# Rapid maturation and stabilisation of middle Archaean continental crust: the Akia terrane, southern West Greenland

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Garde, Adam A., Friend, R.L., Nutman, A.P. & Marker, M. 2000–09–18: Rapid maturation and stabilisation of middle Archaean continental crust: the Akia terrane, southern West Greenland. *Bulletin of the Geological Society of Denmark*, Vol. 47, pp. 1–27, Copenhagen. https://doi.org/10.37570/bgsd-2000-47-01

New ion probe U-Pb zircon analyses of twelve samples of grey orthogneiss, granite and post-kinematic diorite from the Akia terrane, southern West Greenland, supported by Sm-Nd isotope geochemistry, document its middle Archaean accretional history and provide new evidence about the location of its northern boundary. Zircon populations in grey gneiss and inherited zircons in granite show that magmatic accretion of new continental crust, dominated by intrusion of tonalite sheets in a convergent island arc setting, occurred between *c.* 3050 and 3000 Ma, around and within a *c.* 3220 Ma continental core. In the central part of the terrane, tonalite sheets were intercalated with older supracrustal rocks of oceanic affinity by intrusion, thrusting and folding during the Midterhøj and Smalledal deformation phases of Berthelsen (1960). Continued tonalite injection led to a thermal maximum with granulite facies conditions at *c.* 2980 Ma, dated by metamorphic zircons in grey gneiss. The metamorphic maximum was contemporaneous with upright, angular folds of the Påkitsoq deformation phase. Within a few million years followed high-grade retrogression and intrusion of two large dome-shaped tonalite-granodiorite complexes, granites *s.l.* derived from remobilisation of grey gneiss, and post-kinematic diorite plugs. Whereas the relative chronology of these events is firmly established from field observations, zircons from the post-granulite facies intrusions all yielded statistically indistinguishable emplacement ages of *c.* 2975 Ma. These results show that crustal growth occurred in several short-lived events starting at *c.* 3220 Ma, and that final maturation and stabilisation of new, thick continental crust took place rapidly (within *c.* 20 Ma) at *c.* 2975 Ma.

*Key words:* Archaean, southern West Greenland, Akia terrane, continental crust, deformation, granulite facies, zircon, ion probe, U-Pb, Sm-Nd.

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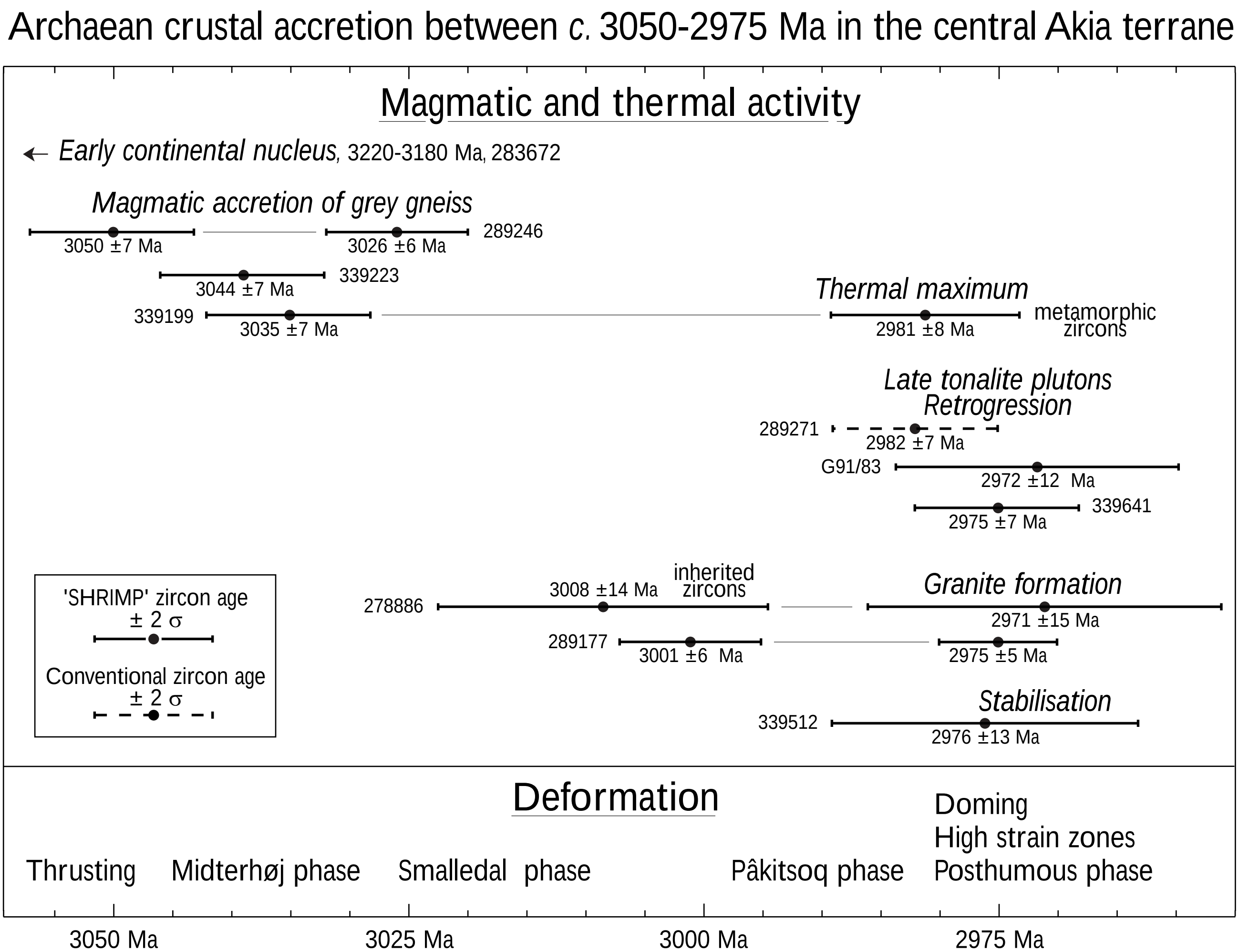
During the past three decades there have been several major advances in the understanding of the Archaean evolution of southern West Greenland, many of which were reached by combinations of careful studies in the field with increasingly refined geochronological methods. Around 1970 it was established with the Rb-Sr and Pb-Pb whole-rock methods that the Amîtsoq gneisses of McGregor (1973) in the vicinity of Godthåbsfjord were early Archaean (Moorbath, O'Nions, Pankhurst, Gale & McGregor 1972), at that time the oldest rocks known on Earth. In those early days of geochronology the duration of single events of Archaean crustal accretion and differentiation was unclear, in part due to the large analytical errors on age determinations (e.g. Moorbath 1976, 1977). A decade later, increasing numbers of more precise age determinations using zircon U-Pb and whole-rock Rb-Sr and Pb-Pb methods combined with structural studies led Friend, Nutman & McGregor (1988) to propose that the Godthåbsfjord region consists of a number of discrete tectono-stratigraphic terranes with individual and mostly short-lived geological histories. However, many whole-rock age determinations still gave large errors, not least because samples from unrelated suites of rocks were mixed in many of the isochron calculations (e.g. Taylor et al.

Table 1. Zircon geochronology around 3000 Ma in the Akia terrane. In the central part, relatively long-lived magmatic accretion of grey gneiss occurred between 3050–3000 Ma (during the Midterhøj and Smalledal deformation phases), followed by granulite facies metamorphism (during the Pâkitsoq phase) and rapid emplacement of late tonalite-granodiorite complexes, granites and post-kinematic diorites at 3080–3075 Ma during maturation and stabilisation of the continental crust. In the northern part of the terrane, granulite facies metamorphism took place at *c.* 2950 Ma.




1980, with the exception of their c. 3020 Ma Pb-Pb isochron from Nûk gneisses, east Bjørneøen, northern Godthåbsfjord). The Early Archaean history of the Akulleq terrane in central Godthåbsfjord was subsequently scrutinised with support from ion probe zircon geochronology, and studies in the Godthåbsfjord region (e.g. McGregor, Friend & Nutman 1991) showed that the terranes were not amalgamated into a common continental mass until *c.* 2720 Ma ago (Friend, Nutman, Baadsgaard, Kinny & McGregor 1996).

New SHRIMP (sensitive high-resolution ion microprobe) geochronology is reported here from the northernmost of these terranes, the Akia terrane. Whereas it was previously known that the the Akia terrane is around 3000 Ma old (e.g. Taylor et al. 1980, McGregor 1993 and references therein), the new data (Table 1) demonstrate that the Akia terrane was stabilised at around 2975 Ma long before the final terrane assembly at *c.* 2720 Ma, and that several independent, short-lived magmatic events took place immediately before the stabilisation and cooling: emplacement of large TTG (tonalite-trondhjemite-granodiorite) bodies, emplacement of granites remobilised from grey gneiss, and emplacement of diorites derived from crustally contaminated ultramafic magma.

## The Akia terrane

The Akia terrane, which contains the *c.* 3000 Ma type Nûk gneisses (McGregor 1973; Baadsgaard & McGregor 1981), is the northernmost of the Archaean terranes in the Godthåbsfjord region (Fig. 1). The southernmost part of the Akia terrane was described by McGregor (1993), and a detailed account of the magmatic accretion, structural evolution and metamorphic history of its central part around Fiskefjord was published by Garde (1997). SHRIMP U-Pb zircon geochronology showed that the Akia terrane also contains older, *c.* 3220 Ma sialic crust represented principally by dioritic gneiss in Nordlandet (Fig. 2, Garde 1997) together with other slices, which are found in the vicinity of Nuuk (analyses by A.P. Nutman and H. Baadsgaard quoted by Garde 1997). Widespread granulite facies metamorphism in the southern portion of the terrane was dated at *c.* 3000 Ma (Friend & Nutman 1994). Field evidence, conventional zircon U-Pb age determinations, and whole-rock Rb-Sr and Pb-Pb age determinations around Fiskefjord all indicated that the voluminous complex of grey tonalitic gneiss and supracrustal amphibolite adjacent to the 3220 Ma Nordlandet dioritic gneiss was accreted and stabilised at around 3000 Ma. However, the isotopic age data available to Garde (1997) were not sufficiently precise to qualify this.

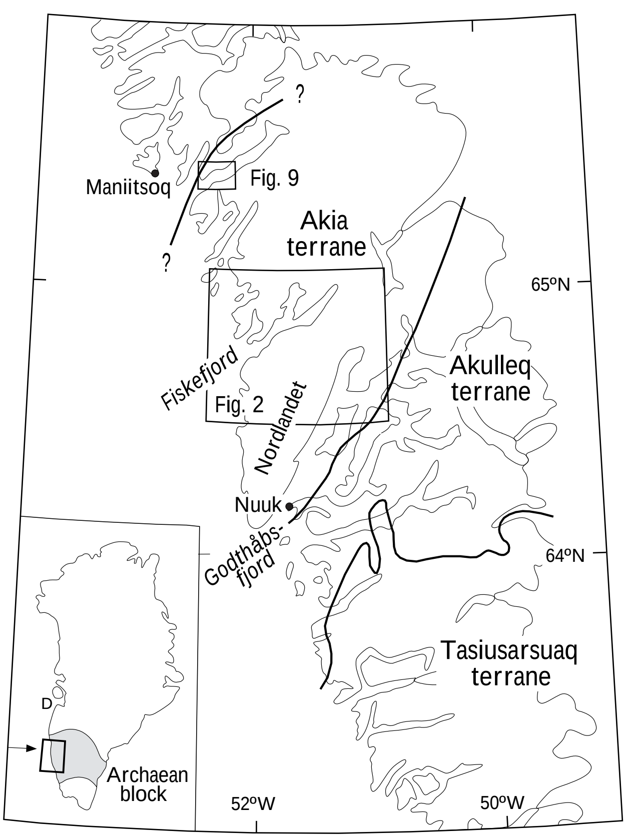



Fig. 1. Positions of the Akia, Akulleq and Tasiusarsuaq terranes in southern West Greenland; insets show the positions of Figs 2 and 9.

