. Rare flakes of muscovite and prismatic zircon are accessory minerals. Potassium feldspar is represented by perthite with wide patches of albite, the latter altered to a dusty sericite-quartz-carbonate aggregate.

Petrochemistry

Petrochemical comparison shows (Table 1, Fig. 3) that all three tillite clasts fall in the same granite field in the Ab-An-Or plot (Fig. 3A) as other even-grained granitoids of Nordaustlandet (ca. 940 Ma Kontaktberget, Gee et al. 1995, ca. 400 Ma Rijpfjorden and Djupkilsodden, Johansson & Larionov, unpubl. results). No other similarities were found on closer inspection. Samples g50-1 and g50-2 are enriched while g50-3 is much poorer in Al_2O_3 than the other rocks; g50-2 contains significantly higher CaO. The differences in bulk chemistry are illustrated by diagrams Fig. 3B–D. For example, all the known even-grained Nordaustlandet granites and

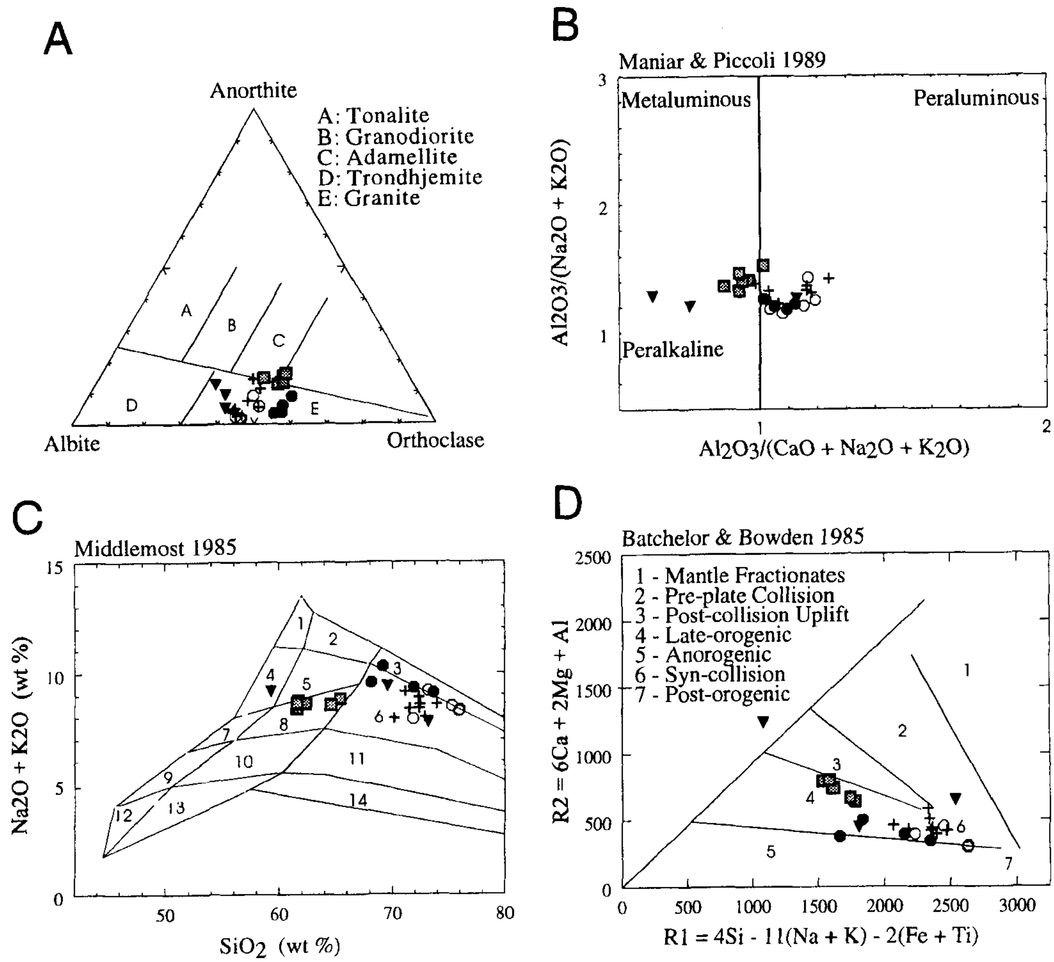

Fig. 3. Bulk chemistry diagrams for granitoids of Nordaustlandet and tillite boulders of Wahlenbergfjorden. Solid triangles = Granitoid boulders from tillite (this paper); crosses = Rijpfjorden Granites; open circles = Kontaktberget Granite; solid circles = Djupkilsodden Granite; solid squares = Quartz monzonite of Djupkilsodden.

