

Establishment of a 3.83-Ga magmatic age for the Akilia tonalite (southern West Greenland)

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This paper is dedicated to the late Vic McGregor who first recognized, described, and mapped the rocks of the 'Akilia association' in southern West Greenland.

Abstract

A recurring challenge to ion microprobe U–Pb zircon geochronology has been to discriminate between preservation of original igneous zircon populations and inherited grains. This has proved particularly problematic in studying the polyphase metamorphic rocks that dominate Early Archean gneissic terranes. For example, differing interpretations exist for the origin of complex zircon populations investigated by U–Pb ion microprobe zircon geochronology from a granitoid (orthogneiss) body, previously used to establish a minimum age for a supracrustal enclave on Akilia (island) in southern West Greenland. We describe a method whereby the geochemistry of the Akilia orthogneiss, coupled with a U–Th–Pb vs. age depth profile in a zircon from the same rock, permits direct assessment of zircon inheritance. Results reveal evidence for three phases of concentric zircon growth at 3.83 Ga, ~ 3.6 Ga and 2.7–2.5 Ga; zircon growth at both ~ 3.6 Ga and 2.7–2.5 Ga is consistent with precipitation from a metamorphic fluid. Depth profile U–Th–Pb data demonstrate that only the > 3.8 -Ga zircon core could have crystallized from the host rock. We conclude that the magmatic age of this rock is 3.83 ± 0.01 Ga, not ~ 3.65 Ga as has been previously proposed. The U–Th–Pb zircon depth profile technique has wider applications to resolving other geochronological debates in high-grade metamorphic terranes where zircons populations are diverse and individual grains record complex overgrowth and dissolution/re-precipitation features. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Archean; West Greenland; zircon; geochronology; life origin; ion probe data

1. Introduction

Early Archean supracrustal rocks, preserved within highly metamorphosed granitoid gneiss complexes, provide the only direct record of the state of the continental crust, hydrosphere and biosphere prior to ~ 3.5 Ga. These ancient volcano-sedimentary assemblages form the baseline for understanding early planetary processes, including the timing of the emergence of life on Earth and

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its potential to have appeared elsewhere in the solar system. In these terranes, sediments typically appear as highly metamorphosed and strongly deformed supracrustal enclaves, ranging in size from less than a meter wide to tens of kilometers in length. All are locked within voluminous granitoid gneisses [1]. The oldest recognized supracrustal enclave [2,3] is a ~5-m-thick layer of quartz–magnetite ‘ironstone’ interposed between 10–40-m-thick layers of amphibolite and ultramafic rocks on the southwestern point of Akilia (island) [4], Ameralik fjord region, West Greenland (Fig. 1). Tonalitic to granodioritic orthogneisses on Akilia found in contact with the northern and eastern margins of the supracrustal enclave yield complex U–Pb zircon ages as old as 3.87 Ga [3,5–7]. These results have been interpreted [3,5] as the age of the igneous protoliths to the orthogneisses and provide a minimum age of the associated supracrustal rocks. Carbon isotope data [2] have been interpreted to indicate bioorganic activity during deposition of the metasedimentary rocks on Akilia (cf. [35]). If these interpretations are correct, it would mean that life emerged on Earth significantly earlier than previously established [2,3,8–10]. Other carbon isotope evidence from the Isua supracrustal belt 150 km northeast of Akilia, places the emergence of life at least before 3.77 Ga [8,11], thereby raising the likelihood for an early and rapid emergence of the biosphere on Earth.

However, several authors [12,13] have argued based on whole-rock and mineral common Pb data that the geologically diverse ‘Amîtsoq’ orthogneisses of West Greenland, including those that host Akilia sedimentary enclaves, are the product of a single ~3.6-Ga crustal formational event. This interpretation is in conflict with the view that the at present large (3000 km²) and geologically heterogeneous ‘Itsaq Gneiss Complex’ [5] formed in a protracted fashion from ~3.9 to 3.6 Ga. If the age of generically termed ‘Amîtsoq’ granitoid crystallization is actually ca. 3.6 Ga, this would suggest that all >3.8-Ga zircons contained in various orthogneisses of West Greenland thus far analyzed, including those on Akilia and nearby islands, are inherited.

Resolving the question of inheritance vs. protolith igneous origin of complex zircons, particu-

larly with regard to the age of the orthogneisses on Akilia, has implications for the age of rocks hosting the oldest known sediments and reported evidence for life contained therein [2], as well as for the timing and nature of events at the surface during the emergence of the biosphere. Confirmation of a >3.8-Ga age for the Akilia orthogneisses and the associated metasediments and their biological signatures is significant because it would place their deposition prior to termination of an extended (and ill-defined) period of meteoritic and cometary bombardment of the inner solar system centered at ca. 3.85 Ga [14,15] and coeval with the presence of liquid water on early Mars [16,17].

2. Zircon growth events in the Archean (~3.8 Ga, 3.6 Ga and 2.7 Ga)

There is general agreement that the gneisses on Akilia contain at least three zircon age populations: ca. 3.85 Ga, ~3.6 Ga, and ~2.7 Ga [3,5–7]. A recently proposed explanation [6,7,13] for this age variation is that the ~2.7-Ga zircons are metamorphic overgrowths, the ~3.6-Ga grains are igneous and all of the oldest grains are inherited [12].

That the tonalitic protolith of the Akilia orthogneiss in question can only be ~3.6 Ga [6,7,12,13] is problematic in our view for the following reasons.

(1) The strongly zircon *undersaturated* [18] nature of the original magma (Table 1; Fig. 2) intruding at ~950°C [19] into zircon-poor supracrustal rocks such as amphibolite and hornblende on Akilia is unlikely to preserve widespread inherited zircon. Tonalitic orthogneiss sample GR9716 [16] studied here (equivalent to G93/05 of Nutman et al. [3,5] and SM/GR/97/7 of Whitehouse et al. [6,7]) has a Zr abundance of 144 ppm (Table 1) and the observed whole rock composition is probably close to that of the protolith magma [19]. Thus, at temperatures ~950°C and $M = (Na+K+2Ca/Si \times Al)$ [18] of 1.54, the solubility of zircon in the tonalite melt would have been close to 900 ppm (Fig. 2) far below the 144 ppm Zr present in GR9716.