Berthelsen's (1960) analysis of the peninsula Tovqussap nunâ in the central part of the Akia terrane (Figs 2–3) was one of the earliest structural studies of the Archaean craton of West Greenland. Like most contemporary geologists studying high-grade crystalline rocks in shield areas, Berthelsen assumed that he was dealing with an originally flat-lying, conformable package of amphibolites and sedimentary gneisses, some of which had subsequently been transformed to granites by granitisation. Although later research has shown that these general assumptions were not correct, Berthelsen was able to resolve the geometry of superimposed folds over the entire peninsula by careful mapping of structural marker horizons, and he demonstrated that the extremely complicated refolded fold structures he had uncovered were the results of four successive episodes of deformation, and that each of these produced a relatively simple set of new enveloping structures with a uniform geometry.

The aims of the present paper are (1) to constrain the timing and duration of the main episodes of crustal accretion of the Akia terrane with new ion probe U-Pb zircon analyses, (2) to demonstrate that its maturation and stabilisation took place very rapidly, (3) to show that Berthelsen's (1960) structural analysis from Tovqussap nunâ is also valid in neighbouring parts of the terrane, and (4) to interpret his deformation history in a plate-tectonic context using the new geochronology. The zircon geochronology also provides new information about the extent of the terrane towards north-west.

## Structural evolution of around central Fiskefjord

### Tovqussap nunâ

Berthelsen (1960) recognised four main phases of deformation on Tovqussap nunâ (Fig. 3). During the first two phases (Midterhøj and Smalledal), large, recumbent isoclinal folds with first NW- to N-S trending, and then ENE- to NE-trending axes were developed (Table 1). The Tovqussap dome, a prominent structure in the western part of the peninsula, was interpreted as having formed by a combination of antiformal folding of earlier structures and (?diapiric) movement of material towards the top of the structure. The subsequent Pâkitsoq phase resulted in a series of conspicuous upright to overturned, open to tight folds of moderate size with SE- to S-plunging axes; compared with the earlier recumbent folds their wavelengths are much shorter (*c.* 2–3 km) and their hinge zones more angular, and commonly a new axial pla-

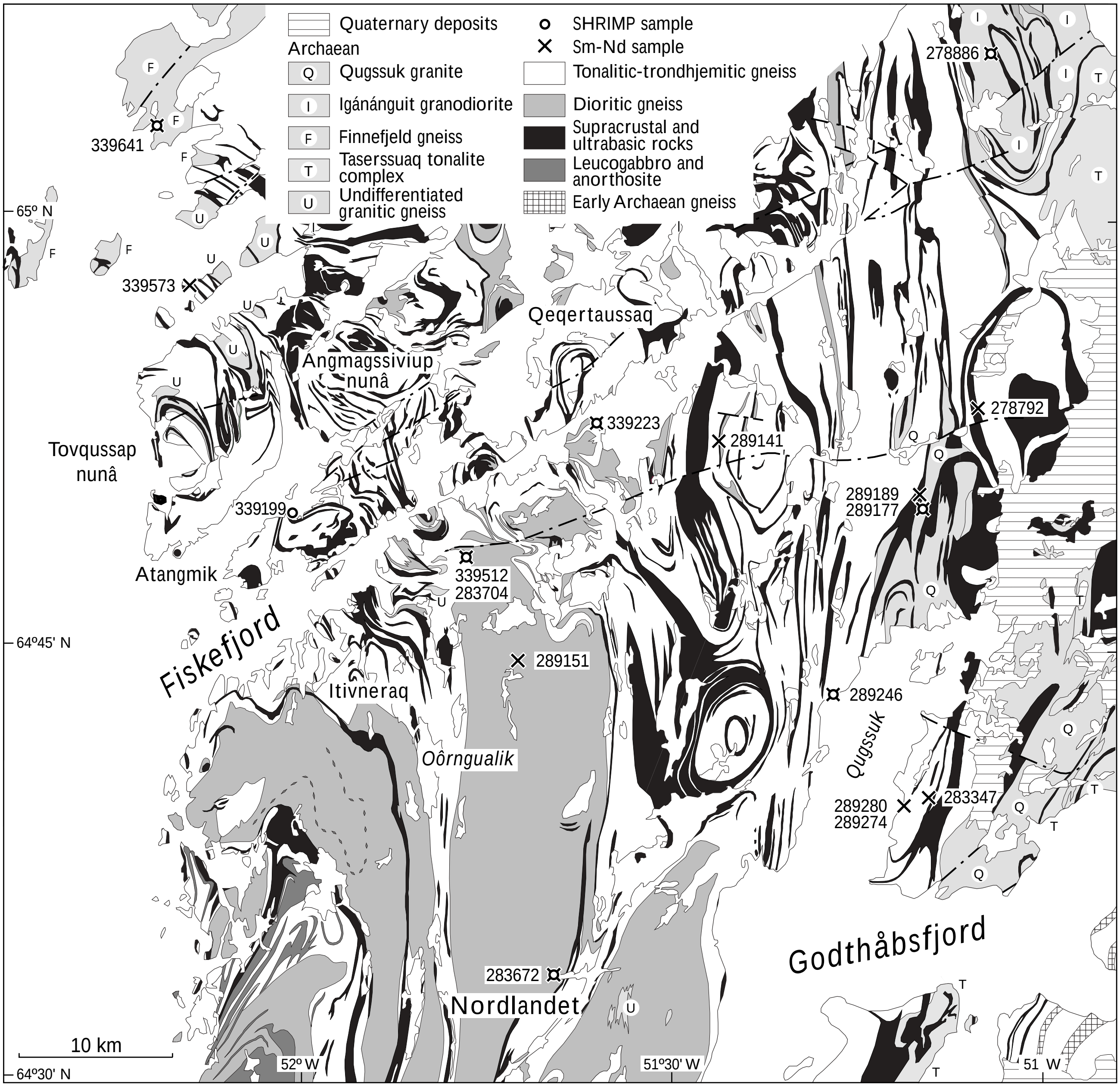



Fig. 2. Simplified geological map of the central part of the Akia terrane with locations of samples used for SHRIMP geochronology. Modified from Garde (1997).

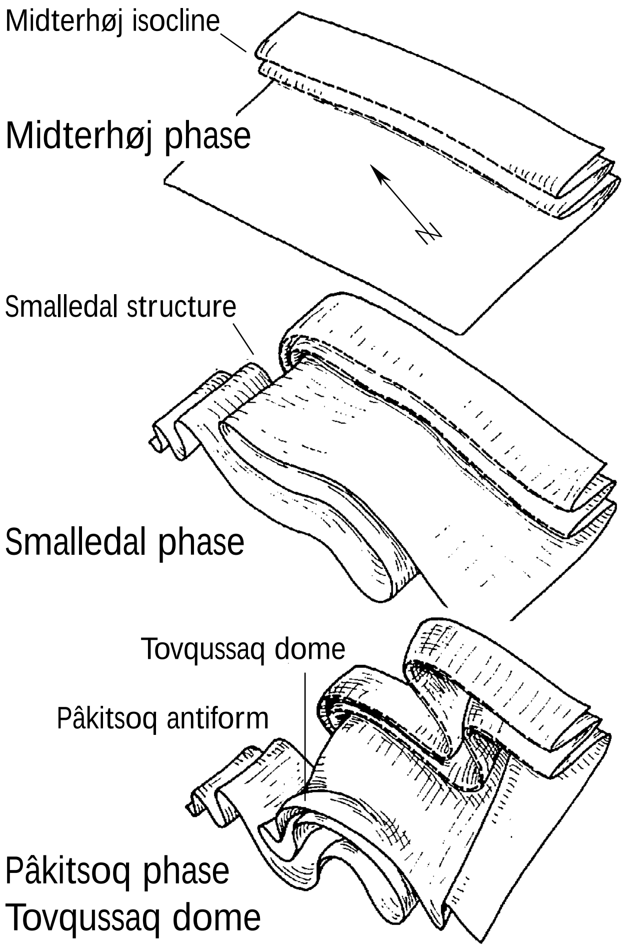



Fig. 3. Schematic diagram illustrating the kinematic evolution of the Tovqussaq structures at Tovqussap nunâ during the Midterhøj, Smalledal and Pâkitsoq deformation phases. Modified from Berthelsen (1960, fig. 78).

nar foliation and mineral or rodding lineation is developed. The Pâkitsoq phase was contemporaneous with the culmination of granulite facies metamorphism. During the final, Posthumous phase, localised steep high strain zones were developed under retrogressive amphibolite facies conditions.

Berthelsen (1960, p. 212) noted that part of his structural analysis would fall apart if structures he had described as isoclinal fold closures were instead formed by the tips of wedge-shaped intrusions, and in view of the magmatic origin of the granitic gneiss in the core of Berthelsen's supposed isoclinal closure, it now seems unlikely that the Midterhøj phase exists on Tovqussap nunâ. However, early isoclinal folds of similar orientation have later been documented near central Fiskefjord, see below.

## Early thrusts on the mainland adjacent to Tovqussap nunâ

In the western part of Angmagssiviup nunâ adjacent to Tovqussap nunâ (Fig. 2), an up to *c.* 300 m thick unit of intensely deformed tonalitic gneiss is intercalated with closely spaced, centimetre- to decimetre-thick lenses of schistose supracrustal amphibolite. The sequence is interpreted as having formed by tectonic mixing of basic metavolcanic rocks of oceanic crustal affinity and early members of the *c.* 3000 Ma old tonalites during thrusting at a shallow crustal level, and records the earliest deformation affecting both supracrustal amphibolite and grey gneiss belonging to the *c.* 3000 Ma complex; the sequence is folded by recumbent isoclinal folds described in the following section.

## Midterhøj, Smalledal and Pâkitsoq deformation phases around central and outer Fiskefjord

Recumbent isoclinal folds refolded by a second set of recumbent, E–W trending isoclinal folds, both with wavelengths of several kilometres, occur both north and south of central Fiskefjord (Fig. 4; Garde, Jensen & Marker 1987). The two sets of recumbent folds closely correspond to Berthelsen's (1960) Midterhøj and Smalledal deformation phases on Tovqussap nunâ. They are refolded by upright, NE–SW trending open folds of the Pâkitsoq phase (see below). Refolded isoclinal folds also occur, for instance, at Itivneraq south of outer Fiskefjord and west of Qôrngualik (Fig. 2); the latter are located within the *c.* 3220 Ma core of dioritic gneiss, and the earliest folds in this area may therefore predate the *c.* 3000 Ma crustal accretional event.

The Pâkitsoq deformation phase can be recognised in most parts of the Fiskefjord region and is characterised by relatively small, upright to overturned, NE- to N–S trending folds with wavelengths between 1-5 km, which were probably produced during E-W orientated crustal shortening. Figure 5 shows an example east of Itivneraq, outer Fiskefjord, where south-plunging folds of the Pâkitsoq phase refold recumbent folds with similar fold axis orientations.