g50-1 are peraluminous while g50-2 and g50-3 are metaluminous and lie outside the granite and quartz-monzonite fields (Fig. 3B). Sample g50-1 is the most similar to the other Nordaustlandet granites, but it differs from those in its higher contents of Al_2O_3 and Na_2O. Samples g50-2 (due to secondary carbonate) and g50-3 differ significantly from the main types of granites (Fig. 3B, C, D).

The petrographical studies and petrochemical correlation indicate that only g50-1 is a relatively well-preserved, primary igneous rock, while g50-2 and g50-3 have experienced extensive secondary alteration. The clasts studied are not similar to granites known elsewhere on Nordaustlandet.

Zircon morphology

Zircons were separated from the sampled granitoids by standard techniques. The structure and morphology of the grains were examined by optical microscopy. The morphology of the zircons, described below, corresponds to that typical for crystals of magmatic origin. Because the majority of the grains are turbid, a metamict

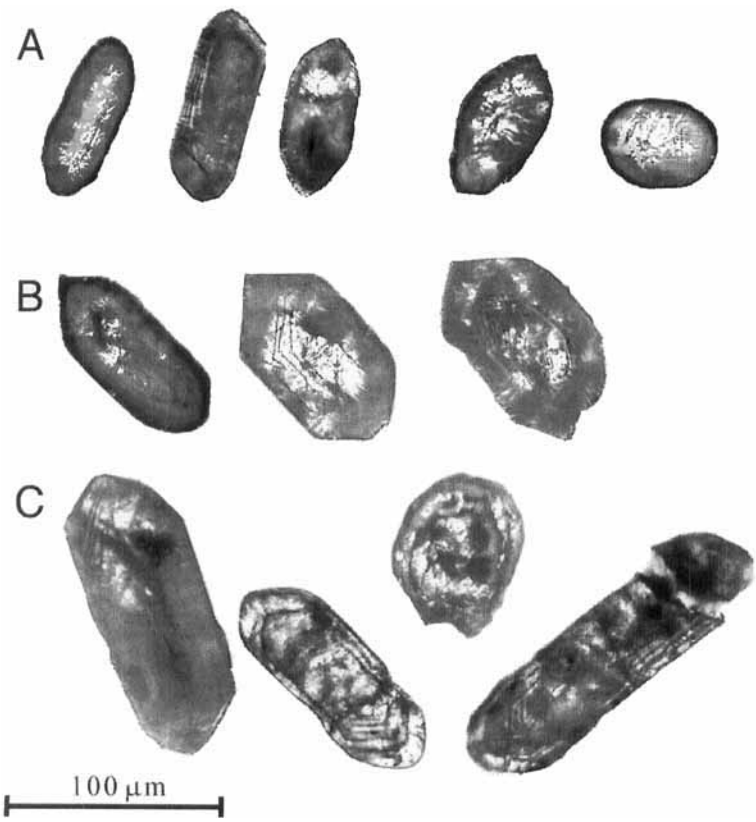

Fig. 4. Typical zircons from sample: A. g50-1; B. g50-2; C. g50-3. Average size of grains ca. 100 μm. Photographs in glycerine, transmitted light.

structure is inferred. The most transparent and inclusion-free grains were selected for analysis.

