SHRIMP U-Pb zircon ages for Archaean granitoid rocks, Ataa area, north-east Disko Bugt, West Greenland

Allen P. Nutman and Feiko Kalsbeek

Zircons from four samples of granitoid rocks from the Ataa area have been studied by SHRIMP ion microprobe. A trondhjemite from the Atâ intrusive complex (Atâ tonalite) yielded an age of 2803 ± 4 Ma, in agreement with earlier age determinations. A sample from the regional migmatitic biotite gneisses gave 2815 ± 4 Ma. A homogeneous granitoid rock, from field observations believed to be younger than the regional gneisses, has two main zircon populations, 2835 ± 4 Ma and *c.* 2800 Ma, respectively, and a granite that intrudes the Atâ complex yielded an age of 2758 ± 2 Ma.

A.P.N., *Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 0200, Australia*. E-mail: *Allen.Nutman@anu.edu.au.*
F.K., *Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark.*

Keywords: Archaean rocks, Disko Bugt, SHRIMP, U-Pb ages, zircon ages, West Greenland

Most of the area north-east of Disko Bugt is made up of different generations of quartzofeldspathic plutonic rocks, variably deformed and migmatised to form a regional gneiss complex (Garde & Steenfelt 1999, this volume). Rocks of the 2800 Ma Atâ intrusive complex (Atâ Tonalite on the 1:250 000 geological map of Garde 1994, enclosed in this volume; Fig. 1; Escher & Burri 1967; Kalsbeek *et al.* 1988; Garde & Steenfelt 1999, this volume; Kalsbeek & Skjernaa 1999, this volume) are better preserved than most other granitoid rocks, and locally display clear intrusive relationships with older migmatitic gneisses. However, the Atâ complex itself is intruded by younger granitoid rocks which in turn may also be deformed and gneissified. The purpose of the present study is to obtain an impression of the age range of Precambrian rocks in the Ataa area, north-east Disko Bugt (see the geological map Ataa 69 V.3 Nord, Escher 1995), using SHRIMP zircon U-Pb age determinations.

Four samples (Fig. 1) were investigated: (1) a representative specimen of the regional migmatitic grey biotite gneisses south of the Atâ complex (GGU 358675); (2) a non-migmatitic, homogeneous tonalitic orthogneiss (GGU 358673), which, from field evidence, is believed to be younger than the regional migmatitic gneisses. This sample has yielded a Sm-Nd model age (T_{DM}, DePaolo 1981) of 2.93 Ga (Kalsbeek & Taylor 1999, this volume; see p. 53); (3) a trondhjemitic sample of the Atâ complex (GGU 269310) with T_{DM} 2.80 Ga (Kalsbeek *et al.* 1988); and (4) a late granite intruding rocks belonging to the Atâ complex near its southern margin on Arveprinsen Ejland (GGU 348683).

Analytical method and calculation of ages

U-Th-Pb isotope ratios and concentrations were determined using the SHRIMP 1 ion microprobe (SHRIMP = Sensitive High Resolution Ion MicroProbe) at the Australian National University in Canberra. They were calibrated against the standard Sri Lanka zircon SL 13 ($^{206}Pb/^{238}U$ = 0.0928; age 572 Ma). Details of analytical procedures and data assessment are given by Compston *et al.* (1984) and Williams *et al.* (1996).

In polyphase gneiss areas the interpretation of zircon U-Pb isotope data in terms of rock ages is not always straightforward. First, the analysed zircons may