## Magmatic accretion of orthogneiss, thermal metamorphism and retrogression

The Midterhøj, Smalledal and Pâkitsoq deformation events were accompanied by magmatic accretion leading to progressively thicker continental crust, domi-

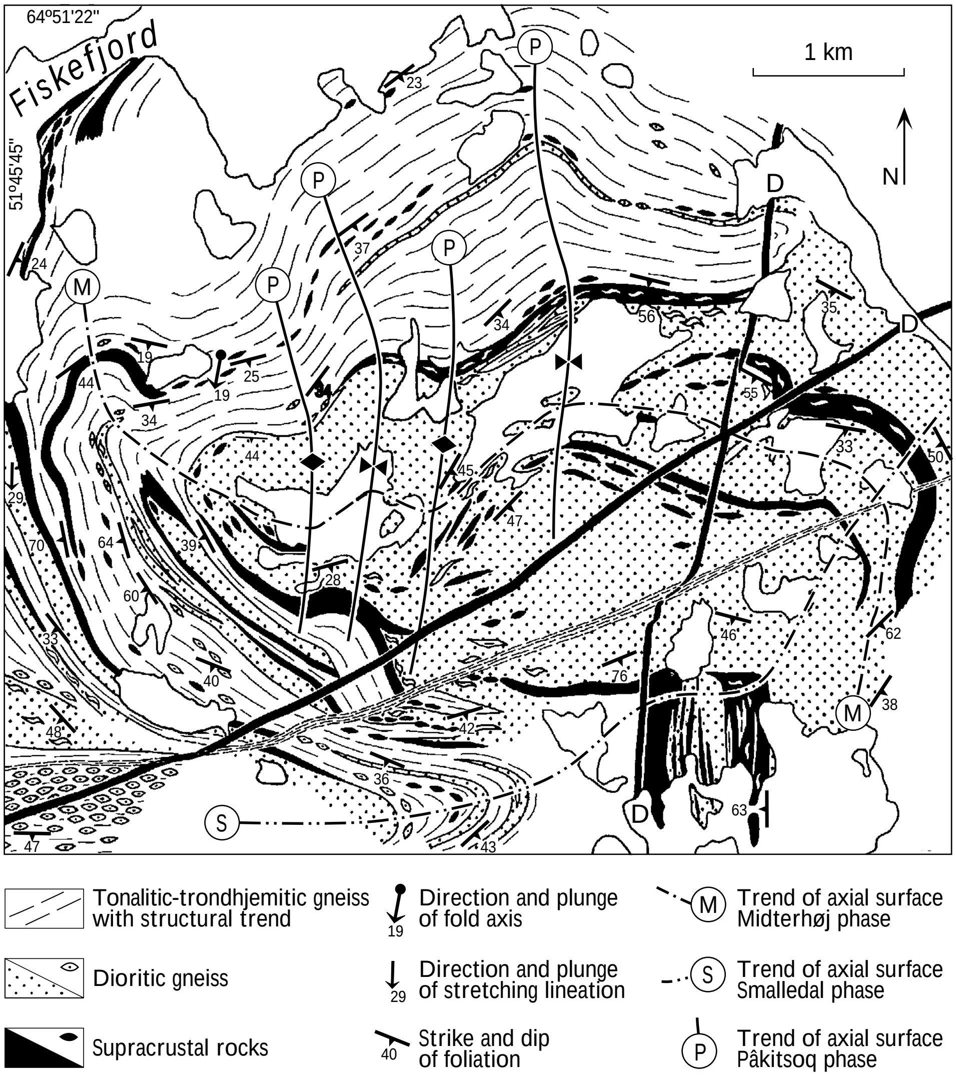



Fig. 4. Fold interference patterns south-east of central Fiskefjord showing a large recumbent isoclinal fold of the Midterhøj deformation phase refolded by another, NE-SW trending isoclinal fold of the Smalledal phase. Both folds are refolded by upright N-S trending folds of the Påkitsoq phase. D: dolerite dyke (Proterozoic). Modified from Garde *et al.* (1987).

nated by sheet-like bodies of TTG affinity (Garde 1997), which were continuously emplaced into and on top of each other. The geochemically distinct Qeqertaussaq diorite (Garde 1997) is an early dioritic, quartz-dioritic and mafic tonalitic member of the main phase of grey gneiss around the peninsula Qeqertaussaq in central Fiskefjord (Fig. 2). The diorite forms partially or wholly retrogressed enclaves ranging in size from less than a metre to a couple of kilometres, embedded in younger tonalitic-trondhjemitic orthogneiss.

As shown by Wells (1980), repeated injection of hot tonalitic magmas into the middle crust may lead to thermal granulite facies metamorphism, and this has been proposed to have happened in large parts of the Akia terrane (Riciputi, Valley & McGregor 1990). In the central part of the terrane there is a gradual transition from granulite facies orthogneiss with equilibrium metamorphic parageneses comprising orthopyroxene + hornblende ± clinopyroxene ± biotite in the west, to grey gneiss around the head of Fiskefjord displaying blebby textures with clusters of secondary biotite, orthoamphibole or actinolitic hornblende intergrown with quartz and formed under static, high to low amphibolite facies conditions. In the east, the retrogressed grey gneiss gives way to grey gneiss with un-retrogressed, equilibrium amphibolite facies textures, typically with finely dispersed biotite ± hornblende (Garde 1990 1997). With support from whole-rock and mineral geochemistry and Rb-Sr isotope geochemistry the latter author interpreted the retrogression as having mainly occurred very shortly after the granulite facies event in the upper part of the dehydrated rock column, whereby water and LIL elements, previously removed by the progressive thermal dehydration and melting, were partially reintroduced from below and from crystallisation of local partial melts. An opposing view was presented by

McGregor (1993), who argued that *all* the retrogression took place during late Archaean terrane assembly and localised Proterozoic reworking.

Two large tonalite-granodiorite intrusions, the Taserssuaq tonalite complex (Allaart, Jensen, McGregor & Walton 1977; Kalsbeek & Garde 1989) and the Finnefjeld gneiss (Berthelsen 1962; Marker & Garde 1988), were emplaced east and north of Fiskefjord late in the deformation history and mark a change from the intrusion of subhorizontal tonalite sheets into initially thin and wet but relatively cold and brittle crust, to much larger, dome-shaped bodies emplaced into drier and already hot crust (Nutman & Garde 1989). The Taserssuaq tonalite was emplaced at 2982 ±7 Ma (conventional U-Pb zircon geochronology of R. Pidgeon reported in Garde, Larsen & Nutman 1986) during the transition from granulite facies metamorphism to early retrogression. Field observations along the southern margin of the Finnefjeld gneiss north of Fiskefjord (Marker & Garde 1988) show that its emplacement post-dated the multiple folding of grey gneiss and amphibolite and apparently also the granulite facies event; four intrusive phases of Finnefjeld gneiss with equilibrium amphibolite facies parageneses were recorded, none of which display signs of former granulite facies metamorphism or pervasive retrogression.

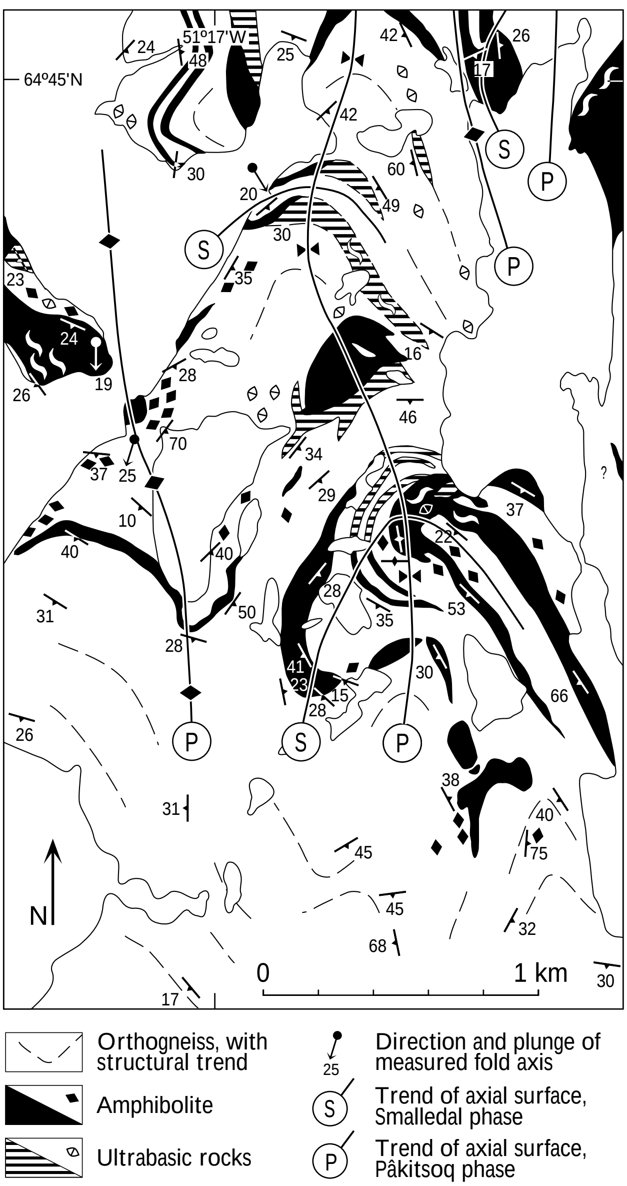



Fig. 5. N–S trending folds of the Pâkitsoq deformation phase with wavelengths of *c.* 1 km, refolding recumbent isoclinal folds. East of Itivneraq south of outer Fiskefjord. Modified from Garde (1997).

## High strain zones

The central and eastern parts of the Fiskefjord area contain several N-S to NE-SW trending, steep to vertical, high strain zones which were developed relatively late in the deformation history and broadly correlate with the Posthumous phase of Berthelsen (1960), see Table 1. The most prominent of these zones, the Qugssuk-Ulamertoq zone at the head of Fiskefjord (Garde 1997), comprises large patches of high strain granulite facies orthogneiss surrounded by gneiss affected by static retrogression to amphibolite facies, and must therefore have been established already during the granulite facies event. The high strain zones are thought to have formed in response to continued E-W orientated forces during the beginning of stabilisation of the newly accreted crust, when it was still hot but partially dehydrated and hence less ductile than during the immediately preceding Pâkitsoq phase. Some or all of the high strain zones were probably reactivated during the terrane assembly.