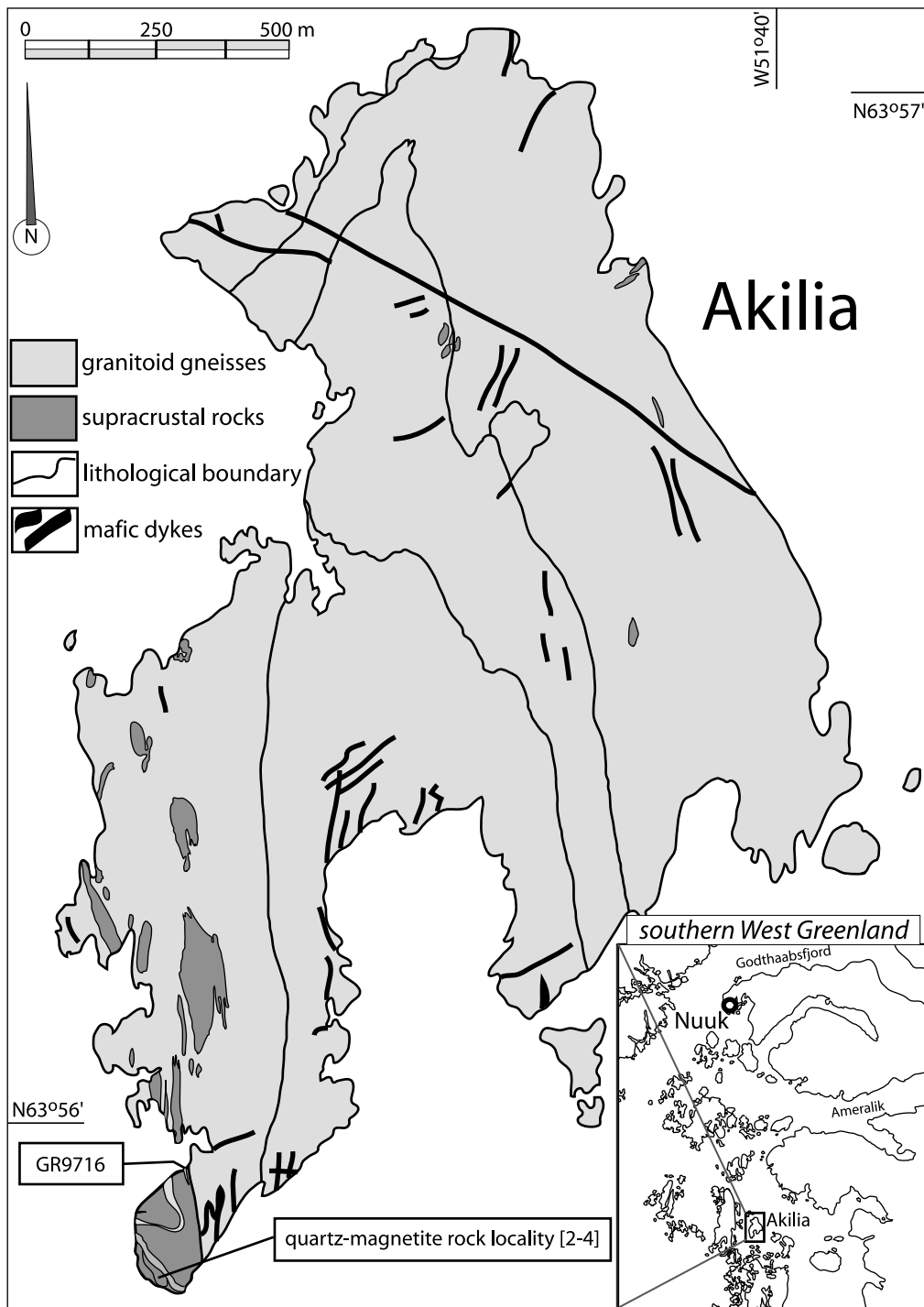


Fig. 1. Locality map showing Akilia (island) within the Early Archean 'Itsaq Gneiss Complex' in the vicinity of Ameralik (fjord) in southern West Greenland (inset). A complex association of supracrustal rocks and associated gneisses are found on Akilia (island). Adjacent islands and coastal areas contain similar relationships [3–5,22,26,27] that await further detailed study. Map modified after A.P. Nutman (unpublished manuscript).

(2) While Kamber and Moorbath [13] emphasized the lack of 3.8-Ga common Pb in feldspars from Akilia orthogneisses, metamorphism at ~ 3.6 Ga occurred under granulite grade conditions ($> 750^\circ\text{C}$ and 7 kbar; [20]) that would readily cause exchange of primitive Pb isotopes in feldspar [21] with radiogenic Pb released from U-rich phases, dominantly zircon. Thus, their observation [13] is the expected result of a 3.6-Ga high-grade metamorphic event and does not preclude a 3.8-Ga protolith age.

It has been pointed out [22] that the diverse rocks arbitrarily assigned a common ‘Amîtsoq gneiss’ origin and analyzed together by Kamber and Moorbath [13] are in fact petrogenetically unrelated and therefore do not provide data relevant to the ages of the Akilia supracrustal enclaves or the orthogneisses that surround and in some cases, intrude them. Hence, the controversy we address here is based on zircon U–Pb isotope geochronology on an Akilia orthogneiss that was originally assigned an igneous protolith age of 3.85 Ga [3] but was subsequently reevaluated by Whitehouse et al. [6,7] who have argued for widespread zircon inheritance and a protolith age of ~ 3.65 Ga.

Table 1
Whole rock geochemistry of sample GR9716

| Major elements | wt% |
|--------------------------------|------|
| SiO ₂ | 65.5 |
| Al ₂ O ₃ | 16.9 |
| Fe ₂ O ₃ | 3.91 |
| MnO | 0.06 |
| MgO | 2.26 |
| CaO | 4.65 |
| Na ₂ O | 3.75 |
| K ₂ O | 1.31 |
| TiO ₂ | 0.38 |
| P ₂ O ₅ | 0.29 |
| LOI | 0.54 |
| Total | 99.6 |
| Trace elements | ppm |
| Zr | 144 |
| Th | 1.8 |
| U | 0.5 |
| Pb | 8.0 |

$M = 1.54^a$

^a [18].

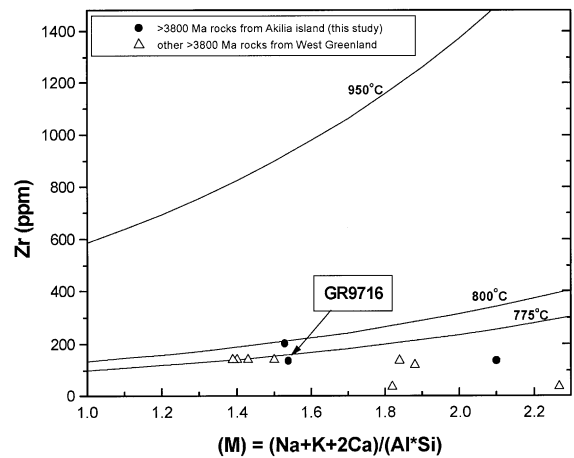


Fig. 2. Zircon saturation curves [18] plotted for a source temperature of 950°C and lower temperatures (800°C , 775°C) plotted near the freezing point of tonalitic melts [19]. We note that at the source temperature of 950°C all homogeneous orthogneisses identified from southern West Greenland that provide U–Pb zircon ages older than 3.8 Ga [4,5,16,22] are severely undersaturated in Zr and any zircon entrained in such melts would have a strong likelihood of dissolving. Hence, the chance for widespread zircon inheritance (cf. [6,7,12,13]) in any of these rocks is low.

In this paper, we undertake two new styles of analysis in order to evaluate the likelihood of zircon inheritance in the Akilia tonalitic orthogneisses, i.e. U–Th–Pb isotope depth profiling of individual zircons and in situ analysis of zircon in petrographic thin section.

3. Methods

We analyzed zircons from the same tonalitic orthogneiss locality collected from the northern margin of the southwestern peninsula of Akilia, West Greenland (Fig. 1), from which Nutman et al. [3], Whitehouse et al. [6,7] and Mojzsis and Harrison [16] (sample GR9716) obtained their results.

3.1. Conventional ion microprobe U–Pb geochronology

All U–Pb ion microprobe analyses of zircons, extracted by conventional heavy mineral separa-

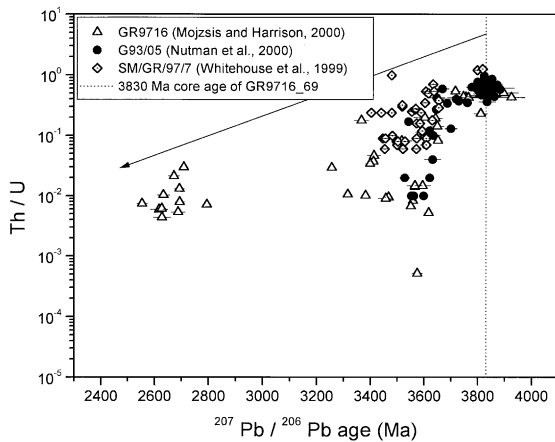


Fig. 3. Compilation of $^{207}\text{Pb}/^{206}\text{Pb}$ ion microprobe ages of zircons from orthogneiss sample GR9716 in contact with the supracrustal enclave on Akilia [3,5–7,22,27]. The zircon population at ~ 3.85 Ga, interpreted here to represent the magmatic age of the granitoid, has uniformly high Th/U values. Younger zircons generally exhibit lower Th/U values more characteristic of a metamorphic origin and correlate with well-documented metamorphic events in West Greenland at ~ 3.6 Ga and ~ 2.7 Ga [3–5,20,22].