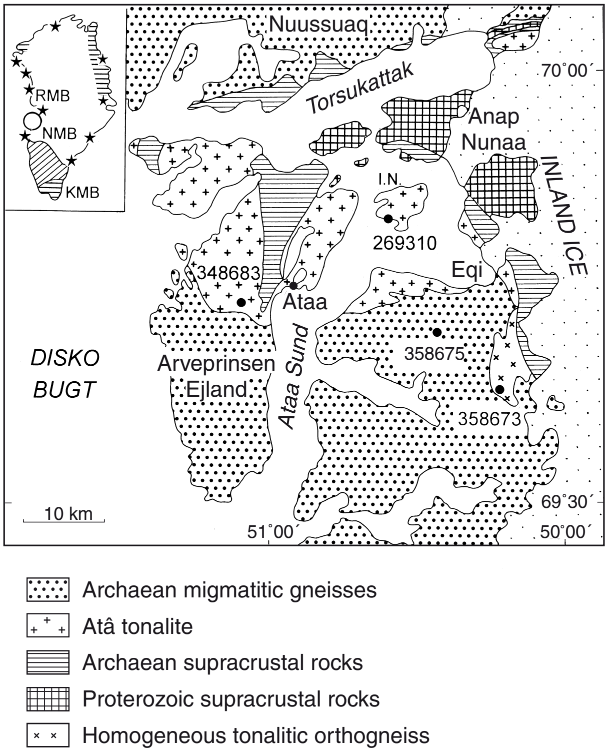

Fig. 1. Geological sketch map of the Ataa area with locations of the investigated samples. I.N. denotes the island Illuluarsuit Nunataat. The inset map shows the main structural elements within the Precambrian shield of Greenland with the location of the Ataa area in West Greenland between the Nagssugtoqidian and Rinkian mobile belts (NMB and RMB, respectively). The Archaean craton of southern Greenland is indicated by oblique ruling. Stars indicate the presence of dated Archaean rocks outside the Archaean craton. Horizontal ruling shows outcrop areas of new-formed early Proterozoic rocks. KMB is the Ketilidian mobile belt of South Greenland. Slightly modified from Garde (1994).

have suffered loss of Pb during later high-grade metamorphism. If metamorphism takes place shortly after emplacement of the igneous precursor of the analysed sample, the analytical data may show a scatter in the concordia diagram towards lower $^{207}Pb/^{206}Pb$ ages without causing detectable discordance. The strategy for calculating a reliable $^{207}Pb/^{206}Pb$ age is then to successively reject analyses which yield the lowest $^{207}Pb/^{206}Pb$ dates, until the remaining ones are undistinguishable from their weighted mean. Second, more than one zircon population may be present, of which the one with the highest $^{207}Pb/^{206}Pb$ ages may be inherited from the parent material which was reworked to form the rock under consideration.

Results

GGU 358675, migmatitic grey biotite gneiss. This is a representative sample of the regional migmatitic orthogneiss complex (Escher *et al.* 1999, this volume), and was collected from the mainland east of Ataa Sund at 69°42.3′ N, 50°23.6′ W (Fig. 1).

Zircons are prismatic, euhedral to subhedral and yellow to dark brown in colour. They display pronounced micron scale euhedral zoning, parallel to the exteriors of the grains. They are interpreted as a homogeneous magmatic population. The centres of a few grains consist of homogeneous structureless zircon whose outline mimics that of the grain exterior, and hence there is no reason to suppose it represents much older inherited material.

Seventeen spots were analysed on 15 zircon crystals (Fig. 2A; Table 1). U and Th contents range from 118–630 ppm and 4–102 ppm, respectively, with relatively low Th/U ratios (0.02–0.24). Most $^{207}Pb/^{206}Pb$ ages lie between 2800 and 2830 Ma. One zircon yielded an age of 2868 Ma and may represent an inherited grain. A few grains have lower $^{207}Pb/^{206}Pb$ ages and may have suffered ancient lead loss. Nine of the remaining analyses yield a mean $^{207}Pb/^{206}Pb$ age of 2815 ± 4 Ma (ages quoted at 2σ), which we interpret to date the time of emplacement of the igneous precursor of the gneiss.

GGU 358673, homogeneous tonalitic orthogneiss. This sample was collected at 69°37.1′ N, 50°13.6′ W (Fig. 1) from a mappable unit of non-migmatitic orthogneisses which is discordant to the regional structure of the migmatitic grey biotite gneisses, and may be younger than the latter (Escher *et al.* 1999, this volume). Zircons are prismatic euhedral crystals, sometimes with rounded terminations. Most crystals are yellow to light brown with distinct euhedral zoning, a few are dark brown and metamict. Some grains are composite with dark brown cores surrounded by lighter coloured zircon.