In *Sample g50-1* zircons (Fig. 4A) occur as slightly magnetic subhedral grains, short- to long-prismatic, dark-pink to brown in colour, with the exception of B which is a subrounded piece of a dark-pink, partly turbid grain (probably a contaminant from the matrix). The crystals are usually semi-transparent to turbid, with the terminations being more turbid and darker than the interiors. Most of the grains have facets (100) + (110) + (121) + (101). The surfaces usually are not smooth (probably due to growth relief). The inner structure of the zircons is simple; although no cores were found, growth zoning was observed in some crystals. Black flake-shaped inclusions are quite common.

Most of the zircons from *Sample g50-2* are sub- to euhedral grains (Fig. 4B). They are pink to brown in colour, semi-transparent to turbid. Well developed facets include (100) and (101), while (110) and (121) are uncommon. Surfaces are more or less smooth, with growth relief. Black inclusions are common. Some zircons from this sample show growth zoning.

Zircons from *Sample g50-3* are sub- and euhedral, mainly long to mid-prismatic, brown and dark-pink, translucent and semi-transparent to turbid (Fig. 4C). Facets usually are (100) + (110) + (121) + (101). Some grains contain black inclusions. Growth zoning is not uncommon. Zircon A differs from the majority of grains by being colourless, with brown turbid domains and with no (100) facets. Thus, we believe it to be a contaminant, possibly from the tillite matrix.

The majority of the zircons from the studied samples may be characterised as subhedral grains often with fine zoning, inclusions and surface growth relief. These features suggest that the

Table 2. Results of single grain Pb-Pb evaporation analysis of zircons from granitoid boulders from the Wahlenbergfjorden tillites.

Sample	Grain	No. of platings	Morphology	Age, Ma
g50-1	B	2	debr. pink, semi-transp., rough surf.	>1730 ± 17
	C	4	debr. pink, semi-transp., black incl.	2829 ± 6
	E	1	pink, transp., smooth surf.	>2778 ± 280
	F	1	pink/brown, semi-transp., relief surf.	>2865 ± 3
	J	6	brown, semi-transp., relief surf., zon.?	2856 ± 80
	K	1	brown, transp., relief surf., fractur.	>2831 ± 9
Average C + F + J + K				2830 ± 5
g50-2	A	3	brown, semi-transp., relief surf., zon.?	1804 ± 7
	D	1	pink, transp., black incl., relief surf.	>1798 ± 14
	E	8	brown, turb., zon.	1806 ± 7
	F	7	brown, semi-transp., relief surf., incl.	1804 ± 2
	G	4	brown, semi-transp., fract., zon.?	1800 ± 2
Average on all the grains				1802 ± 4
g50-3	A	2	brown, semi-transp., smooth surf.	>1006 ± 47
	B	1	brown, turb., fract., black incl.	>1434 ± 30
	C	5	brown, turb., fract., aon.?, black incl.	1514 ± 9
	E	1	pink/brown, semi-transp.	>1484 ± 15
	F	4	brown, turb.	>1440 ± 87
	G	6	brown, turb., black incl.	1507 ± 10
	H	2	brown, semi-transp. zon.?	>1467 ± 4
	J	3	pink, semi-transp. smooth surf.	1511 ± 8
Average on grains C + E + G + H + J				1497 ± 26

Age calculated as weighted average for selected blocks. Error given in Ma for 2 s interval. Calculations have been made using the "ISOPLOT" program by Ludwig (1991); figures marked with ">" show a "minimum age", other are "plateau ages".

zircons are of magmatic origin. The turbidity of the crystals may suggest their metamict structure, which in turn could imply partial lead loss.

Single-zircon Pb-Pb evaporation procedure

Five to eight zircons have been analysed from each sample. Step-wise single-zircon Pb-evaporation analyses were performed following standard techniques (Kober 1986, 1987). All the analyses were carried out in the Laboratory for Isotope Geology of the Swedish Museum of Natural History using a Finnigan MAT 261 mass-spectrometer.