tion of whole-rock powders or by in situ measurements in petrographic thin section, were determined using the UCLA CAMECA ims 1270 ion microprobe. Separated zircon grains were hand-picked, mounted in epoxy and polished on $0.25\ \mu\text{m}$ alumina; all samples were coated with $\sim 100\ \text{\AA}$ of Au using a sputter-coater. The standard operating conditions for analysis presented here are a O_2^- primary beam focused to a $\sim 20 \times 25\ \mu\text{m}$ spot; the ion microprobe was operated at a mass resolving power of 6000 with an energy window of 50 eV. An offset voltage of 5–15 eV was used for $^{238}\text{U}^+$ relative to Pb^+ and UO^+ to compensate for their contrasting energy distributions. Oxygen flooding to a pressure of 3.5×10^{-5} torr was employed to increase Pb^+ yields. U–Pb ages were determined by comparison with a working curve defined by multiple measurements of standard zircon AS-3 that yield concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of 1099.1 ± 0.5 Ma [23].

All studies to date of the contested orthogneiss outcrop on Akilia using U–Pb zircon spot ages on separated zircons yield a similar age distribution and a general trend toward lower Th/U ratio with

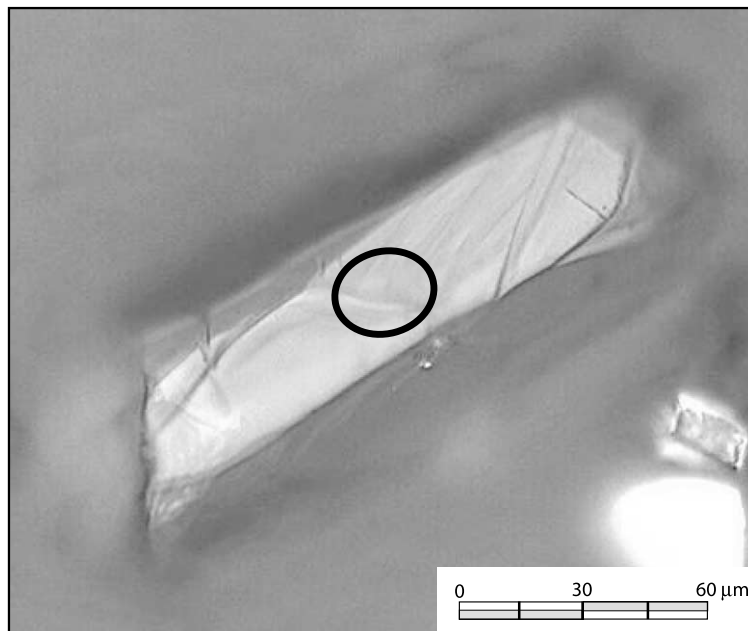


Fig. 4. Optical micrograph of unpolished euhedral zircon grain GR9716_69 used in U–Th–Pb depth profile analysis.