## Late granitic domes and sheets

Leucocratic granitic sheets and domes with compositions approaching minimum melt granites (Garde 1989, 1997) were emplaced at various stages in the *c.* 3000 Ma accretional event of the Akia terrane (Table 1). Two prominent members, the Qugssuk granite and Igánánguit granodiorite dome, were both formed late in the accretional history of the Akia terrane by partial melting and remobilisation of grey gneiss, triggered by the granulite facies thermal event. The Qugssuk granite was intruded as steep sheets, and on the north coast of Qugssuk also as a dome; in this area it

Table 2. Shrimp U-Pb zircon data from the central part of the Akia terrane and its northern boundary region. Errors of individual analyses are quoted at 1σ levels.

| Spot | U ppm | Th ppm | Th / U | $f_{206}$ % | $^{206}Pb/^{238}U$ | $^{207}Pb/^{206}Pb$ | Age, Ma | Concord. |
|---|---|---|---|---|---|---|---|---|
| 283672 | | | | | | | | |
| -1.1 | 16 | 8 | 0.50 | 0.58 | 0.623 ±22 | 0.2450 ±49 | 3153 ±32 | 99 |
| 2.1 | 68 | 46 | 0.67 | 0.25 | 0.567 ±12 | 0.2554 ±21 | 3219 ±13 | 90 |
| 3.1 | 24 | 10 | 0.44 | 0.46 | 0.641 ±29 | 0.2549 ±64 | 3215 ±40 | 99 |
| 4.1 | 23 | 10 | 0.42 | 0.02 | 0.622 ±26 | 0.2560 ±56 | 3222 ±35 | 97 |
| -5.1 | 25 | 12 | 0.46 | 0.39 | 0.652 ±25 | 0.2477 ±31 | 3170 ±20 | 102 |
| 6.1 | 43 | 26 | 0.59 | 0.00 | 0.643 ±23 | 0.2577 ±40 | 3233 ±25 | 99 |
| -7.1 | 47 | 29 | 0.61 | 0.13 | 0.632 ±16 | 0.2473 ±24 | 3167 ±16 | 100 |
| 7.2 | 67 | 41 | 0.61 | 0.06 | 0.648 ±16 | 0.2536 ±31 | 3207 ±19 | 100 |
| -8.1 | 29 | 21 | 0.70 | 0.47 | 0.613 ±32 | 0.2391 ±40 | 3114 ±27 | 99 |
| 9.1 | 38 | 16 | 0.42 | 0.43 | 0.631 ±19 | 0.2512 ±35 | 3192 ±22 | 99 |
| 10.1 | 16 | 7 | 0.41 | 0.45 | 0.615 ±20 | 0.2495 ±40 | 3182 ±26 | 97 |
| 11.1 | 21 | 9 | 0.40 | 0.26 | 0.628 ±20 | 0.2593 ±36 | 3243 ±22 | 97 |
| 12.1 | 31 | 13 | 0.42 | 0.29 | 0.645 ±22 | 0.2572 ±37 | 3230 ±23 | 99 |
| 13.1 | 22 | 10 | 0.46 | 0.001 | 0.630 ±24 | 0.2606 ±28 | 3250 ±17 | 97 |
| 14.1 | 34 | 13 | 0.38 | 0.13 | 0.624 ±20 | 0.2544 ±72 | 3213 ±45 | 97 |
| -15.1 | 47 | 21 | 0.44 | 0.03 | 0.657 ±15 | 0.2513 ±20 | 3193 ±12 | 102 |
| 339199 p: prismatic grains, m: stubby prismatic, small rounded grains and overgrowths | | | | | | | | |
| p1.1 | 434 | 95 | 0.22 | 0.03 | 0.594 ±17 | 0.2280 ±23 | 3038 ±16 | 99 |
| m2.1 | 267 | 31 | 0.12 | 0.20 | 0.577 ±12 | 0.2209 ±10 | 2987 ±08 | 98 |
| m2.2 | 105 | 70 | 0.67 | 0.71 | 0.544 ±14 | 0.2242 ±25 | 3011 ±18 | 93 |
| m3.1 | 160 | 34 | 0.21 | 0.24 | 0.582 ±14 | 0.2202 ±21 | 2982 ±15 | 99 |
| m4.1 | 166 | 49 | 0.30 | 0.33 | 0.543 ±18 | 0.2226 ±23 | 3000 ±17 | 93 |
| m5.1 | 41 | 47 | 1.15 | 0.42 | 0.573 ±19 | 0.2255 ±55 | 3021 ±40 | 97 |
| p6.1 | 1160 | 572 | 0.49 | 0.05 | 0.591 ±12 | 0.2246 ±17 | 3014 ±12 | 99 |
| p7.1 | 492 | 114 | 0.23 | 0.68 | 0.559 ±12 | 0.2258 ±13 | 3022 ±09 | 95 |
| p8.1 | 528 | 109 | 0.21 | 0.08 | 0.562 ±12 | 0.2294 ±09 | 3048 ±06 | 94 |
| p9.1 | 572 | 202 | 0.35 | 0.19 | 0.592 ±13 | 0.2274 ±14 | 3034 ±10 | 99 |
| m10.1 | 243 | 55 | 0.23 | 0.10 | 0.563 ±13 | 0.2205 ±17 | 2984 ±12 | 97 |
| m11.1 | 475 | 132 | 0.28 | 0.08 | 0.583 ±13 | 0.2203 ±27 | 2983 ±20 | 99 |
| -12.1 | 1065 | 549 | 0.52 | 0.01 | 0.596 ±12 | 0.2234 ±10 | 3005 ±07 | 100 |
| m13.1 | 98 | 82 | 0.83 | 0.13 | 0.575 ±13 | 0.2168 ±25 | 2957 ±18 | 99 |
| m14.1 | 163 | 38 | 0.23 | 0.10 | 0.577 ±14 | 0.2172 ±20 | 2960 ±15 | 99 |
| m15.1 | 123 | 55 | 0.45 | 0.09 | 0.584 ±13 | 0.2187 ±18 | 2972 ±13 | 100 |
| p16.1 | 189 | 47 | 0.25 | 0.12 | 0.617 ±15 | 0.2299 ±28 | 3051 ±19 | 102 |
| m17.1 | 375 | 18 | 0.05 | 0.14 | 0.581 ±12 | 0.2181 ±36 | 2967 ±27 | 100 |
| p18.1 | 641 | 90 | 0.14 | 0.02 | 0.566 ±14 | 0.2273 ±12 | 3033 ±09 | 95 |
| m18.2 | 328 | 41 | 0.12 | 0.03 | 0.557 ±11 | 0.2181 ±18 | 2966 ±14 | 96 |
| 289246 s: stubby prisms and cores, p: prisms and overgrowths | | | | | | | | |
| s1.1 | 462 | 437 | 0.95 | 0.02 | 0.607 ±13 | 0.2292 ±10 | 3046 ±07 | 100 |
| p2.1 | 176 | 65 | 0.37 | 0.11 | 0.594 ±15 | 0.2239 ±16 | 3009 ±12 | 100 |
| s3.1 | 141 | 65 | 0.46 | 0.36 | 0.608 ±16 | 0.2290 ±14 | 3045 ±10 | 101 |
| s4.1 | 258 | 284 | 1.10 | 0.10 | 0.592 ±16 | 0.2309 ±20 | 3058 ±14 | 98 |
| p5.1 | 194 | 189 | 0.98 | 0.12 | 0.584 ±15 | 0.2275 ±19 | 3034 ±14 | 98 |
| s6.1 | 214 | 44 | 0.20 | 0.10 | 0.581 ±13 | 0.2303 ±21 | 3054 ±15 | 97 |
| p5.2 | 352 | 161 | 0.46 | 0.07 | 0.584 ±14 | 0.2260 ±09 | 3024 ±06 | 98 |
| p7.1 | 162 | 96 | 0.59 | 0.07 | 0.596 ±17 | 0.2253 ±47 | 3019 ±34 | 100 |
| s8.1 | 192 | 119 | 0.62 | 0.01 | 0.603 ±14 | 0.2288 ±18 | 3044 ±13 | 100 |
| -9.1 | 126 | 42 | 0.33 | 0.19 | 0.538 ±13 | 0.2218 ±14 | 2994 ±10 | 93 |
| p10.1 | 208 | 231 | 1.11 | 0.01 | 0.603 ±15 | 0.2276 ±08 | 3035 ±06 | 100 |
| s11.1 | 52 | 23 | 0.44 | 0.49 | 0.613 ±19 | 0.2336 ±28 | 3077 ±20 | 100 |
| s12.1 | 160 | 92 | 0.58 | 0.11 | 0.598 ±18 | 0.2298 ±10 | 3051 ±07 | 99 |
| -13.1 | 533 | 177 | 0.33 | 0.05 | 0.516 ±11 | 0.2269 ±26 | 3030 ±19 | 89 |
| -14.1 | 345 | 46 | 0.13 | 0.06 | 0.548 ±15 | 0.2262 ±35 | 3026 ±25 | 93 |
| s15.1 | 90 | 50 | 0.55 | 0.001 | 0.597 ±14 | 0.2320 ±33 | 3066 ±23 | 98 |
| p16.1 | 296 | 183 | 0.62 | 0.03 | 0.604 ±12 | 0.2268 ±12 | 3030 ±09 | 101 |
| p17.1 | 65 | 28 | 0.44 | 0.13 | 0.606 ±14 | 0.2232 ±22 | 3004 ±16 | 102 |
| p18.1 | 444 | 79 | 0.18 | 0.00 | 0.584 ±11 | 0.2212 ±27 | 2990 ±20 | 99 |