Data have been collected in a peak-jumping mode, using a secondary electron multiplier. No correction for mass-fractionation has been made. Correction for common lead was done using the measured $^{206}Pb/^{204}Pb$ and the common lead isotope ratios by Stacey & Kramers (1975).

Lead emission was observed at temperatures between ca. 1400–1500°C; for the age calculation, only the results obtained from evaporation steps made at temperatures of ca. 1450–1500°C were included. This approach was applied because during the low temperature steps lead is usually released from the most metamict parts of zircon, where the isotope composition has been disturbed by partial Pb-loss.

Age was first calculated for every block of ten scans using the records from the acquisition program. Thereafter, the age for each grain, as well as for groups of grains of similar age, was calculated using the Weighted Average calculation procedure of the ISOPLOT program (Ludwig 1991).

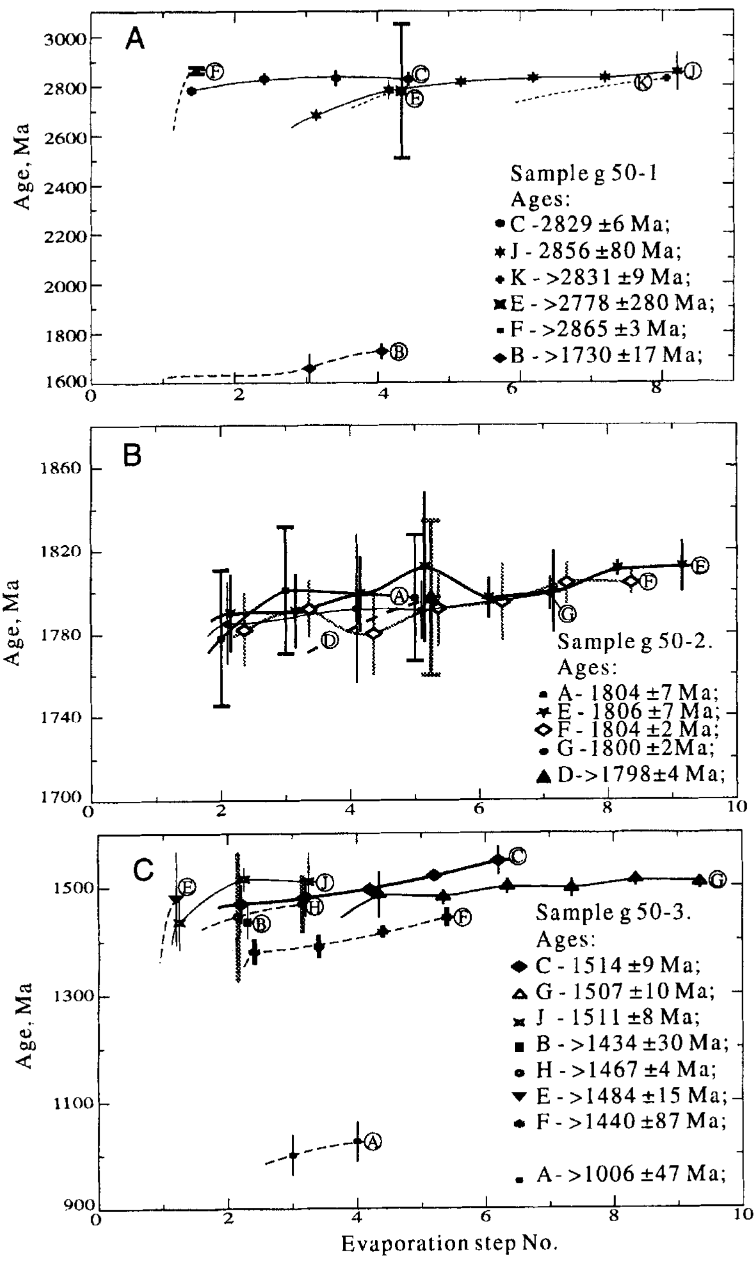

Fig. 5. Results of the single grain Pb-Pb evaporation analysis of zircons from granitoid boulders from the Wahlenbergfjorden tillites. Dashed lines show the course of analyses with a minimum age marked with ">", while solid lines are drawn for analyses in which a plateau ages were obtained.