Table 2
Ion microprobe depth profile analyses of zircon GR9716_69

| Depth (μm) | $^{206}\text{Pb}^*/^{238}\text{U}$ | $^{207}\text{Pb}^*/^{235}\text{U}$ | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ age (Ma) | $\%^{206}\text{Pb}^*$ | Th/U | $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ |
|----------------------------|------------------------------------|------------------------------------|---------------------------------------|---|-----------------------|--------|---------------------------------------|
| 0.00 | 0.455 ± 0.011 | 10.96 ± 0.35 | 0.1745 ± 0.0032 | 2602 ± 17 | 99.78 | 0.0134 | 0.0093 |
| 0.19 | 0.471 ± 0.011 | 11.46 ± 0.26 | 0.1764 ± 0.0020 | 2619 ± 10 | 99.73 | 0.0169 | 0.0068 |
| 0.37 | 0.479 ± 0.016 | 12.03 ± 0.37 | 0.1823 ± 0.0035 | 2674 ± 17 | 99.89 | 0.0151 | 0.0074 |
| 0.56 | 0.536 ± 0.012 | 12.33 ± 0.31 | 0.1669 ± 0.0022 | 2527 ± 12 | 99.65 | 0.004 | 0.0063 |
| 0.74 | 0.574 ± 0.025 | 13.62 ± 0.55 | 0.1721 ± 0.0022 | 2578 ± 12 | 99.93 | 0.0047 | 0.0029 |
| 0.93 | 0.582 ± 0.033 | 14.27 ± 0.79 | 0.1777 ± 0.0029 | 2632 ± 14 | 99.98 | 0.0042 | 0.0026 |
| 1.12 | 0.550 ± 0.011 | 13.34 ± 0.25 | 0.1759 ± 0.0016 | 2614 ± 8 | 99.95 | 0.0075 | 0.0045 |
| 1.30 | 0.546 ± 0.013 | 13.54 ± 0.31 | 0.1800 ± 0.0016 | 2653 ± 8 | 99.97 | 0.0136 | 0.0049 |
| 1.49 | 0.567 ± 0.015 | 14.10 ± 0.34 | 0.1806 ± 0.0013 | 2658 ± 7 | 100 | 0.0147 | 0.0055 |
| 1.67 | 0.551 ± 0.011 | 14.02 ± 0.29 | 0.1846 ± 0.0015 | 2695 ± 7 | 99.98 | 0.0212 | 0.0064 |
| 1.86 | 0.537 ± 0.018 | 13.79 ± 0.50 | 0.1861 ± 0.0024 | 2708 ± 11 | 99.98 | 0.0212 | 0.0064 |
| 2.05 | 0.522 ± 0.011 | 13.31 ± 0.30 | 0.1850 ± 0.0029 | 2698 ± 14 | 100 | 0.0174 | 0.007 |
| 2.23 | 0.439 ± 0.011 | 11.30 ± 0.27 | 0.1868 ± 0.0015 | 2714 ± 7 | 99.99 | 0.0226 | 0.0073 |
| 2.42 | 0.415 ± 0.015 | 10.54 ± 0.34 | 0.1843 ± 0.0013 | 2692 ± 6 | 100 | 0.0181 | 0.0061 |
| 2.60 | 0.358 ± 0.011 | 9.15 ± 0.24 | 0.1855 ± 0.0030 | 2703 ± 15 | 99.99 | 0.0113 | 0.0042 |
| 2.79 | 0.325 ± 0.009 | 8.33 ± 0.24 | 0.1859 ± 0.0031 | 2706 ± 15 | 99.99 | 0.0111 | 0.0035 |
| 2.98 | 0.310 ± 0.006 | 8.00 ± 0.16 | 0.1871 ± 0.0032 | 2717 ± 15 | 100 | 0.0084 | 0.0033 |
| 3.16 | 0.299 ± 0.005 | 7.69 ± 0.13 | 0.1864 ± 0.0018 | 2711 ± 9 | 100 | 0.0053 | 0.002 |
| 3.35 | 0.515 ± 0.028 | 12.01 ± 0.69 | 0.1690 ± 0.0028 | 2548 ± 15 | 99.81 | 0.0009 | 0.0054 |
| 3.53 | 0.538 ± 0.011 | 13.10 ± 0.29 | 0.1766 ± 0.0017 | 2621 ± 9 | 99.93 | 0.0014 | 0.0021 |
| 3.72 | 0.559 ± 0.017 | 13.73 ± 0.40 | 0.1782 ± 0.0023 | 2636 ± 11 | 99.97 | 0.0012 | 0.0015 |
| 3.91 | 0.717 ± 0.134 | 30.70 ± 5.57 | 0.3104 ± 0.0088 | 3523 ± 20 | 99.98 | 0.0149 | 0.0059 |
| 4.09 | 0.786 ± 0.094 | 33.83 ± 3.98 | 0.3120 ± 0.0039 | 3531 ± 9 | 99.99 | 0.0114 | 0.0048 |
| 4.28 | 0.705 ± 0.153 | 30.80 ± 6.49 | 0.3170 ± 0.0079 | 3555 ± 18 | 99.93 | 0.0165 | 0.0052 |
| 4.47 | 0.823 ± 0.069 | 37.66 ± 3.10 | 0.3320 ± 0.0045 | 3626 ± 9 | 100 | 0.0162 | 0.0037 |
| 4.65 | 0.782 ± 0.069 | 36.11 ± 3.19 | 0.3348 ± 0.0049 | 3639 ± 10 | 100 | 0.0155 | 0.0036 |
| 4.84 | 0.800 ± 0.120 | 36.20 ± 5.42 | 0.3281 ± 0.0061 | 3608 ± 12 | 99.95 | 0.0156 | 0.0037 |
| 5.02 | 0.638 ± 0.094 | 32.06 ± 5.07 | 0.3647 ± 0.0095 | 3769 ± 17 | 100 | 0.4487 | 0.1329 |
| 5.21 | 0.714 ± 0.229 | 36.24 ± 11.71 | 0.3680 ± 0.0151 | 3783 ± 27 | 99.86 | 0.4135 | 0.1392 |
| 5.40 | 0.600 ± 0.066 | 30.31 ± 3.33 | 0.3666 ± 0.0090 | 3777 ± 16 | 99.83 | 0.4521 | 0.1373 |
| 5.58 | 0.806 ± 0.105 | 35.79 ± 4.57 | 0.3218 ± 0.0039 | 3579 ± 8 | 100 | 0.0131 | 0.0039 |
| 5.77 | 0.850 ± 0.136 | 38.56 ± 6.30 | 0.3291 ± 0.0079 | 3613 ± 16 | 99.99 | 0.0103 | 0.0032 |
| 5.95 | 0.717 ± 0.082 | 31.45 ± 3.64 | 0.3182 ± 0.0045 | 3561 ± 9 | 99.97 | 0.0118 | 0.0035 |
| 6.14 | 0.782 ± 0.059 | 35.05 ± 2.64 | 0.3250 ± 0.0054 | 3593 ± 11 | 100 | 0.0081 | 0.0032 |
| 6.33 | 0.838 ± 0.059 | 37.29 ± 2.64 | 0.3227 ± 0.0046 | 3583 ± 9 | 100 | 0.0135 | 0.0029 |
| 6.51 | 0.840 ± 0.107 | 36.97 ± 4.99 | 0.3194 ± 0.0067 | 3567 ± 14 | 100 | 0.0102 | 0.0032 |
| 6.70 | 0.772 ± 0.082 | 34.97 ± 3.41 | 0.3284 ± 0.0066 | 3610 ± 13 | 99.96 | 0.0166 | 0.0062 |
| 6.88 | 0.848 ± 0.063 | 39.03 ± 2.86 | 0.3337 ± 0.0042 | 3634 ± 8 | 100 | 0.0431 | 0.0163 |
| 7.07 | 0.654 ± 0.074 | 29.81 ± 3.55 | 0.3304 ± 0.0064 | 3619 ± 13 | 100 | 0.0755 | 0.0223 |
| 7.26 | 0.607 ± 0.040 | 28.13 ± 1.92 | 0.3362 ± 0.0056 | 3646 ± 11 | 100 | 0.0784 | 0.0279 |
| 7.44 | 0.745 ± 0.095 | 34.89 ± 4.49 | 0.3395 ± 0.0060 | 3660 ± 12 | 99.89 | 0.1111 | 0.0417 |
| 7.63 | 0.730 ± 0.108 | 35.06 ± 5.49 | 0.3486 ± 0.0123 | 3701 ± 23 | 99.92 | 0.1421 | 0.0522 |
| 7.81 | 0.885 ± 0.177 | 43.50 ± 8.76 | 0.3563 ± 0.0071 | 3734 ± 13 | 99.92 | 0.1961 | 0.0687 |
| 8.00 | 0.717 ± 0.074 | 35.81 ± 3.70 | 0.3623 ± 0.0095 | 3760 ± 17 | 100 | 0.2606 | 0.095 |
| 8.19 | 0.846 ± 0.126 | 43.17 ± 6.48 | 0.3701 ± 0.0097 | 3792 ± 17 | 99.95 | 0.2754 | 0.1101 |
| 8.37 | 0.759 ± 0.099 | 38.17 ± 5.17 | 0.3647 ± 0.0072 | 3770 ± 13 | 100 | 0.3275 | 0.1164 |
| 8.56 | 0.818 ± 0.111 | 41.72 ± 5.38 | 0.3698 ± 0.0078 | 3790 ± 14 | 100 | 0.2991 | 0.1054 |
| 8.74 | 0.801 ± 0.116 | 40.85 ± 5.99 | 0.3697 ± 0.0133 | 3790 ± 23 | 99.8 | 0.4075 | 0.1182 |
| 8.93 | 0.626 ± 0.074 | 32.08 ± 3.95 | 0.3715 ± 0.0088 | 3798 ± 15 | 100 | 0.41 | 0.1313 |
| 9.12 | 0.778 ± 0.090 | 39.40 ± 4.26 | 0.3675 ± 0.0106 | 3781 ± 19 | 99.75 | 0.4266 | 0.1302 |
| 9.30 | 0.818 ± 0.182 | 41.04 ± 9.25 | 0.3637 ± 0.0142 | 3766 ± 25 | 100 | 0.3975 | 0.1277 |
| 9.49 | 0.744 ± 0.143 | 37.45 ± 7.14 | 0.3653 ± 0.0082 | 3772 ± 15 | 99.75 | 0.3961 | 0.1305 |
| 9.67 | 0.708 ± 0.168 | 36.74 ± 8.63 | 0.3762 ± 0.0126 | 3816 ± 20 | 99.87 | 0.4164 | 0.1335 |

Table 2 (Continued).