Spots marked - are omitted from calculations of age groups

| Spot | U ppm | Th ppm | Th / U | $f_{206}$ % | $^{206}Pb / ^{238}U$ | $^{207}Pb / ^{206}Pb$ | Age, Ma | Concord. |
|---|---|---|---|---|---|---|---|---|
| 339223 | | | | | | | | |
| 1.1 | 237 | 121 | 0.51 | 0.04 | 0.596 ±16 | 0.2304 ±12 | 3055 ±08 | 99 |
| 2.1 | 220 | 161 | 0.73 | 0.11 | 0.595 ±16 | 0.2282 ±13 | 3040 ±09 | 99 |
| 3.1 | 242 | 167 | 0.69 | 0.01 | 0.576 ±17 | 0.2266 ±28 | 3028 ±20 | 97 |
| 4.1 | 263 | 189 | 0.72 | 0.05 | 0.612 ±20 | 0.2282 ±13 | 3040 ±09 | 101 |
| 5.1 | 314 | 244 | 0.78 | 0.04 | 0.606 ±21 | 0.2305 ±14 | 3055 ±10 | 100 |
| 6.1 | 129 | 159 | 1.23 | 0.13 | 0.628 ±23 | 0.2268 ±15 | 3030 ±11 | 104 |
| 7.1 | 252 | 174 | 0.69 | 0.07 | 0.593 ±22 | 0.2264 ±29 | 3027 ±21 | 99 |
| 8.1 | 238 | 197 | 0.83 | 0.02 | 0.590 ±18 | 0.2287 ±19 | 3043 ±13 | 98 |
| 9.1 | 187 | 125 | 0.67 | 0.06 | 0.578 ±18 | 0.2314 ±24 | 3062 ±17 | 96 |
| 10.1 | 204 | 144 | 0.71 | 0.02 | 0.600 ±17 | 0.2287 ±18 | 3043 ±13 | 100 |
| -11.1 | 184 | 140 | 0.76 | 0.21 | 0.615 ±21 | 0.2246 ±15 | 3014 ±10 | 103 |
| -12.1 | 159 | 131 | 0.82 | 0.06 | 0.541 ±17 | 0.2323 ±14 | 3068 ±10 | 91 |
| 339641 | | | | | | | | |
| 1.1 | 160 | 66 | 0.41 | 0.07 | 0.562 ±20 | 0.2207 ±27 | 2986 ±20 | 96 |
| 1.2 | 239 | 121 | 0.51 | 0.06 | 0.597 ±14 | 0.2196 ±10 | 2978 ±07 | 101 |
| 2.1 | 188 | 83 | 0.44 | 0.08 | 0.580 ±13 | 0.2216 ±13 | 2992 ±09 | 99 |
| 3.1 | 154 | 57 | 0.37 | 0.11 | 0.548 ±13 | 0.2203 ±18 | 2983 ±13 | 94 |
| 4.1 | 184 | 122 | 0.66 | 0.08 | 0.582 ±15 | 0.2183 ±34 | 2968 ±25 | 100 |
| -4.2 | 256 | 143 | 0.56 | 0.08 | 0.567 ±11 | 0.2130 ±13 | 2929 ±10 | 99 |
| 5.1 | 265 | 113 | 0.43 | 0.10 | 0.569 ±13 | 0.2182 ±15 | 2968 ±11 | 98 |
| -6.1 | 511 | 249 | 0.49 | 0.02 | 0.589 ±17 | 0.2225 ±12 | 2999 ±09 | 100 |
| 7.1 | 147 | 67 | 0.45 | 0.23 | 0.563 ±16 | 0.2165 ±22 | 2955 ±16 | 97 |
| -8.1 | 125 | 71 | 0.56 | 0.11 | 0.556 ±17 | 0.2160 ±16 | 2951 ±12 | 97 |
| 9.1 | 132 | 57 | 0.43 | 0.20 | 0.579 ±15 | 0.2190 ±16 | 2973 ±12 | 99 |
| -10.1 | 341 | 140 | 0.41 | 0.03 | 0.567 ±11 | 0.2148 ±24 | 2942 ±18 | 99 |
| -11.1 | 317 | 158 | 0.50 | 0.001 | 0.552 ±13 | 0.2119 ±20 | 2920 ±15 | 97 |
| -12.1 | 147 | 64 | 0.43 | 0.06 | 0.567 ±11 | 0.2156 ±12 | 2948 ±09 | 98 |
| 13.1 | 319 | 155 | 0.49 | 0.01 | 0.582 ±13 | 0.2160 ±26 | 2951 ±20 | 100 |
| 14.1 | 145 | 62 | 0.43 | 0.08 | 0.580 ±12 | 0.2189 ±12 | 2973 ±09 | 99 |
| 15.1 | 171 | 54 | 0.31 | 0.04 | 0.590 ±14 | 0.2178 ±13 | 2964 ±10 | 101 |
| G91-83 p: prismatic | | | | | | | | |
| p1.1 | 35 | 35 | 1.00 | 0.01 | 0.614 ±39 | 0.2295±177 | 3048±129 | 101 |
| p1.2 | 46 | 52 | 1.13 | 0.01 | 0.567 ±47 | 0.2299 ±66 | 3051 ±47 | 95 |
| -2.1 | 549 | 148 | 0.27 | 0.15 | 0.531 ±11 | 0.2131 ±12 | 2929 ±09 | 94 |
| p3.1 | 58 | 80 | 1.38 | 0.15 | 0.542 ±31 | 0.2157 ±78 | 2949 ±60 | 95 |
| -4.1 | 106 | 96 | 0.91 | 0.48 | 0.566 ±15 | 0.2138 ±31 | 2934 ±23 | 99 |
| p5.1 | 205 | 187 | 0.91 | 0.25 | 0.579 ±28 | 0.2180 ±26 | 2966 ±19 | 99 |
| -5.2 | 312 | 194 | 0.62 | 0.09 | 0.564 ±22 | 0.2100 ±23 | 2905 ±18 | 99 |
| p6.1 | 47 | 48 | 1.02 | 1.96 | 0.688±156 | 0.2141±336 | 2937±279 | 115 |
| p6.2 | 505 | 206 | 0.41 | 0.97 | 0.530 ±14 | 0.2203 ±20 | 2983 ±14 | 92 |
| p7.1 | 120 | 82 | 0.69 | 0.24 | 0.584 ±15 | 0.2196 ±24 | 2978 ±18 | 100 |
| p8.1 | 336 | 249 | 0.74 | 0.22 | 0.498 ±19 | 0.2172 ±22 | 2960 ±17 | 88 |
| p9.1 | 241 | 91 | 0.38 | 0.18 | 0.634 ±33 | 0.2241 ±47 | 3010 ±34 | 105 |
| p10.1 | 516 | 344 | 0.67 | 13.72 | 0.519 ±21 | 0.2136±102 | 2933 ±79 | 92 |
| p11.1 | 51 | 78 | 1.51 | 0.79 | 0.575 ±19 | 0.2139 ±61 | 2935 ±47 | 100 |
| p12.1 | 192 | 70 | 0.37 | 0.34 | 0.587 ±19 | 0.2182 ±21 | 2967 ±16 | 100 |
| p13.1 | 438 | 245 | 0.56 | 0.19 | 0.508 ±11 | 0.2200 ±23 | 2981 ±17 | 89 |
| -14.1 | 580 | 180 | 0.31 | 0.05 | 0.549 ±12 | 0.2134 ±11 | 2931 ±08 | 96 |
| p15.1 | 352 | 86 | 0.24 | 2.49 | 0.546 ±32 | 0.2180 ±85 | 2966 ±64 | 95 |
| p11.2 | 95 | 37 | 0.39 | 1.06 | 0.471 ±22 | 0.1952 ±57 | 2787 ±48 | 89 |
| p12.2 | 203 | 84 | 0.41 | 0.11 | 0.514 ±44 | 0.2245 ±30 | 3013 ±22 | 89 |
| p13.2 | 679 | 82 | 0.12 | 0.09 | 0.517 ±31 | 0.2128 ±43 | 2927 ±33 | 92 |
| 278886 i: inherited grains | | | | | | | | |
| -1.1 | 843 | 727 | 0.86 | 0.16 | 0.562 ±14 | 0.2033 ±06 | 2853 ±05 | 101 |
| i2.1 | 321 | 385 | 1.20 | 1.98 | 0.573 ±11 | 0.2245 ±15 | 3013 ±11 | 97 |
| 3.1 | 744 | 1035 | 1.39 | 0.91 | 0.574 ±12 | 0.2175 ±30 | 2962 ±22 | 99 |
| i4.1 | 497 | 309 | 0.62 | 0.22 | 0.606 ±12 | 0.2231 ±13 | 3003 ±09 | 102 |
| 5.1 | 236 | 55 | 0.23 | 0.44 | 0.538 ±12 | 0.2201 ±22 | 2982 ±16 | 93 |
| -6.1 | 813 | 489 | 0.60 | 0.28 | 0.563 ±11 | 0.2106 ±14 | 2910 ±11 | 99 |
| -7.1 | 1007 | 820 | 0.81 | 0.96 | 0.551 ±10 | 0.2085 ±08 | 2894 ±06 | 98 |
| 8.1 | 195 | 58 | 0.30 | 1.66 | 0.534 ±13 | 0.2191 ±17 | 2974 ±13 | 93 |
| 9.1 | 548 | 640 | 1.17 | 1.54 | 0.557 ±11 | 0.2175 ±21 | 2962 ±16 | 96 |

| Spot | U ppm | Th ppm | Th / U | $f_{206}$ % | $^{206}Pb / ^{238}U$ | $^{207}Pb / ^{206}Pb$ | Age, Ma | Concord. |
|---|---|---|---|---|---|---|---|---|
| 289177 sc: stubby prisms and cores, p: prisms | | | | | | | | |
| sc1.1 | 80 | 34 | 0.43 | 0.01 | 0.598 ±19 | 0.2227 ±20 | 3000 ±14 | 101 |
| p2.1 | 202 | 106 | 0.53 | 0.09 | 0.579 ±13 | 0.2203 ±12 | 2983 ±09 | 99 |
| -3.1 | 373 | 258 | 0.69 | 0.09 | 0.613 ±15 | 0.2161 ±13 | 2952 ±10 | 104 |
| p3.2 | 468 | 434 | 0.93 | 0.25 | 0.568 ±16 | 0.2190 ±08 | 2973 ±06 | 98 |
| p4.1 | 562 | 221 | 0.39 | 0.09 | 0.575 ±13 | 0.2199 ±11 | 2980 ±08 | 98 |
| -5.1 | 222 | 150 | 0.68 | 0.01 | 0.587 ±17 | 0.2270 ±18 | 3031 ±13 | 98 |
| p6.1 | 760 | 315 | 0.41 | 0.02 | 0.612 ±13 | 0.2190 ±06 | 2973 ±05 | 104 |
| sc6.2 | 657 | 288 | 0.44 | 0.01 | 0.600 ±13 | 0.2219 ±07 | 2995 ±05 | 101 |
| p4.2 | 211 | 107 | 0.51 | 0.08 | 0.604 ±13 | 0.2183 ±16 | 2969 ±12 | 103 |
| sc7.1 | 112 | 60 | 0.54 | 0.11 | 0.588 ±15 | 0.2255 ±13 | 3020 ±10 | 99 |
| sc8.1 | 221 | 83 | 0.38 | 0.07 | 0.573 ±12 | 0.2227 ±08 | 3000 ±06 | 97 |
| p9.1 | 224 | 92 | 0.41 | 0.10 | 0.579 ±11 | 0.2187 ±18 | 2971 ±14 | 99 |
| p10.1 | 213 | 157 | 0.74 | 0.04 | 0.591 ±13 | 0.2173 ±24 | 2961 ±18 | 101 |
| -11.1 | 558 | 134 | 0.24 | 0.03 | 0.576 ±11 | 0.2154 ±18 | 2947 ±14 | 100 |
| p12.1 | 215 | 131 | 0.61 | 0.29 | 0.567 ±11 | 0.2195 ±11 | 2977 ±08 | 97 |
| p14.1 | 193 | 125 | 0.65 | 0.18 | 0.593 ±12 | 0.2193 ±13 | 2975 ±09 | 101 |
| sc13.1 | 122 | 69 | 0.56 | 0.25 | 0.590 ±18 | 0.2220 ±12 | 2996 ±09 | 100 |
| sc15.1 | 78 | 22 | 0.28 | 0.35 | 0.618 ±17 | 0.2227 ±23 | 3000 ±17 | 103 |
| -16.1 | 482 | 187 | 0.39 | 0.001 | 0.532 ±22 | 0.2281 ±64 | 3039 ±45 | 91 |
| 339512 c: cores, b: brown margins, r: pale rims and small pale grains | | | | | | | | |
| r1.1 | 96 | 135 | 1.40 | 0.05 | 0.590 ±15 | 0.2193 ±18 | 2975 ±13 | 100 |
| r1.2 | 80 | 118 | 1.47 | 0.08 | 0.584 ±17 | 0.2198 ±24 | 2979 ±17 | 100 |
| c2.1 | 17 | 7 | 0.43 | 0.001 | 0.618 ±30 | 0.2245 ±31 | 3013 ±22 | 103 |
| b2.2 | 33 | 14 | 0.43 | 0.05 | 0.606 ±20 | 0.2233 ±40 | 3005 ±29 | 102 |
| c3.1 | 42 | 29 | 0.69 | 0.15 | 0.588 ±16 | 0.2247 ±21 | 3015 ±15 | 99 |
| b3.2 | 144 | 96 | 0.67 | 0.04 | 0.577 ±14 | 0.2235 ±21 | 3006 ±15 | 98 |
| b3.3 | 183 | 131 | 0.71 | 0.09 | 0.601 ±14 | 0.2235 ±13 | 3006 ±10 | 101 |
| c4.1 | 75 | 36 | 0.48 | 0.17 | 0.592 ±15 | 0.2269 ±46 | 3031 ±33 | 99 |
| b5.1 | 35 | 28 | 0.79 | 0.41 | 0.594 ±23 | 0.2237 ±28 | 3008 ±20 | 100 |
| b6.1 | 103 | 53 | 0.52 | 0.12 | 0.573 ±14 | 0.2236 ±27 | 3007 ±20 | 97 |
| r7.1 | 39 | 33 | 0.85 | 0.001 | 0.591 ±18 | 0.2193 ±17 | 2975 ±12 | 101 |
| r8.1 | 144 | 78 | 0.54 | 0.11 | 0.582 ±13 | 0.2204 ±19 | 2984 ±14 | 99 |
| r9.1 | 100 | 110 | 1.11 | 0.08 | 0.586 ±14 | 0.2177 ±29 | 2964 ±21 | 100 |
| G94-3 m: low-U (metamorphic) grains, p: high-U, commonly prismatic grains | | | | | | | | |
| m1.1 | 35 | 20 | 0.57 | 0.51 | 0.537 ±30 | 0.2272 ±65 | 3032 ±46 | 91 |
| -2.1 | 118 | 87 | 0.74 | 0.30 | 0.571 ±14 | 0.2182 ±24 | 2967 ±18 | 98 |
| p2.2 | 93 | 63 | 0.68 | 0.08 | 0.576 ±06 | 0.2223 ±15 | 2997 ±11 | 98 |
| p3.1 | 116 | 111 | 0.96 | 0.25 | 0.584 ±20 | 0.2211 ±28 | 2988 ±21 | 99 |
| m4.1 | 112 | 84 | 0.75 | 0.32 | 0.575 ±16 | 0.2097 ±41 | 2904 ±32 | 101 |
| m5.1 | 132 | 120 | 0.90 | 0.34 | 0.543 ±17 | 0.2168 ±22 | 2957 ±16 | 95 |
| -7.1 | 123 | 99 | 0.81 | 0.24 | 0.572 ±16 | 0.2131 ±30 | 2929 ±23 | 100 |
| p7.2 | 73 | 53 | 0.73 | 0.01 | 0.574 ±07 | 0.2222 ±15 | 2997 ±11 | 98 |
| p7.3 | 137 | 127 | 0.93 | 0.01 | 0.564 ±06 | 0.2223 ±18 | 2997 ±13 | 96 |
| m8.1 | 84 | 52 | 0.62 | 0.26 | 0.575 ±17 | 0.2115 ±30 | 2917 ±23 | 100 |
| m9.1 | 71 | 57 | 0.80 | 0.31 | 0.583 ±21 | 0.2187 ±36 | 2971 ±27 | 100 |
| m10.1 | 85 | 66 | 0.78 | 0.27 | 0.591 ±17 | 0.2159 ±46 | 2951 ±35 | 101 |
| m11.1 | 100 | 77 | 0.77 | 0.30 | 0.582 ±17 | 0.2120 ±61 | 2921 ±48 | 101 |
| m12.1 | 139 | 99 | 0.71 | 0.21 | 0.562 ±14 | 0.2109 ±28 | 2913 ±22 | 99 |
| m13.1 | 43 | 24 | 0.55 | 0.82 | 0.617 ±19 | 0.2109 ±34 | 2913 ±27 | 106 |
| -14.1 | 84 | 53 | 0.63 | 0.35 | 0.527 ±18 | 0.1900 ±29 | 2742 ±25 | 100 |
| m15.1 | 138 | 124 | 0.90 | 0.18 | 0.600 ±14 | 0.2143 ±19 | 2938 ±14 | 103 |
| m16.1 | 123 | 108 | 0.87 | 0.52 | 0.594 ±21 | 0.2143 ±21 | 2939 ±16 | 102 |
| p17.1 | 1661 | 11 | 0.01 | 0.02 | 0.595 ±12 | 0.2211 ±27 | 2989 ±20 | 101 |
| -18.1 | 476 | 112 | 0.24 | 0.10 | 0.581 ±13 | 0.2166 ±32 | 2956 ±24 | 100 |
| -18.2 | 642 | 170 | 0.26 | 0.01 | 0.599 ±04 | 0.2328 ±10 | 3071 ±7 | 98 |
| -18.3 | 128 | 53 | 0.41 | 0.10 | 0.563 ±08 | 0.2203 ±15 | 2983 ±11 | 97 |
| p19.1 | 747 | 195 | 0.26 | 0.04 | 0.573 ±11 | 0.2232 ±16 | 3004 ±11 | 97 |
| -20.1 | 2073 | 480 | 0.23 | 0.02 | 0.588 ±12 | 0.2185 ±30 | 2970 ±22 | 100 |
| -21.1 | 1195 | 48 | 0.04 | 0.04 | 0.594 ±12 | 0.2351 ±07 | 3087 ±05 | 97 |
| -22.1 | 1232 | 153 | 0.12 | 0.02 | 0.569 ±11 | 0.2158 ±18 | 2950 ±14 | 98 |
| -23.1 | 495 | 192 | 0.39 | 0.11 | 0.562 ±12 | 0.2136 ±10 | 2933 ±07 | 98 |
| p24.1 | 1062 | 591 | 0.56 | 0.07 | 0.579 ±11 | 0.2258 ±04 | 3022 ±03 | 97 |