Eleven grains were analysed (Fig. 2B; Table 1). U and Th contents are highly variable, 73–3887 ppm and 17–267 ppm respectively. Th/U ratios vary from 0.01 to 0.73. The zircons fall into two age groups with $^{207}Pb/^{206}Pb$ ages 2800–2810 Ma (four grains) and 2820–2850 Ma (six grains), respectively. One grain with very high U (3887 ppm) yielded a younger $^{207}Pb/^{206}Pb$ age of 2775 Ma which may be the result of moderate lead loss. The older zircon population yields a common age of 2835 ± 4 Ma; the younger group gives an age just over 2800 Ma. Two interpretations are consistent

Table 1. SHRIMP zircon U-Pb data for granitoid rocks from the Ataa area, north-east Disko Bugt

Site	U (ppm)	Th (ppm)	Th/U	^{204}Pb (ppb)	Comm. ^{206}Pb(%)	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Age* (Ma)	disc.
GGU 358675 – *migmatitic grey biotite gneiss*										
1-1	212	18	0.09	15	0.20	0.550±10	15.14±0.31	0.1997± 9	2824± 7	0
2-1	575	83	0.14	20	0.11	0.512±10	13.99±0.28	0.1981± 5	2811± 4	–5
3-1	504	99	0.20	26	0.15	0.530±10	14.98±0.30	0.2052± 6	2868± 4	–4
4-1	168	7	0.04	12	0.20	0.562±11	15.36±0.31	0.1982± 9	2811± 7	2
5-1	118	4	0.04	18	0.42	0.571±11	15.63±0.34	0.1986±13	2815±11	3
6-1	126	6	0.05	14	0.31	0.554±11	15.10±0.32	0.1978±13	2808±10	1
7-1	430	102	0.24	10	0.07	0.532±10	14.54±0.29	0.1984± 5	2813± 4	–2
8-1	177	9	0.05	38	0.60	0.549±11	14.77±0.31	0.1952±11	2787± 9	1
9-1	179	24	0.13	9	0.16	0.532±10	14.28±0.29	0.1944± 9	2779± 7	–1
10-1	519	88	0.17	17	0.09	0.539±10	14.71±0.29	0.1980± 5	2810± 4	–1
11-1	630	84	0.13	20	0.10	0.510±10	13.99±0.27	0.1988± 5	2817± 4	–6
12-1	416	63	0.15	7	0.05	0.534±10	14.53±0.29	0.1974± 5	2805± 4	–2
13-1	142	6	0.04	50	0.95	0.575±11	15.81±0.34	0.1996±14	2823±12	4
13-2	209	4	0.02	11	0.15	0.550±11	14.94±0.31	0.1970± 8	2801± 7	1
14-1	164	5	0.03	10	0.17	0.566±11	15.19±0.31	0.1947± 8	2783± 7	4
15-1	254	18	0.07	22	0.25	0.544±11	14.97±0.30	0.1995± 8	2822± 7	–1
15-2	287	50	0.17	5	0.05	0.545±11	15.05±0.30	0.2003± 7	2829± 5	–1
GGU 358673 – *homogeneous tonalitic orthogneiss*										
1-1	201	57	0.29	4	0.06	0.525±11	14.32±0.31	0.1977± 9	2807± 7	–3
2-1	3887	53	0.01	5	<0.01	0.519±10	13.87±0.28	0.1938± 2	2775± 2	–3
3-1	73	21	0.28	3	0.12	0.534±11	14.82±0.34	0.2014±13	2829±15	–3
4-1	498	242	0.49	4	0.02	0.531±11	14.72±0.30	0.2009± 5	2834± 4	–3
5-1	440	17	0.04	5	0.04	0.516±10	14.08±0.30	0.1983± 7	2810± 6	–5
6-1	1764	161	0.09	2	<0.01	0.536±11	14.88±0.30	0.2012± 3	2836± 2	–2
7-1	486	205	0.42	2	0.02	0.523±11	14.40±0.30	0.1997± 6	2823± 5	–4
8-1	274	81	0.30	13	0.14	0.541±11	14.71±0.31	0.1972± 8	2803± 6	–1
9-1	333	126	0.38	1	0.01	0.535±11	14.85±0.31	0.2011± 7	2836± 6	–3
10-1	613	267	0.44	2	0.01	0.554±11	15.09±0.31	0.1976± 5	2807± 4	1