| Depth (μm) | $^{206}\text{Pb}^*/^{238}\text{U}$ | $^{207}\text{Pb}^*/^{235}\text{U}$ | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ age (Ma) | % $^{206}\text{Pb}^*$ | Th/U | $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ |
|----------------------------|------------------------------------|------------------------------------|---------------------------------------|---|-----------------------|--------|---------------------------------------|
| 9.86 | 0.638 \pm 0.140 | 33.09 \pm 7.24 | 0.3761 \pm 0.0167 | 3816 \pm 27 | 100 | 0.4427 | 0.1367 |
| 10.05 | 0.970 \pm 0.140 | 50.12 \pm 7.60 | 0.3747 \pm 0.0134 | 3810 \pm 22 | 99.87 | 0.5511 | 0.1709 |
| 10.23 | 0.713 \pm 0.109 | 37.81 \pm 5.71 | 0.3846 \pm 0.0088 | 3850 \pm 14 | 99.8 | 0.5682 | 0.1856 |
| 10.42 | 0.841 \pm 0.140 | 43.25 \pm 7.23 | 0.3728 \pm 0.0136 | 3803 \pm 22 | 99.74 | 0.5551 | 0.1655 |
| 10.60 | 1.621 \pm 0.547 | 86.47 \pm 28.76 | 0.3869 \pm 0.0103 | 3859 \pm 16 | 100 | 0.5435 | 0.1481 |
| 10.79 | 0.735 \pm 0.232 | 38.71 \pm 12.30 | 0.3818 \pm 0.0092 | 3839 \pm 14 | 100 | 0.5837 | 0.1609 |
| 10.98 | 0.678 \pm 0.232 | 34.49 \pm 12.11 | 0.3691 \pm 0.0198 | 3788 \pm 35 | 96.62 | 0.6046 | 0.1735 |
| 11.16 | 1.206 \pm 0.909 | 61.05 \pm 46.28 | 0.3671 \pm 0.0248 | 3780 \pm 44 | 100 | 0.7226 | 0.2056 |
| 11.35 | 1.021 \pm 0.289 | 53.21 \pm 14.86 | 0.3780 \pm 0.0098 | 3824 \pm 16 | 100 | 0.7054 | 0.1954 |
| 11.53 | 1.224 \pm 0.446 | 66.35 \pm 24.01 | 0.3932 \pm 0.0157 | 3883 \pm 24 | 100 | 0.6005 | 0.2037 |
| 11.72 | 0.915 \pm 0.196 | 48.08 \pm 10.46 | 0.3813 \pm 0.0092 | 3837 \pm 15 | 100 | 0.5421 | 0.1912 |
| 11.91 | 0.802 \pm 0.256 | 41.93 \pm 13.07 | 0.3793 \pm 0.0174 | 3829 \pm 28 | 100 | 0.6326 | 0.1898 |
| 12.09 | 1.038 \pm 0.223 | 53.96 \pm 11.82 | 0.3772 \pm 0.0129 | 3820 \pm 21 | 99.91 | 0.5583 | 0.1744 |
| 12.28 | 0.837 \pm 0.167 | 43.61 \pm 8.81 | 0.3780 \pm 0.0130 | 3824 \pm 21 | 99.8 | 0.6451 | 0.2037 |
| 12.47 | 1.282 \pm 0.556 | 67.58 \pm 29.39 | 0.3824 \pm 0.0168 | 3841 \pm 27 | 100 | 0.5519 | 0.1953 |
| 12.65 | 0.857 \pm 0.367 | 43.66 \pm 18.61 | 0.3696 \pm 0.0179 | 3790 \pm 32 | 99.91 | 0.6612 | 0.1814 |
| 12.84 | 1.193 \pm 0.301 | 62.12 \pm 15.95 | 0.3778 \pm 0.0144 | 3823 \pm 23 | 99.86 | 0.5895 | 0.1916 |
| 13.02 | 0.948 \pm 0.312 | 49.59 \pm 16.01 | 0.3793 \pm 0.0124 | 3829 \pm 20 | 99.72 | 0.6256 | 0.1973 |
| 13.21 | 0.792 \pm 0.299 | 42.50 \pm 15.99 | 0.3892 \pm 0.0292 | 3868 \pm 45 | 100 | 0.6506 | 0.2049 |
| 13.40 | 0.923 \pm 0.216 | 49.51 \pm 11.63 | 0.3889 \pm 0.0160 | 3867 \pm 25 | 100 | 0.6443 | 0.1781 |
| 13.58 | 1.074 \pm 0.207 | 57.28 \pm 10.77 | 0.3868 \pm 0.0112 | 3858 \pm 18 | 99.57 | 0.5988 | 0.1752 |
| 13.77 | 0.826 \pm 0.158 | 44.25 \pm 8.36 | 0.3886 \pm 0.0136 | 3866 \pm 21 | 100 | 0.67 | 0.2014 |
| 13.95 | 0.897 \pm 0.216 | 47.01 \pm 11.06 | 0.3802 \pm 0.0167 | 3833 \pm 27 | 100 | 0.6721 | 0.1853 |
| 14.14 | 1.069 \pm 0.212 | 57.66 \pm 11.47 | 0.3911 \pm 0.0093 | 3875 \pm 14 | 99.7 | 0.6594 | 0.1984 |
| 14.33 | 1.737 \pm 0.700 | 91.77 \pm 37.30 | 0.3832 \pm 0.0158 | 3845 \pm 25 | 99.53 | 0.6534 | 0.1881 |
| 14.51 | 1.097 \pm 0.234 | 56.91 \pm 12.26 | 0.3762 \pm 0.0162 | 3817 \pm 26 | 99.7 | 0.6198 | 0.2051 |
| 14.70 | 1.207 \pm 0.286 | 64.15 \pm 14.42 | 0.3854 \pm 0.0146 | 3853 \pm 23 | 100 | 0.5865 | 0.1822 |
| 14.88 | 0.745 \pm 0.150 | 38.92 \pm 7.84 | 0.3789 \pm 0.0154 | 3827 \pm 24 | 100 | 0.6133 | 0.1879 |
| 15.07 | 0.790 \pm 0.203 | 42.19 \pm 10.80 | 0.3875 \pm 0.0132 | 3861 \pm 21 | 99.76 | 0.7056 | 0.2059 |
| 15.26 | 0.936 \pm 0.341 | 49.44 \pm 18.23 | 0.3830 \pm 0.0131 | 3844 \pm 21 | 99.3 | 0.6575 | 0.1986 |
| 15.44 | 0.729 \pm 0.168 | 37.86 \pm 8.86 | 0.3765 \pm 0.0124 | 3818 \pm 20 | 100 | 0.731 | 0.1896 |
| 15.63 | 1.187 \pm 0.356 | 62.37 \pm 18.54 | 0.3811 \pm 0.0096 | 3836 \pm 15 | 100 | 0.6226 | 0.1766 |
| 15.81 | 0.808 \pm 0.149 | 42.20 \pm 8.05 | 0.3789 \pm 0.0110 | 3827 \pm 18 | 100 | 0.6641 | 0.2166 |
| 16.00 | 0.963 \pm 0.247 | 51.69 \pm 13.16 | 0.3893 \pm 0.0164 | 3868 \pm 25 | 99.89 | 0.6962 | 0.2184 |

% $^{206}\text{Pb}^*$ is the percent of radiogenic ^{206}Pb . Isotopic ratios have been corrected for common Pb. U–Pb ages were determined by comparison with a working curve defined by measurement of standard zircon AS-3 that yields concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of 1099.1 ± 0.5 Ma by conventional methods [23]. Error demagnification was applied to the data; all uncertainties are reported at the 1σ level.

younger ages (Fig. 3). However, in spot analysis mode, the 2-D spatial selectivity of the ion microprobe is limited by the size of the primary beam, typically 10–30 μm . In the case where a crystal contains symmetrical overgrowths, it is possible to use the ion microprobe in depth profiling mode on an initially unpolished surface to increase spatial resolution by up to two orders of magnitude [24]. This approach, applied to zircons and described below, obtains a continuous age

profile as well as provides geochemical signatures that could bear on the conditions of zircon growth coinciding with documented metamorphic episodes. The technique potentially transcends ambiguity of interpretations of zircon inheritance vs. protolith magmatic ages by linking the geochemistry of the host rock with the minute scale of growth and composition of an individual zircon at a spatial resolution unattainable in normal spot analysis of polished grains.

3.2. Zircon U–Th–Pb depth profile analysis

After evaluation by light microscopy, a separated euhedral zircon grain (GR9716_69) that yielded a concordant U–Pb age of ~ 3.85 Ga [16] was plucked from its ion microprobe mount and an original crystal prism surface placed face down onto adhesive tape together with grains of standard zircon AS-3. The enclosing 1" diameter mold was then recast with epoxy. When cured, the mount was removed from its adhesive backing, cleaned in distilled water and Au coated according to our usual procedures [25] but without ini-

tial polishing (Fig. 4). The internal distributions of U–Pb and Th/U in zircon GR9716_69 were then obtained by a high-resolution depth profiling technique [24] utilizing a ~ 5 -nA primary O^- beam focused to a $30 \times 20 \mu\text{m}$ spot. Pre-sputtering times were 120 s and analysis comprised 15 cycles of 10-s measurements. Each data point listed in Table 2 is composed of one block of analyses made up of three cycles. Analytical sessions in depth profiling mode involved a prolonged and continuous collection time (~ 30 min) from the same spot as the ion beam sputters into the unpolished zircon sample. The extended nature of this depth profile required us to develop an approach different from that of conventional ion microprobe zircon geochronology where spots are analyzed on minerals mounted and polished to their centers. After sputtering a $\sim 5 \mu\text{m}$ deep crater with the O^- ion beam, we measured the pit depth using a DekTak[®] surface profilometer and then repolished by hand the sample surface using a $0.25 \mu\text{m}$ diamond-impregnated lapping film under repeated supervision using reflected-light microscopy of the grain until the crater was $\sim 1 \mu\text{m}$ deep. By measuring the depth of the residual pit from the polishing, we could then accurately calculate the thickness of zircon removed from the polishing. Subsequently the zircon was reanalyzed in depth profile mode by ion microprobe after cleaning and Au coating. We repeated this sequence twice to obtain a $\sim 16\text{-}\mu\text{m}$ -long profile from the surface of the grain to the center.