continued

| Spot | U ppm | Th ppm | Th / U | $f_{206}$ % | $^{206}Pb/^{238}U$ | $^{207}Pb/^{206}Pb$ | Age, Ma | Concord. |
|---|---|---|---|---|---|---|---|---|
| G94-3 m: low-U metamorphic, p: commonly prismatic protolith (continued) | | | | | | | | |
| -25.1 | 84 | 63 | 0.75 | 0.52 | 0.566 ±17 | 0.2160 ±35 | 2951 ±26 | 98 |
| p25.2 | 66 | 71 | 1.08 | 0.05 | 0.585 ±11 | 0.2256 ±13 | 3021 ±09 | 98 |
| p26.1 | 913 | 288 | 0.32 | 0.07 | 0.532 ±09 | 0.2249 ±07 | 3016 ±05 | 91 |
| p27.1 | 76 | 55 | 0.73 | 0.16 | 0.572 ±24 | 0.2283 ±69 | 3040 ±49 | 96 |
| p28.1 | 63 | 51 | 0.81 | 0.01 | 0.583 ±08 | 0.2255 ±43 | 3020 ±31 | 98 |
| -29.1 | 97 | 61 | 0.64 | 0.29 | 0.542 ±06 | 0.2040 ±10 | 2858 ±08 | 98 |
| -29.2 | 66 | 57 | 0.86 | 0.05 | 0.577 ±08 | 0.2209 ±17 | 2987 ±12 | 98 |
| -30.1 | 207 | 129 | 0.62 | 0.04 | 0.599 ±08 | 0.2342 ±15 | 3081 ±10 | 98 |
| -30.2 | 50 | 31 | 0.61 | 0.11 | 0.583 ±09 | 0.2248 ±20 | 3015 ±14 | 98 |
| m31.1 | 66 | 47 | 0.71 | 0.09 | 0.560 ±11 | 0.2168 ±18 | 2957 ±14 | 97 |
| -31.2 | 33 | 20 | 0.59 | 0.26 | 0.543 ±13 | 0.1960 ±23 | 2793 ±19 | 100 |
| G94-1 m: metamorphic, p: protolith | | | | | | | | |
| p1.1 | 389 | 103 | 0.27 | 0.06 | 0.560 ±11 | 0.2214 ±19 | 2991 ±14 | 96 |
| p1.2 | 335 | 158 | 0.47 | 0.02 | 0.581 ±11 | 0.2189 ±11 | 2973 ±08 | 99 |
| m2.1 | 91 | 35 | 0.39 | 0.42 | 0.553 ±16 | 0.1961 ±39 | 2794 ±33 | 102 |
| m3.1 | 147 | 72 | 0.49 | 0.16 | 0.571 ±20 | 0.1979 ±25 | 2809 ±21 | 104 |
| -4.1 | 422 | 141 | 0.33 | 0.05 | 0.550 ±10 | 0.2049 ±20 | 2865 ±16 | 99 |
| -5.1 | 735 | 121 | 0.17 | 0.05 | 0.567 ±10 | 0.1997 ±08 | 2824 ±06 | 103 |
| p6.1 | 398 | 159 | 0.40 | 0.05 | 0.572 ±12 | 0.2188 ±25 | 2972 ±19 | 98 |
| -7.1 | 427 | 66 | 0.15 | 0.02 | 0.517 ±10 | 0.1903 ±09 | 2745 ±08 | 98 |
| m7.2 | 613 | 86 | 0.14 | 0.02 | 0.550 ±11 | 0.1989 ±07 | 2817 ±05 | 100 |
| -8.1 | 608 | 45 | 0.07 | 0.06 | 0.535 ±13 | 0.2097 ±32 | 2904 ±25 | 95 |
| p9.1 | 148 | 65 | 0.44 | 0.29 | 0.583 ±17 | 0.2212 ±15 | 2990 ±11 | 99 |
| p10.1 | 414 | 229 | 0.55 | 0.06 | 0.585 ±12 | 0.2206 ±08 | 2985 ±05 | 100 |
| m11.1 | 196 | 93 | 0.48 | 0.25 | 0.538 ±11 | 0.1946 ±28 | 2782 ±24 | 100 |
| m11.2 | 566 | 112 | 0.20 | 0.03 | 0.538 ±11 | 0.1989 ±05 | 2818 ±04 | 98 |
| -12.1 | 123 | 113 | 0.92 | 0.12 | 0.567 ±14 | 0.1933 ±23 | 2770 ±20 | 105 |
| -12.2 | 316 | 132 | 0.42 | 0.00 | 0.523 ±12 | 0.2155 ±15 | 2948 ±11 | 92 |
| -13.1 | 648 | 183 | 0.28 | 0.25 | 0.450 ±13 | 0.2096 ±23 | 2903 ±18 | 83 |
| m14.1 | 254 | 129 | 0.51 | 0.29 | 0.562 ±15 | 0.1992 ±10 | 2820 ±08 | 102 |
| -15.1 | 613 | 186 | 0.30 | 0.17 | 0.592 ±10 | 0.2086 ±16 | 2895 ±12 | 104 |
| -16.1 | 387 | 160 | 0.41 | 0.14 | 0.552 ±12 | 0.2144 ±26 | 2939 ±20 | 97 |
| m17.1 | 292 | 123 | 0.42 | 0.20 | 0.563 ±14 | 0.1949 ±24 | 2784 ±20 | 103 |
| -18.1 | 522 | 110 | 0.21 | 0.17 | 0.546 ±13 | 0.2092 ±36 | 2900 ±28 | 97 |
| p19.1 | 592 | 78 | 0.13 | 0.10 | 0.576 ±16 | 0.2147 ±99 | 2941 ±77 | 100 |
| -19.2 | 802 | 49 | 0.06 | 0.00 | 0.574 ±12 | 0.2125 ±06 | 2925 ±04 | 96 |
| -20.1 | 191 | 231 | 1.21 | 0.62 | 0.612 ±15 | 0.2082 ±23 | 2892 ±18 | 107 |
| -21.1 | 89 | 43 | 0.49 | 0.16 | 0.521 ±13 | 0.2039 ±12 | 2858 ±09 | 95 |
| -21.2 | 809 | 77 | 0.10 | 0.07 | 0.530 ±13 | 0.2133 ±06 | 2931 ±05 | 93 |
| m21.3 | 309 | 88 | 0.29 | 0.08 | 0.482 ±10 | 0.1982 ±09 | 2811 ±08 | 90 |
| m22.1 | 132 | 91 | 0.69 | 0.24 | 0.382 ±14 | 0.1955 ±62 | 2789 ±52 | 75 |
| G94-2 h: homogeneous grains and overgrowths, d: detrital grains | | | | | | | | |
| -1.1 | 2271 | 15 | 0.01 | 0.02 | 0.489 ±09 | 0.1640 ±08 | 2497 ±09 | 103 |
| h2.1 | 1141 | 10 | 0.01 | 0.41 | 0.484 ±10 | 0.1687 ±06 | 2544 ±06 | 100 |
| h3.1 | 3348 | 52 | 0.02 | 0.01 | 0.483 ±09 | 0.1679 ±05 | 2537 ±05 | 100 |
| -4.1 | 2511 | 62 | 0.02 | 0.01 | 0.475 ±10 | 0.1654 ±03 | 2511 ±03 | 100 |
| h5.1 | 1550 | 16 | 0.01 | 0.02 | 0.484 ±13 | 0.1674 ±16 | 2532 ±17 | 100 |
| d6.1 | 65 | 36 | 0.55 | 0.53 | 0.690 ±20 | 0.2534 ±40 | 3206 ±25 | 106 |
| d7.1 | 899 | 511 | 0.57 | 0.03 | 0.567 ±12 | 0.2131 ±12 | 2930 ±09 | 99 |
| h8.1 | 4479 | 25 | 0.01 | 0.004 | 0.487 ±10 | 0.1703 ±07 | 2560 ±07 | 100 |
| -9.1 | 662 | 10 | 0.01 | 0.08 | 0.472 ±10 | 0.1631 ±41 | 2489 ±43 | 100 |
| -9.2 | 7138 | 61 | 0.01 | 0.01 | 0.473 ±09 | 0.1660 ±11 | 2518 ±11 | 99 |
| h10.1 | 1258 | 17 | 0.01 | 0.04 | 0.465 ±10 | 0.1690 ±05 | 2548 ±05 | 97 |
| -11.1 | 1036 | 24 | 0.02 | 0.09 | 0.468 ±09 | 0.1662 ±06 | 2519 ±06 | 98 |
| d12.1 | 171 | 68 | 0.40 | 0.59 | 0.619 ±19 | 0.2474 ±24 | 3168 ±15 | 98 |
| d13.1 | 179 | 131 | 0.73 | 0.15 | 0.625 ±15 | 0.2492 ±36 | 3180 ±23 | 98 |
| h14.1 | 785 | 13 | 0.02 | 0.06 | 0.465 ±07 | 0.1680 ±28 | 2538 ±29 | 97 |
| d15.1 | 102 | 41 | 0.40 | 0.67 | 0.613 ±20 | 0.2425 ±52 | 3137 ±35 | 98 |
| d16.1 | 246 | 154 | 0.63 | 0.45 | 0.490 ±13 | 0.2324 ±15 | 3069 ±10 | 84 |
| d17.1 | 734 | 42 | 0.06 | 0.08 | 0.528 ±22 | 0.1838 ±28 | 2687 ±25 | 102 |
| d18.1 | 114 | 66 | 0.58 | 0.65 | 0.607 ±16 | 0.2479 ±25 | 3172 ±16 | 96 |
| d19.1 | 141 | 32 | 0.23 | 0.22 | 0.590 ±15 | 0.2431 ±32 | 3140 ±21 | 95 |