Results

The results of the single-zircon Pb-Pb analysis are shown in Table 2 and on the plots in Fig. 5. More details concerning the analytical procedure and results (temperature and time for each plating, values of ion current and measured isotope ratios) are available from the first author on request.

In *Sample g50-1*, five zircons yielded Late Archaean ages, two with a well-defined plateau and one (B), a probable contaminant, with a much younger minimum age (1730 ± 30 Ma). Due to metamictisation of the zircons, the calculated age (2830 ± 5 Ma, average of five grains) may be regarded as a minimum age.

The ages obtained on the five zircons from *Sample g50-2* are quite consistent, with an average of 1802 ± 4 Ma.

Analysis of seven zircons from *Sample g50-3* gave a Mid Proterozoic age of 1497 ± 26 Ma for this granitic gneiss. Grain A, with minimum age ca. 1000 Ma, is apparently a contaminant, perhaps from the tillite matrix.

All the grains analysed showed very moderate increases of age from step to step, despite their apparent metamict structure. This implies that any overprint experienced by the studied rocks, as seen, for example, in the partial albitisation of plagioclase, was not strong enough to reset the zircon's U-Pb isotope system.

Discussion and conclusions

The petrology, petrochemistry and ages of the granitoid clasts from the Aldousbreen tillite locality lead to the conclusion they were derived from a source terrane, or terranes, as yet unknown in western and northern Nordaustlandet. The Rb-Sr age of the similar clasts of ca. 1275 Ma reported by Edwards & Taylor (1976) does not correspond to any known geological event.

Previous authors (Krasil'ščikov 1967; Hambrey et al. 1981) have estimated the depth of erosion of the underlying Murchisonfjorden Supergroup (or its equivalent in the source area) to be in the order of 2.5 km, based on the presence of clasts of a distinct quartzite from the Flora Formation in the tillites. However, the increasing frequency of pre-Murchisonfjorden material in the upper parts of the tillites requires much deeper erosion (4–6 km). There is no evidence of major changes in facies and thickness of the Murchisonfjorden Supergroup from west to central Nordaustlandet, while granitoid clasts are exceptionally large at the Aldousbreen locality. This suggests a proximity to the source and its active uplift during Vendian time. It may occur beneath the ice of Austfonna or the Carboniferous cover further south or southeast, the direction of the clastic material transport according to Hambrey et al. (1981) and Harland et al. (1993). On the other hand, according to age determinations, there are no traces of the Grenvillian overprint, which is known to be widespread in northern Nordaustlandet (Gee et al. 1995; Johansson & Larionov 1996). This implies a more distant provenance and transport with rafting ice.

This initial study emphasises the importance of isotope-age investigations of detritus in the tillite. A more comprehensive study of granite clasts, both in the Aldousbreen locality and further west, along with systematic work on the matrix, will undoubtedly yield better constraints on the source areas exposed to erosion during Vendian deposition. Such studies will also throw new light on Vendian tectonics.

Acknowledgements. – Field work on Svalbard during the spring and early summer of 1995 was financed by the Japanese Arctic Glaciological Expedition (JAGE) and by the Russian Polar Marine Geological Expedition (PMGE). Co-operation with the Norwegian Polar Institute is also acknowledged. Special thanks are due to assistant A. Birjukov who helped collect and carry samples during extremely stormy weather and poor visibility. Discussion with Å. Johansson (LIG, NRM) and A. A. Krasil'ščikov (PMGRE) has been fruitful and led to improvement of some parts of the manuscript. Illustrations were made with the help of P. Witt-Nilsson (Uppsala University). The analytical work reported here was carried out by AL, with support from the Swedish Institute. The paper is a contribution to the TIMPEBAR project of the EUROPROBE programme.

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