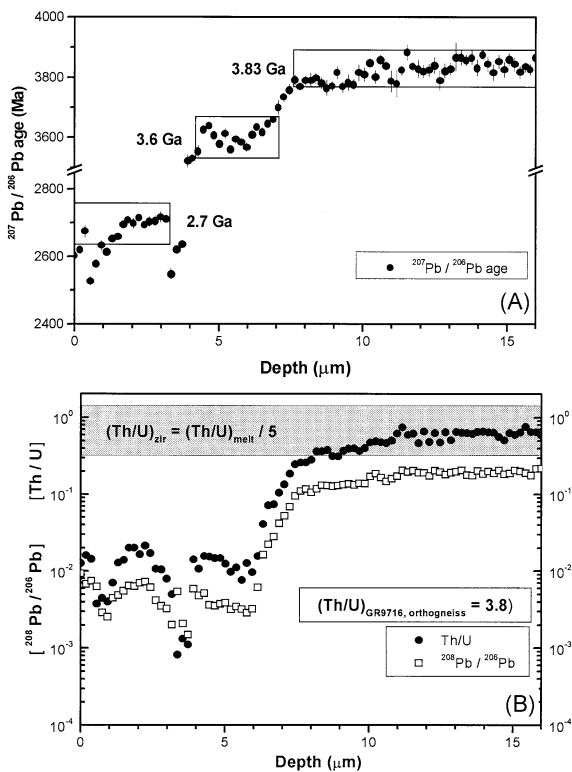


Fig. 5. (a) U–Pb age vs. depth profile in zircon GR9716_69. The spectrum of ages is interpreted to be due to a magmatic core with an age of 3828 ± 8 Ma and metamorphic overgrowths at ~ 3.6 Ga and 2.5–2.7 Ga. (b) Depth profiles of measured Th/U and $^{208}\text{Pb}/^{206}\text{Pb}$. Note the correlation between Th/U increasing from $\sim 10^{-2}$ to 0.8 and increasing age from ~ 3.6 Ga to 3.83 Ga. Grey region shows predicted zircon Th/U crystallizing from a melt of $\text{Th}/\text{U} = 3.8$ assuming $K_{\text{Th}/\text{U}}^{\text{liq}/\text{zir}} = 5$ (\pm factor of two) [30].

4. Results

Our depth profile data (Table 2; Fig. 5) reveal a concentrically zoned crystal containing the previously recognized age components in the Akilia orthogneisses [3,5–7,16,22,26,27]: between 0–3 μm depth, concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages increase essentially monotonically from 2.5 to 2.7 Ga; ages then rise abruptly to a ~ 3.6 -Ga plateau between 3 and 5 μm ; between ~ 8 and 16 μm ages are consistent with a single population. The weighted mean of all 43 $^{207}\text{Pb}/^{206}\text{Pb}$ ages between ~ 8 and 16 μm depth (Table 2) is 3828 ± 8 Ma (2σ ; MSWD = 1.2) (Fig. 5A).

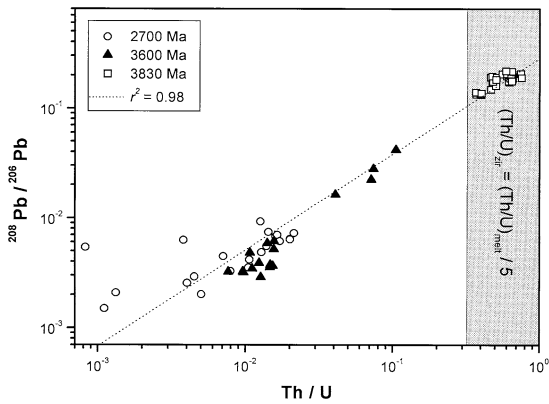


Fig. 6. Correlation diagram of $^{208}\text{Pb}/^{206}\text{Pb}$ vs. Th/U for ion microprobe depth profile data of zircon GR9716_69. The variability of data for the ~ 3.6 -Ga and ~ 2.7 -Ga zones of the zircon are in contrast to the relatively small spread of values for the 3830-Ga component.

4.1. Whole-rock and zircon Th/U chemistry

These depth profile data also show a clear correlation between both the measured Th/U and time-integrated Th/U ($^{208}\text{Pb}/^{206}\text{Pb}$) with apparent U–Pb age. Because zircon is the only magmatic phase in this rock that could significantly fractionate Th from U, the crystallizing tonalitic melt would maintain a Th/U ratio similar to the whole rock value of 3.8 (typical of continental crust [28]) until zircon became saturated (Table 1; Fig. 2) [29]. A zircon grown from a melt with $\text{Th}/\text{U} = 3.8$ is expected to have a Th/U ratio of ~ 0.8 (i.e. $D_{\text{Th}/\text{U}}^{\text{zircon/melt}} = 0.2$) [30]. The only portion of zircon GR9716_69 characterized by a similar value is the 3.83-Ga component, which closely matches the predicted Th/U (Fig. 5B). In contrast, Th/U for the ~ 3.6 -Ga and ~ 2.5 – 2.7 -Ga zones are indistinguishable from one another and are nearly two orders of magnitude lower than the 3.83-Ga portion (Fig. 6).

Because there is agreement that zircon growth at ca. 2.7 Ga is metamorphic [3,5–7], the simplest explanation for the ~ 3.6 -Ga portion is that it too precipitated from an aqueous metamorphic fluid. During prograde metamorphism, Th/U generally increases in orthogneisses from an average crustal value of ~ 4 to as high as 50, implying that U is

preferentially leached relative to Th and that metamorphic fluids are characterized by low Th/U [31,32]. Thus our expectation is that the Th/U ratio of zircon precipitated from a metamorphic fluid would be substantially lower than the magmatic value, both because of the low Th/U of the intergranular fluid and the preferential partitioning of U with respect to Th into the precipitating zircon. The combination of these two effects could explain the decrease in Th/U by two orders of magnitude in the 2.5–2.7-Ga and ~ 3.6 -Ga overgrowths relative to the 3.83-Ga core. We interpret these data to indicate that the only primary magmatic component of this zircon is associated with an age of 3828 ± 8 Ma.