is cut by a small plug of post-kinematic diorite. It is a two-feldspar biotite granite emplaced under amphibolite facies conditions, and it is essentially undeformed. It is locally transgressive to the regional structure, and according to Garde (1997) its emplacement coincided with or post-dated retrogression from granulite facies. The large (*c.* 20 by 10 km), composite Igánánguit granodiorite dome north-east of the head of Fiskefjord was intruded into an area that had largely escaped the granulite facies event, but its field relationships with the surrounding grey gneiss show that is younger than the regional deformation, and it probably also post-dates the retrogression. The Igánánguit granodiorite is a fine- to medium grained and generally texturally homogeneous rock with evenly dispersed biotite flakes, but it also contains common wisps of biotite-rich restite up to a few millimetres thick, which may indicate incomplete melting and homogenisation of its source materials (Garde 1997).

### Post-kinematic diorites

The central part of the Akia terrane contains at least twenty bodies of post-kinematic diorite which range in size from a few metres to a couple of kilometres. The intrusions form plugs, dykes and inclined sheets emplaced into amphibolite, grey gneiss, Igánánguit granodiorite and Qugssuk granite. They are undeformed and unaffected by the regional 'high-grade' retrogression, and therefore mark the termination of the 3000 Ma crustal accretion. They are cut by Palaeoproterozoic dolerite dykes, ruling out the possibility that they might be contemporaneous with the Mesoproterozoic Nain plutonic suite in Labrador or even younger.

## Zircon geochronology

Single zircon ion probe U-Pb age determinations have been performed on nine samples of plutonic rocks from the central part of the Akia terrane. These samples were all collected from established geological units with well-known field relationships, which represent key stages in the terrane's magmatic and metamorphic evolution. Three additional samples were collected in an attempt to establish the extent of the terrane to the north-west in a region where no systematic detailed mapping has been carried out.

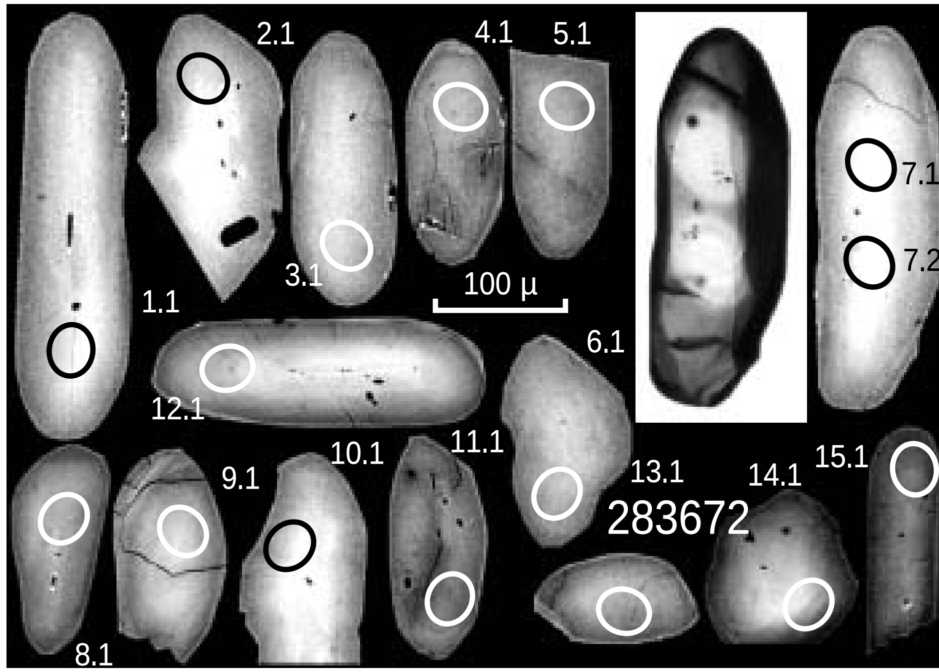
Geochronological studies from younger and better preserved dioritic, tonalitic, trondhjemitic and granodioritic complexes from many parts of the world have firmly established that such complexes may be emplaced very fast and that the majority of their zircons were formed during their emplacement, and hence that the zircons date the individual plutons and were rarely inherited from their magma sources. We believe that this was also the case in the Archaean. However, it is apparent from the foregoing descriptions that parts of the Akia terrane have had a complex post-magmatic high-grade history, and we demonstrate that this has affected some of the zircon populations as discussed in the following.

The analytical work was performed on the SHRIMP-1 instrument at the Australian National University, Canberra. U, Th and Pb isotopic ratios were referenced to the zircon standard SL 13 from Sri Lanka (572 Ma). Ages are quoted at the 95% ($2\sigma$) level of confidence and all represent weighted means of individual $^{207}Pb/^{206}Pb$ age determinations with statistically indistinguishable ages, from the least disturbed sites of morphologically and generally also geochemically similar grains. See Compston, Williams & Myer (1984), Claoué-Long, Compston, Roberts & Fanning (1995) and Stern (1998) for further details of the analytical technique and Friend & Nutman (1994), Nutman (1994), Nutman, Mojzsis & Friend (1997) and Pidgeon, Nemchin & Hitchen (1998) for discussions of criteria applicable to the recognition of least disturbed analytical sites. This approach does not entirely exclude the possibility that the selection of data sets for age calculations from complex zircon populations becomes biased; the alternative is to regard large parts of the zircon populations as inherited, as discussed above. Analytical data are given in Table 2; sample locations are shown on Figure 2, zircon morphology on Figures 6 and 11, and concordia diagrams on Figures 7, 8 and 10. Geographical coordinates are given with the samples and in Table 3.

### Central Akia terrane

*Sample no. 283672, Nordlandet dioritic gneiss.* The Nordlandet dioritic gneiss is the oldest recognised orthogneiss unit of the Akia terrane. The sample is granular, medium grained and weakly foliated with irregular aggregates of orthopyroxene, clinopyroxene and dark-red Ti-rich biotite in textural equilibrium, and in addition some younger radiating biotite aggregates; cm-thick veins of granular quartz-plagioclase (former partial melts?) in different directions are common. The zircons are large, clear and mostly euhedral with very low U contents (15–50 ppm), without signs of internal zonation or metamorphic overgrowth (Fig. 6a). An age of 3221 ±13 Ma (Fig. 7), calculated from measurements of 11 grains, is interpreted

Fig. 6a. Morphology and backscatter imaging of analysed zircons from sample no. 284672, Nordlandet dioritic gneiss from northern Nordlandet. The zircons are all prismatic and internally almost featureless. The insert on white background is a microphotograph in transmitted light.




as the protolith age (Garde 1997); a comparable age of 3235 ±9 Ma was obtained by Friend et al. (1996) from south-eastern Nordlandet. An age of *c.* 3180 Ma obtained from five other, morphologically similar grains, may either be interpreted as reflecting a slightly younger thermal event or early lead loss. It is also possible that most of the population has been affected to some degree by lead loss, in which case the true age may be a little older than 3221 Ma; thus, a calculation based on only the four oldest grains yields an age of 3241 ±21 Ma.

*Sample no. 339199, grey retrogressed gneiss.* This leucocratic tonalitic gneiss, retrogressed under static conditions, contains few mm large aggregates of fine-grained secondary biotite sheaves. It was collected along the northern limb of a refolded recumbent fold north of outer Fiskefjord (Fig. 2; 64°49′30″N, 51°01′36″W) and is hence clearly older than the Pâkitsoq phase of deformation and possibly as old as the Midterhøj phase. It contains two well-defined zircon populations (Fig. 6b, Table 2): an older group of prismatic, pale, clear grains with concentric igneous-type fine-scale zoning (e.g. Pidgeon *et al.* 1998) displayed by backscatter (BS) imaging and relatively high U contents (around *c.* 600 ppm) and variable Th (*c.* 20–575 ppm), and a younger group of dark, stubby prismatic or rounded grains and overgrowths with generally lower U contents between *c.* 40–475 ppm and low Th contents, *c.* 30–130 ppm. Seven pale, prismatic zircons yielded a concordant age of 3035 ±7 Ma, which dates the magmatic protolith (Fig. 8). The second population (12 sites) yields a concordant age of 2981 ±8 Ma which is interpreted as dating the granulite facies event.