11-1	261	190	0.73	5	0.05	0.532±11	14.89±0.32	0.2029± 9	2849± 8	–3
GGU 269310 – *trondhjemite, Atâ intrusive complex*										
1-1	200	15	0.07	3	0.06	0.457± 7	13.31±0.21	0.2110± 9	2913± 7	–17
1-2	263	37	0.14	1	0.01	0.505± 7	13.70±0.21	0.1969± 7	2800± 6	–6
2-1	96	40	0.41	<1	<0.01	0.515± 8	14.09±0.24	0.1984±12	2813±10	–5
3-1	52	30	0.56	5	0.27	0.555± 9	14.73±0.31	0.1925±22	2763±19	3
4-1	194	55	0.28	25	0.47	0.430± 6	11.83±0.20	0.1994±15	2821±12	–18
5-1	400	53	0.13	15	0.11	0.515± 8	13.92±0.21	0.1963± 6	2796± 5	–4
6-1	604	446	0.74	<1	<0.01	0.522± 7	14.25±0.21	0.1982± 5	2811± 4	–4
7-1	314	142	0.45	13	0.12	0.534± 8	14.54±0.22	0.1974± 7	2805± 6	–2
8-1	721	267	0.37	16	0.07	0.486± 7	12.70±0.19	0.1895± 5	2738± 4	–7
9-1	457	90	0.20	11	0.07	0.536± 8	14.47±0.22	0.1957± 6	2790± 5	–1
10-1	622	136	0.22	6	0.03	0.527± 7	14.27±0.21	0.1963± 5	2796± 4	–2
11-1	670	702	1.05	7	0.04	0.495± 7	13.32±0.20	0.1954± 5	2788± 4	–7
12-1	244	35	0.15	20	0.25	0.503± 7	13.24±0.21	0.1910± 9	2751± 8	–7
13-1	938	202	0.21	4	0.01	0.514± 7	13.70±0.20	0.1933± 4	2770± 3	–3
14-1	387	191	0.49	<1	<0.01	0.524± 8	14.26±0.21	0.1975± 6	2805± 5	–3
15-1	903	227	0.25	15	0.05	0.483± 7	12.68±0.18	0.1905± 4	2746± 3	–8
GGU 348683 – *granite cutting Atâ intrusive complex*										
1-1	1504	958	0.64	7	0.02	0.502±11	13.42±0.29	0.1939± 3	2776± 3	–6
2-1	802	515	0.64	6	0.04	0.493±10	13.08±0.28	0.1924± 4	2762± 4	–6
3-1	1159	1105	0.95	12	0.05	0.512±11	13.54±0.29	0.1917± 3	2757± 3	–3
4-1	2257	1696	0.75	5	0.01	0.531±11	14.01±0.30	0.1915± 2	2755± 2	0
5-1	807	733	0.91	7	0.04	0.522±11	13.84±0.30	0.1924± 4	2763± 3	–2
6-1	895	708	0.79	3	0.02	0.489±10	12.89±0.28	0.1912± 4	2753± 3	–7
6-2	870	788	0.91	152	0.78	0.486±10	10.84±0.24	0.1616± 6	2472± 6	3
7-1	320	172	0.54	1	0.01	0.511±11	11.83±0.26	0.1681± 6	2538± 6	5
8-1	153	65	0.51	2	0.06	0.507±11	13.32±0.31	0.1905±10	2747± 9	–4
8-2	194	108	0.56	2	0.06	0.477±10	12.63±0.29	0.1919±13	2758±11	–9
9-1	1087	566	0.52	73	0.30	0.497±10	12.65±0.27	0.1845± 4	2693± 4	–3
10-1	1493	443	0.30	11	0.03	0.480±10	12.72±0.27	0.1923± 3	2762± 3	–9
11-1	667	452	0.68	97	0.66	0.477±10	12.09±0.26	0.1839± 6	2689± 5	–7
12-1	1093	1071	0.98	12	0.05	0.522±11	13.58±0.29	0.1888± 3	2731± 3	–1
13-1	430	292	0.68	1	0.01	0.535±11	14.17±0.31	0.1921± 6	2760± 5	0
14-1	614	391	0.64	<1	<0.01	0.533±11	14.05±0.30	0.1912± 4	2752± 4	0
15-1	411	197	0.48	<1	<0.01	0.549±12	14.35±0.31	0.1896± 5	2739± 5	3
16-1	265	71	0.27	104	1.82	0.465±10	11.73±0.28	0.1832±14	2682±13	–8

* $^{207}Pb/^{206}Pb$ ages corrected for very small amounts of common lead. Uncertainties given at 1σ level.
'disc.' (discordance in per cent) calculated as 100 ($^{206}Pb/^{238}U$ age)/($^{207}Pb/^{206}Pb$ age) – 100.