4.2. In situ measurements of zircon in petrographic thin sections

We gained additional insight into the zircon age distribution by U–Pb dating zircons in petrographic thin section of GR9716. Zircons are the dominant Th/U carrying phase and occur in three textural relationships in GR9716, i.e. (1) small ($< 50 \mu\text{m}$) zircons hosted entirely within minimum-melt leucosomes; (2) similarly small zircons hosted by plagioclase; and (3) zircons ranging in size from $50\text{-}\mu\text{m}$ to rarely $250\text{-}\mu\text{m}$ grains, hosted by mafic phases. Eighty-eight U–Pb ages from 71 grains were measured in situ by this technique. In general, ages span the range from ca. 3.8 to 2.5 Ga (Table 3; Fig. 7) with the exception of one zircon encompassed within in biotite that yielded an anomalous age of 4.1 Ga. Zircons in leucosomes yielded only ~ 3.6 -Ga ages. This latter observation is consistent with the earlier inference [20] that partial melting accompanied granulite facies metamorphism at that time [5] and potentially explains the variation of Th/U in ~ 3.6 -Ga zircons (Fig. 3). Both values consistent with primary magmas (~ 0.5) and those expected for precipitation from a metamorphic fluid ($\leq 10^{-1}$) are represented in our data (Fig. 7). We propose that the dissolution/re-precipitation of a significant fraction ($> 50\%$?) of the protolith zircon at ~ 3.6 Ga via partial melting, solution in an aqueous fluid, or Ostwald ripening [33,34], provides a source of radiogenic Pb at that time

Table 3
 Ion microprobe analyses of zircons in situ from orthogneiss sample GR9716

| Grain spot | $^{206}\text{Pb}^*/^{238}\text{U}$ age | $^{207}\text{Pb}^*/^{235}\text{U}$ age | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ age | Th/U |
|------------|--|--|---|--------|
| g1-1 | 3738 ± 173 | 3963 ± 66 | 4079 ± 18 | 0.0740 |
| g11-1 | 3444 ± 105 | 3440 ± 40 | 3437 ± 14 | 0.1480 |
| z11-1 | 3249 ± 58 | 3496 ± 21 | 3641 ± 4 | 0.0700 |
| z14-1 | 3452 ± 49 | 3529 ± 18 | 3574 ± 6 | 0.0910 |
| g6-1 | 3491 ± 54 | 3631 ± 20 | 3709 ± 6 | 0.4070 |
| g17-1 | 3475 ± 62 | 3617 ± 22 | 3696 ± 8 | 0.3640 |
| g17-2 | 3383 ± 86 | 3570 ± 33 | 3677 ± 10 | 0.6030 |
| z1-1 | 3295 ± 69 | 3472 ± 26 | 3576 ± 7 | 0.3960 |
| z1-2 | 2335 ± 95 | 3002 ± 46 | 3485 ± 19 | 0.4480 |
| z2-1 | 3773 ± 64 | 3746 ± 22 | 3732 ± 7 | 0.4560 |
| g4-2 | 3793 ± 54 | 3755 ± 18 | 3735 ± 5 | 0.7630 |
| g4-1 | 3376 ± 47 | 3554 ± 17 | 3656 ± 6 | 0.7570 |
| g16-1 | 3108 ± 78 | 3438 ± 31 | 3636 ± 4 | 0.3320 |
| g16-2 | 1690 ± 40 | 2706 ± 27 | 3586 ± 14 | 0.7210 |
| z13-1 | 1213 ± 40 | 2368 ± 34 | 3598 ± 14 | 0.3610 |
| g5-1 | 3801 ± 96 | 3756 ± 33 | 3732 ± 11 | 0.4050 |
| g2-1 | 2791 ± 139 | 3053 ± 60 | 3231 ± 12 | 0.1040 |
| z3-1 | 3614 ± 71 | 3624 ± 25 | 3629 ± 7 | 0.2250 |
| z4-1 | 3627 ± 65 | 3606 ± 25 | 3594 ± 7 | 0.9690 |
| z6-1 | 3349 ± 82 | 3514 ± 30 | 3610 ± 10 | 0.5920 |
| z8-1 | 3573 ± 46 | 3612 ± 16 | 3633 ± 5 | 0.1720 |
| z10-1 | 3201 ± 88 | 3222 ± 35 | 3236 ± 14 | 0.4660 |
| g3-2 | 3281 ± 158 | 3480 ± 60 | 3597 ± 5 | 0.0930 |
| g3-1 | 2702 ± 65 | 2896 ± 31 | 3033 ± 20 | 0.1470 |
| g9-1 | 1768 ± 66 | 2850 ± 44 | 3741 ± 14 | 0.2780 |
| g18-1 | 3083 ± 81 | 3428 ± 34 | 3636 ± 11 | 0.3310 |
| g14-1 | 2434 ± 80 | 2556 ± 38 | 2654 ± 16 | 0.0440 |
| z5-1 | 2811 ± 77 | 3002 ± 34 | 3133 ± 15 | 0.2760 |
| z7-1 | 3343 ± 82 | 3465 ± 32 | 3536 ± 8 | 0.1490 |
| g8-1 | 3129 ± 99 | 3468 ± 40 | 3670 ± 5 | 0.6620 |
| g12-1 | 3115 ± 87 | 3333 ± 36 | 3466 ± 13 | 0.1190 |
| z9-1 | 3464 ± 43 | 3623 ± 16 | 3713 ± 3 | 0.4430 |
| z12-1 | 3495 ± 52 | 3625 ± 20 | 3697 ± 7 | 0.0930 |
| z15-1 | 2935 ± 62 | 3307 ± 27 | 3540 ± 9 | 0.1560 |
| z16-1 | 3397 ± 46 | 3517 ± 17 | 3587 ± 6 | 0.1630 |
| z17-1 | 3174 ± 33 | 3413 ± 14 | 3556 ± 7 | 0.2310 |
| z18-1 | 3314 ± 41 | 3545 ± 15 | 3678 ± 4 | 0.3080 |
| 15_2_29_1 | 3577 ± 47 | 3606 ± 24 | 3623 ± 14 | 0.2160 |
| 15_2_29_2 | 3546 ± 58 | 3535 ± 42 | 3528 ± 28 | 0.2660 |
| 15_2_33_1 | 3550 ± 34 | 3569 ± 17 | 3580 ± 10 | 0.5920 |
| 15_2_38_1 | 3773 ± 107 | 3597 ± 45 | 3500 ± 20 | 0.1570 |
| 15_2_38_2 | 3730 ± 68 | 3650 ± 38 | 3607 ± 24 | 0.2360 |
| 15_2_39_1 | 3538 ± 25 | 3545 ± 10 | 3548 ± 4 | 0.1200 |
| 15_2_40_1 | 3313 ± 18 | 3457 ± 8 | 3542 ± 6 | 0.0778 |
| 15_2_42_1 | 2855 ± 51 | 3021 ± 39 | 3133 ± 28 | 0.2520 |
| 15_2_5_1 | 3316 ± 29 | 3457 ± 17 | 3540 ± 11 | 0.2150 |
| 15_2_6_1 | 2957 ± 37 | 3072 ± 32 | 3148 ± 25 | 0.0808 |
| 16_2_10_1 | 2817 ± 18 | 2840 ± 14 | 2857 ± 11 | 0.0848 |
| 16_2_11_1 | 3606 ± 32 | 3611 ± 17 | 3614 ± 11 | 0.2190 |
| 16_2_1_1 | 3693 ± 21 | 3699 ± 10 | 3702 ± 7 | 0.3950 |
| 16_2_21_1 | 3337 ± 37 | 3379 ± 18 | 3404 ± 11 | 0.3140 |
| 16_2_23_1 | 3197 ± 47 | 3303 ± 24 | 3369 ± 13 | 0.1060 |
| 16_2_24_1 | 3312 ± 29 | 3417 ± 18 | 3478 ± 11 | 0.0802 |
| 16_2_2_1 | 3389 ± 26 | 3513 ± 12 | 3584 ± 5 | 0.1210 |

Table 3 (Continued).