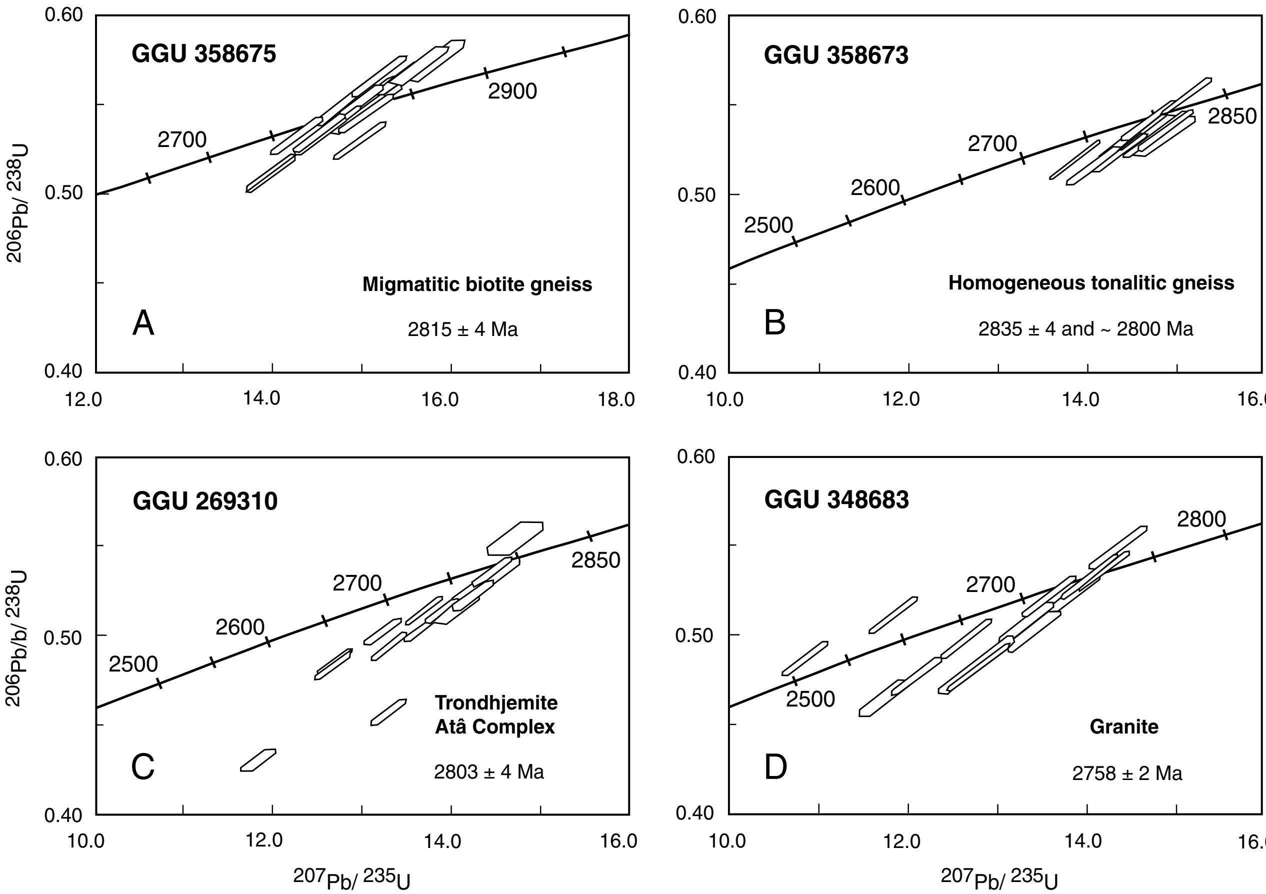

Fig. 2. U-Pb concordia diagrams for zircons from granitoid rocks in the Ataa area, north-east Disko Bugt.

with the data: (1) The older group dates the emplacement of the granitoid rock at *c.* 2835 Ma; the younger $^{207}Pb/^{206}Pb$ ages would then be the result of ancient lead loss. (2) The older group can be regarded as an inherited component within a granitoid rock emplaced *c.* 2800 Ma ago. Neither the analytical data nor the morphology of the zircons permit distinction between the two alternative models.

GGU 269310, trondhjemite from the Atâ intrusive complex. This sample was collected on Illuluarsuit Nunataat (69°50.1′ N, 50°33.8′ W, Fig. 1) from the central part of the eastern Atâ complex (Kalsbeek & Skjernaa 1999, this volume). The rocks are here trondhjemitic in composition and hardly deformed.

Zircons are euhedral prismatic crystals and vary from nearly colourless to dark brown. Euhedral zoning is common, and cores of dark zircon may be present within light brown crystals.

Sixteen analysed spots on 15 zircons show a variation in U and Th from 52 to 938 ppm and from 15 to 702 ppm respectively; Th/U 0.07–1.05 (Table 1). $^{207}Pb/^{206}Pb$ ages range from 2738 to 2913 Ma with a main group around 2800 Ma (Fig. 2C). The two grains with highest $^{207}Pb/^{206}Pb$ ages are highly discordant, and may represent inherited zircon. Successively eliminating analyses with lowest $^{207}Pb/^{206}Pb$ (on the assumption that this is the result of ancient lead loss), a remaining group of 7 grains yields an age of 2803 ± 4 Ma. We interpret this as the age of emplacement of the trondhjemite.

GGU 348683, granite intruding the Atâ complex. The sample was collected on Arveprinsen Ejland at 69°44.8′ N, 51°04.6′ W (Fig. 1) from an undeformed granite which intrudes strongly strained tonalite of the Atâ complex. Most zircons are euhedral prismatic grains up to *c.* 400 µm long, with colours in variable shades of yellow and brown, from water clear to dark brown. A few large brown stubby crystals are also present: one zircon fragment is 550 µm long and 260 µm wide.

Eighteen spots were analysed on 16 zircon grains (Fig. 2D; Table 1). U and Th contents range from 153 to 2257 and from 65 to 1696 ppm respectively, while Th/U shows a moderate range, 0.27–0.98. Thirteen zircons yield $^{207}Pb/^{206}Pb$ ages in the range of 2730–2770 Ma; five analyses gave ages < 2700 Ma, suggesting major lead loss after initial zircon crystallisation. Eliminating a few more analyses on the basis of apparent minor lead loss, 8 remaining grains yield a mean $^{207}Pb/^{206}Pb$ age of 2758 ± 2 Ma, which we interpret to date the time of granite emplacement. Three analyses on stubby brown zircon grains were not significantly different from those on prismatic crystals.

Discussion

The oldest reliable age obtained in this study is 2815 Ma for the grey migmatitic biotite gneiss (GGU 358675). Data for the non-migmatitic tonalitic orthogneiss GGU 358673 do not yield a reliable age. The age obtained for the older group of zircons is 2835 ± 4 Ma. Field evidence (p. 49) has been interpreted to suggest that this rock is younger than the grey migmatitic biotite gneisses. If that is indeed the case the age of emplacement of the tonalitic precursor of GGU 358673 may be around or slightly older than 2800 Ma, equivalent to the age of GGU 269310 from the Atâ intrusive complex. In the field the non-migmatitic tonalitic orthogneisses are reminiscent of rocks from the Atâ intrusive complex, and they occur as a unit along strike of outcrops of the Atâ complex east of Eqi (Fig. 1). However, field relationships in high-grade polyphase gneiss regions are often extremely complex, and heterogeneous strain in an area of plutonic rocks, emplaced as a series of intrusions with age differences of a few million years makes correlations over large distances less reliable. Moreover, the Sm-Nd model age of 2930 Ma obtained for this sample (Kalsbeek & Taylor 1999, this volume) suggests it may contain a component of older crustal material. In summary, the available data do not permit a reliable interpretation of the zircon dates.