| Grain spot | $^{206}\text{Pb}^*/^{238}\text{U}$ age | $^{207}\text{Pb}^*/^{235}\text{U}$ age | $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ age | Th/U |
|------------|--|--|---|--------|
| 16_2_35_1 | 2729 ± 18 | 2755 ± 25 | 2775 ± 23 | 0.0166 |
| 16_2_43_1 | 2826 ± 22 | 2915 ± 13 | 2977 ± 10 | 0.0436 |
| 16_2_47_1 | 3714 ± 42 | 3619 ± 21 | 3567 ± 13 | 0.3480 |
| 16_2_4_1 | 3170 ± 30 | 3270 ± 15 | 3332 ± 8 | 0.1680 |
| 16_2_6_1 | 3571 ± 42 | 3578 ± 21 | 3582 ± 12 | 0.4350 |
| 16_2_7_1 | 2523 ± 18 | 2571 ± 11 | 2609 ± 8 | 0.0123 |
| 15_10_1_1 | 3890 ± 211 | 3715 ± 74 | 3622 ± 17 | 0.9770 |
| 15_10_1_2 | 4078 ± 265 | 3833 ± 91 | 3707 ± 23 | 0.2770 |
| 15_10_1_3 | 3432 ± 224 | 3494 ± 87 | 3529 ± 20 | 0.8750 |
| 15_10_3_1 | 3222 ± 251 | 3314 ± 105 | 3370 ± 28 | 0.1840 |
| 15_10_3_3 | 3174 ± 160 | 3381 ± 72 | 3507 ± 25 | 0.9940 |
| 15_6_1_1 | 2893 ± 270 | 2741 ± 111 | 2631 ± 13 | 0.0767 |
| 15_6_2_2 | 2587 ± 63 | 2601 ± 29 | 2612 ± 8 | 0.0539 |
| 15_6_3_1 | 2569 ± 89 | 3055 ± 41 | 3392 ± 8 | 0.0765 |
| 15_6_4_1 | 3524 ± 127 | 3516 ± 47 | 3512 ± 6 | 0.1230 |
| 15_6_5_1 | 3656 ± 77 | 3611 ± 28 | 3586 ± 5 | 0.1690 |
| 15_6_6_1 | 2621 ± 93 | 3061 ± 43 | 3364 ± 13 | 0.2340 |
| 15_6_7_1 | 3266 ± 121 | 3257 ± 48 | 3251 ± 12 | 0.1540 |
| 15_7_10_1 | 3374 ± 198 | 3429 ± 76 | 3461 ± 12 | 0.1220 |
| 15_7_11_1 | 3395 ± 218 | 3386 ± 84 | 3380 ± 22 | 0.3850 |
| 15_7_11_2 | 2985 ± 129 | 3227 ± 56 | 3381 ± 21 | 0.1590 |
| 15_7_1_1 | 3308 ± 160 | 3444 ± 64 | 3524 ± 11 | 0.6300 |
| 15_7_2_1 | 3477 ± 128 | 3555 ± 48 | 3599 ± 7 | 0.6490 |
| 15_7_2_2 | 3574 ± 176 | 3530 ± 64 | 3505 ± 13 | 0.2740 |
| 15_7_2_3 | 3204 ± 190 | 3349 ± 75 | 3437 ± 16 | 0.1120 |
| 15_7_3_1 | 3550 ± 81 | 3554 ± 30 | 3557 ± 4 | 0.0688 |
| 15_7_4_1 | 3196 ± 100 | 3356 ± 40 | 3454 ± 12 | 0.1510 |
| 15_7_5_1 | 3225 ± 97 | 3399 ± 40 | 3502 ± 9 | 0.1070 |
| 15_7_6_1 | 3060 ± 145 | 3322 ± 58 | 3484 ± 11 | 0.3080 |
| 15_7_7_1 | 3065 ± 120 | 3341 ± 51 | 3511 ± 13 | 0.6420 |
| 15_7_7_2 | 3859 ± 267 | 3612 ± 93 | 3478 ± 12 | 0.1090 |
| 15_7_8_1 | 2778 ± 148 | 3025 ± 67 | 3193 ± 22 | 0.2840 |
| 15_7_9_1 | 2905 ± 130 | 3245 ± 56 | 3461 ± 14 | 1.3700 |
| 15_7_9_2 | 2740 ± 123 | 2956 ± 56 | 3106 ± 21 | 0.0888 |

Ages are expressed in millions of yr (Ma). Nomenclature is sample+grain number+ion microprobe spot number. ‘g’, ‘z’, ‘15’ and ‘16’ analyses were done during separate sessions; ‘15_’ and ‘16_’ are aliquots of the same sample GR9716. Isotopic ratios have been corrected for common Pb. U–Pb ages were determined by comparison with a working curve defined by measurement of standard zircon AS-3 that yields concordant $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages of 1099.1 ± 0.5 Ma by conventional methods [23]. Error demagnification was applied to the data; all uncertainties are reported at the 1 σ level.

to reset the common Pb isotopic composition of the coexisting feldspars.

An anomalous ~ 4.1 -Ga zircon age we observed for one grain in thin section is unusual in both its surprising antiquity (no U–Pb zircon age this old has been reported for the ‘Itsaq Gneiss Complex’) and low Th/U value (0.074) relative to the cluster of ages at ~ 3.8 Ga (Table 3). While we noted earlier the unlikelihood of the parent tonalite melt containing a high fraction of inher-

ited zircons (see [6]), this specific and isolated occurrence can be explained by the fact that the zircon is included within biotite. This association suggests that zircon survived the magmatic episode because it was incorporated into the magma late in its crystallization history and was temporarily armored against dissolution by the encompassing stable phase. The apparent rarity of this relationship suggests that the postulated armoring mechanism is not robust and thus the inherited

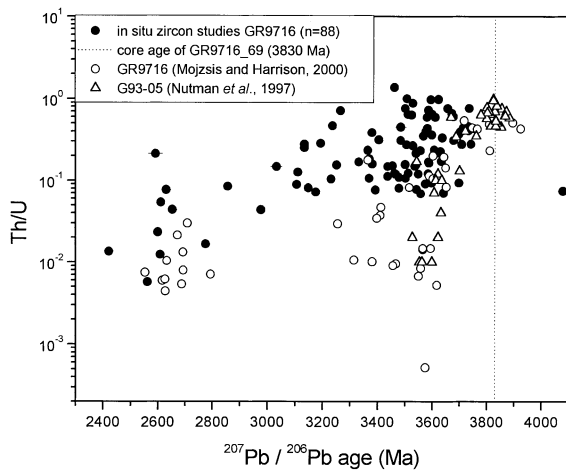


Fig. 7. Results of zircon U–Th–Pb in situ studies of orthogneiss GR9716 plotted with data from [3,6,16] and listed on Table 3.

zircon is unlikely to have been transported far from its source, otherwise the grain and its host biotite would have been resorbed by the tonalite. Indeed, based on this finding it is of interest whether there may be rocks even older than the 3.83-Ga Akilia orthogneiss present somewhere in the ‘Itsaq Gneiss Complex’ of West Greenland and perhaps in the vicinity of Akilia.

5. Conclusions

Our conclusions regarding the age and origin of the contested orthogneiss on Akilia are as follows.

(1) Age profiles from near surface ($\leq 5 \mu\text{m}$) regions of individual zircons can be obtained using the depth profiling mode of the ion microprobe. The increased spatial resolution of this zircon geochronological technique permits detection of age variations at the $\sim 200\text{-nm}$ scale. By employing sequential repolishing, depth–age–composition profiles of zircons of essentially unlimited length can be obtained.

(2) U–Pb age depth profiling of a complex tonalitic orthogneiss from Akilia, West Greenland, reveals evidence for three phases of concentric zircon growth at 3.83 Ga, ~ 3.6 Ga and 2.7–2.5 Ga.

(3) Zircon growth at both ~ 3.6 Ga and 2.7–2.5 Ga is consistent with precipitation from a metamorphic fluid. Only the zircon core is consistent with crystallization from magma of the composition of the host rock.

(4) The crystallization age of the previously contested Southwest Akilia tonalitic orthogneiss is 3828 ± 8 Ma. Hence, sediments [3] and evidence for life therein [2] on Akilia are > 3.83 Ga in age.

(5) That these data do not agree with common-Pb compositions of the Akilia orthogneiss [12] calls for quantitative studies of open-system behavior of Pb during multiple periods of high-grade (granulite) metamorphism. An important aspect of future work would be the evaluation of fluid transport of U and Th that proceeded during granulitization of, for example, West Greenland orthogneisses.

(6) An anomalously old (~ 4.1 Ga) zircon (Table 3; g1-1) measured in situ in thin section may point to the unforeseen existence of primordial crust in the vicinity of the ‘Itsaq Gneiss Complex’.

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