The Atâ complex is a composite intrusion with older, more deformed tonalitic phases and younger, largely undeformed trondhjemites and granodiorites (Kalsbeek & Skjernaa 1999, this volume). The sample investigated in this study (GGU 269310) belongs to a young trondhjemitic phase of the complex. The age of 2803 ± 4 Ma is closely similar to the earlier age estimate of *c.* 2800 Ma for the Atâ complex (Kalsbeek *et al.* 1988). These authors report a multigrain U-Pb age of 2794 ± 15 Ma on zircons from an older, deformed tonalite collected near the abandoned village Ataa (Fig. 1). The two ages are the same within error, and the different phases of the complex are probably not very different in age. Kalsbeek *et al.* (1988) report a Sm-Nd (T_{DM}) model age of 2800 ± 40 Ma for GGU 269310, which suggests that it hardly contains significant proportions of older crustal material.

In the southern parts of its outcrop area the Atâ complex is cut by a multitude of thin granitoid dykes. These were interpreted by Kalsbeek *et al.* (1988) as cooling joints filled by late stage melts related to the complex itself. However, subsequent field work during GGU's Disko Bugt Project showed (1) that granitoid dykelets gradually disappear towards the north, and (2) that the Atâ complex is intruded by younger granites at its southern margin. One of these younger granites (GGU 348683), investigated during the present study, has yielded an age of 2758 ± 2 Ma, significantly younger than samples from the Atâ complex. It now seems more likely that the granitoid dykes in the southern parts of the Atâ complex are not related to the complex itself but to the younger intrusions at its southern margin.

Most of the analysed zircons from all four samples are concordant or near concordant. This is consistent with suggestions from other lines of evidence (e.g. the finding of a reasonably well-fitted 2825 ± 50 Ma Rb-Sr isochron for a pink granite from Arveprinsen Ejland; Kalsbeek & Taylor 1999, this volume) that Archaean rocks in the Ataa region did not undergo nearly the same degree of Proterozoic disturbance as in the Nagssugtoqidian and Rinkian mobile belts, respectively to the south and to the north of the Ataa area.

Acknowledgements

We thank Professor W. Compston for permission to use the ion microprobe at the Australian National University, Canberra, for this study, Mogens Marker (at the time with the Danish Lithosphere Centre, Copenhagen) for providing us with samples GGU 358673 and GGU 358675, and Adam A. Garde (Geological Survey of Denmark and Greenland) for constructive comments on the manuscript.

References

Compston, W., Williams, I.S. & Meyer, C. 1984: U-Pb geochronology of zircons from Lunar Breccia 73217 using a sensitive high mass-resolution ion microprobe. Proceedings of the 14th Lunar and Planetary Science Conference, Journal of Geophysical Research Supplement **89**, B525–534.

DePaolo, D.J. 1981: Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature (London) **291**, 193–196.

Escher, A. & Burri, M. 1967: Stratigraphy and structural development of the Precambrian rocks in the area north-east of Disko Bugt, West Greenland. Rapport Grønlands Geologiske Undersøgelse **13**, 28 pp.

Escher, J.C. 1995: Geological map of Greenland, 1:100 000, Ataa 69 V.3 Nord. Copenhagen: Geological Survey of Greenland.

Escher, J.C., Ryan, M.J. & Marker, M. 1999: Early Proterozoic thrust tectonics east of Ataa Sund, north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 171–179 (this volume).

Garde, A.A. 1994: Precambrian geology between Qarajaq Isfjord and Jakobshavn Isfjord, West Greenland, 1:250 000. Copenhagen: Geological Survey of Greenland.

Garde, A.A. & Steenfelt, A. 1999: Precambrian geology of Nuussuaq and the area north-east of Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 6–40 (this volume).

Kalsbeek, F. & Skjernaa, L. 1999: The Archaean Atâ intrusive complex (Atâ tonalite), north-east Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 103–112 (this volume).

Kalsbeek, F. & Taylor, P.N. 1999: Review of isotope data for Precambrian rocks from the Disko Bugt region, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 41–47 (this volume).

Kalsbeek, F., Taylor, P.N. & Pidgeon, R.T. 1988: Unreworked Archaean basement and Proterozoic supracrustal rocks from northeastern Disko Bugt, West Greenland: implications for the nature of Proterozoic mobile belts in Greenland. Canadian Journal of Earth Sciences **25**, 773–782.

Williams, I.S., Buick, I.S. & Cartwright, I. 1996: An extended episode of early Mesoproterozoic fluid flow in the Reynolds Range, central Australia. Journal of Metamorphic Geology **14**, 29–47.