*Sample no. 289246, grey retrogressed gneiss.* This orthogneiss, collected on the west coast of Qugssuk (Fig. 2; 64°43′28″N, 51°17′22″W), is medium grained with a well-developed blebby texture consisting of up to cm-sized aggregates of spongy amphibole-quartz intergrowths and secondary biotite sheaves, suggesting complete retrogression from granulite to amphibolite facies; hence it is impossible to determine if the sample originally contained more than one lithological

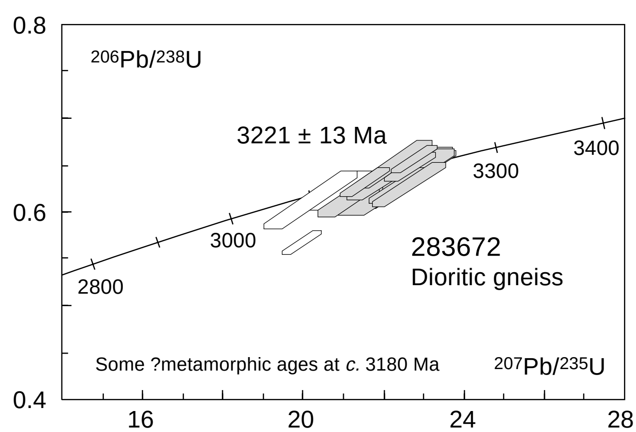



Fig. 7. U-Pb concordia diagram displaying SHRIMP zircon geochronology of sample 283672, Nordlandet dioritic gneiss.

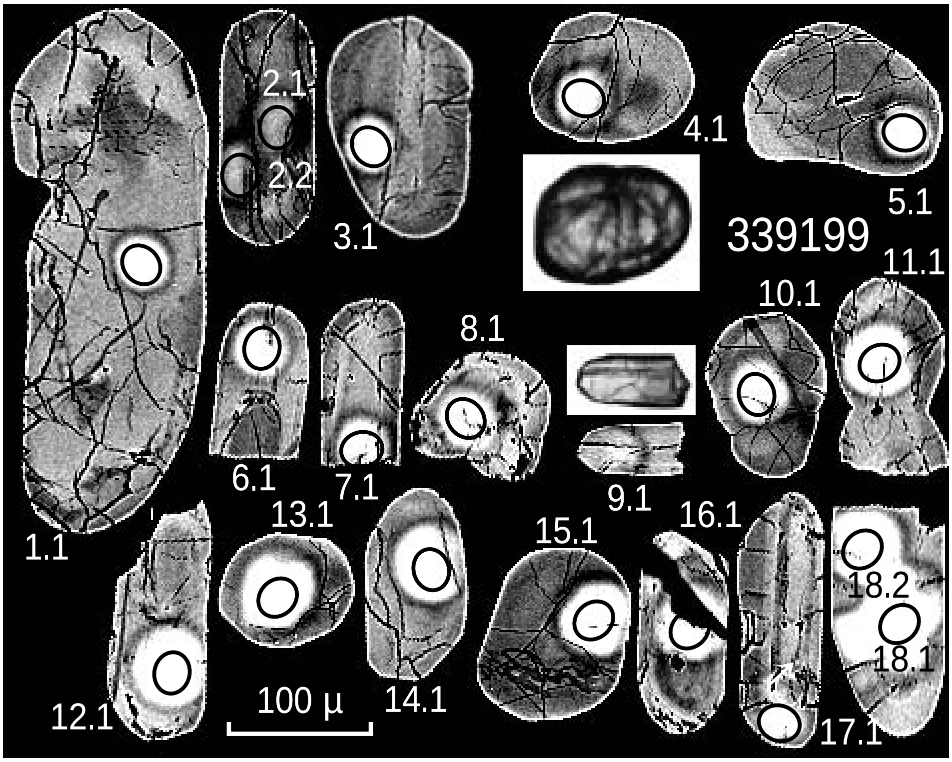


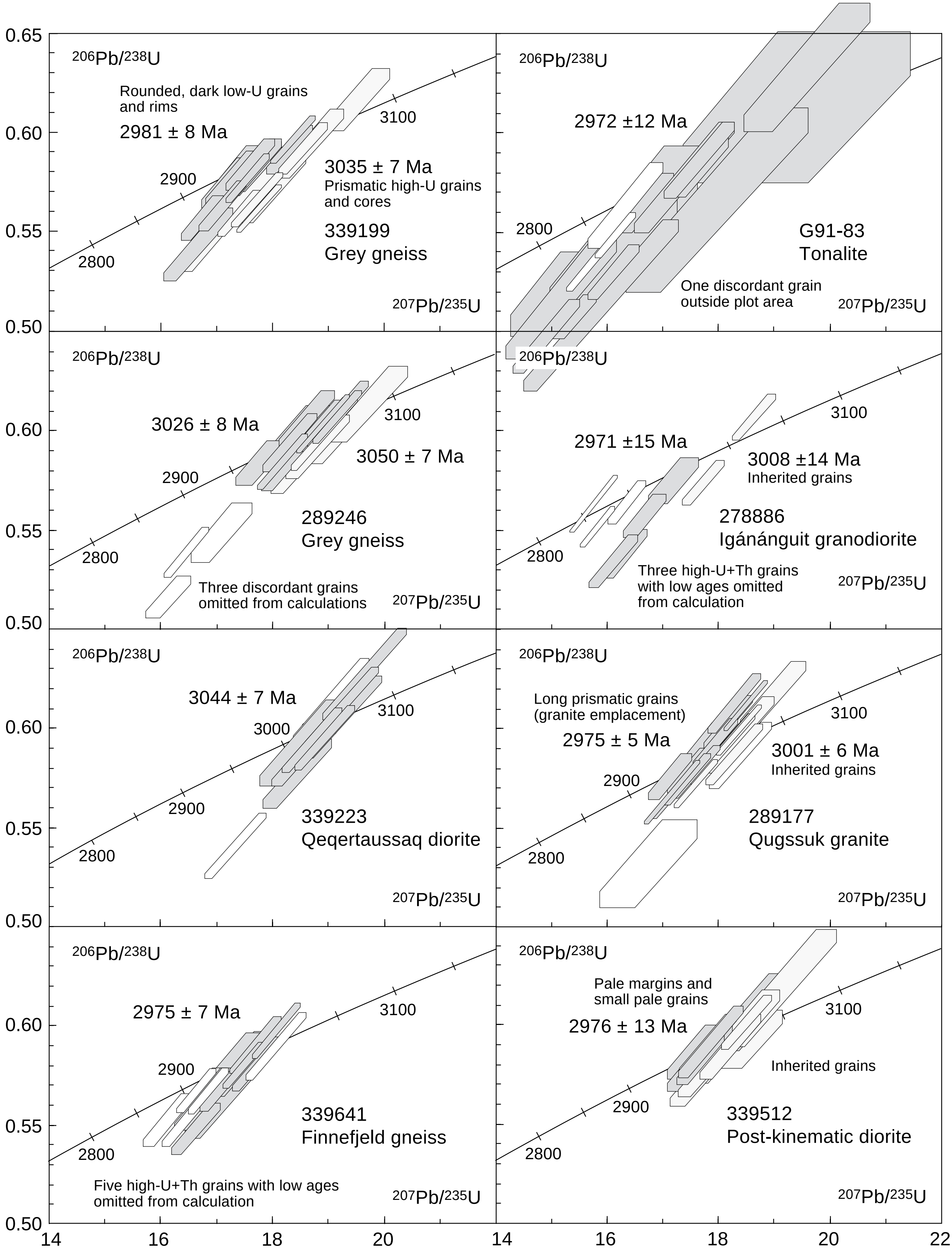

Fig. 6b. Morphology and backscatter imaging of analysed zircons from sample no. 339199, grey retrogressed gneiss north of outer Fiskefjord. The insert on white background is a microphotograph in transmitted light. Note the two different morphologies.

component as commonly observed in un-retrogressed amphibolite facies orthogneisses. The zircons are short to long prismatic, display igneous zoning (Fig. 6c), and have intermediate U contents averaging 235 ppm. The ages of individual sites, which are nearly all concordant, spread over a large interval from *c.* 2990–3075 Ma. An older group of eight, mostly stubby prisms and cores gives a weighted mean of 3050 ±7 Ma (Fig. 8). The remaining eight sites (elongate prisms and rims) form a younger group of 3026 ±6 Ma, or two statistically overlapping groups of *c.* 3030 and 3010 Ma; it is possible that minor early lead loss may have lowered some of the apparent $^{207}Pb/^{206}Pb$ ages a little. Three discordant grains were omitted from the calculation. Neither the morphology nor U contents of the zircons suggest growth under metamorphic conditions. Regardless whether two or three events are recorded in the zircons, the age data are interpreted as yielding the age(s) of emplacement and possibly inherited zircons, and not dating metamorphic events; the granulite facies metamorphism was much less pervasive in this area than further west around the above discussed sample 339199.

The grey gneiss is considerably younger than the Nordlandet dioritic gneiss, a little younger than the Qeqertaussaq diorite and significantly older than the Igánánguit granodiorite, Qugssuk granite and post-kinematic diorites, in agreement with field observations. Comparable SHRIMP zircon ages have previously been obtained from type Nûk gneisses at Nuuk town and Bjørneøen (see McGregor 1993).

*Sample no. 339223, Qeqertaussaq diorite.* The analysed sample, collected from an enclave surrounded by tonalitic gneiss at central Fiskefjord (Fig. 2; 64º53′53″N, 51º36′38″W), displays static retrogression from granulite facies, with relics of clinopyroxene and clusters of secondary biotite and amphibole; titanite and apatite are common accessories. It has a homogeneous population of very clear, pale pinkish, euhedral to slightly corroded zircons with weak zonation and occasional thin overgrowths (Fig. 6d, arrow). U and Th contents are respectively *c.* 200 and 150 ppm (Table 2). Ten grains yielded a concordant age of 3044 ±7 Ma (Fig. 8), which is readily interpreted as the age of emplacement (Garde 1997). The Qeqertaussaq diorite, like grey gneiss samples 289246 and 339199, represents an early phase in the main, *c.* 3000 Ma magmatic accretion of the Akia terrane. However, its unusual geochemical composition with low contents of high field strength elements but elevated $P_2O_5$, LREE, Sr and Ba compared to other grey gneiss members points to a different source involving metasomatised mantle; full geochemical data and a discussion of the ori-

Fig. 8. U-Pb concordia diagrams displaying SHRIMP zircon geochronology of samples from the central part of the Akia terrane.



0.65
0.60
0.55
0.50
$^{206}Pb/^{238}U$
Rounded, dark low-U grains and rims
2981 ± 8 Ma
2900
2800
3100
3035 ± 7 Ma
Prismatic high-U grains and cores
339199
Grey gneiss
$^{207}Pb/^{235}U$
2972 ±12 Ma
2800
G91-83
Tonalite
One discordant grain outside plot area
3026 ± 8 Ma
3050 ± 7 Ma
289246
Grey gneiss
Three discordant grains omitted from calculations
2971 ±15 Ma
3008 ±14 Ma
Inherited grains
278886
Igánánguit granodiorite
Three high-U+Th grains with low ages omitted from calculation
3044 ± 7 Ma
3000
339223
Qeqertaussaq diorite
Long prismatic grains (granite emplacement)
2975 ± 5 Ma
3001 ± 6 Ma
Inherited grains
289177
Qugssuk granite
2975 ± 7 Ma
339641
Finnefjeld gneiss
Five high-U+Th grains with low ages omitted from calculation
Pale margins and small pale grains
2976 ± 13 Ma
Inherited grains
339512
Post-kinematic diorite
14
16
18
20
22

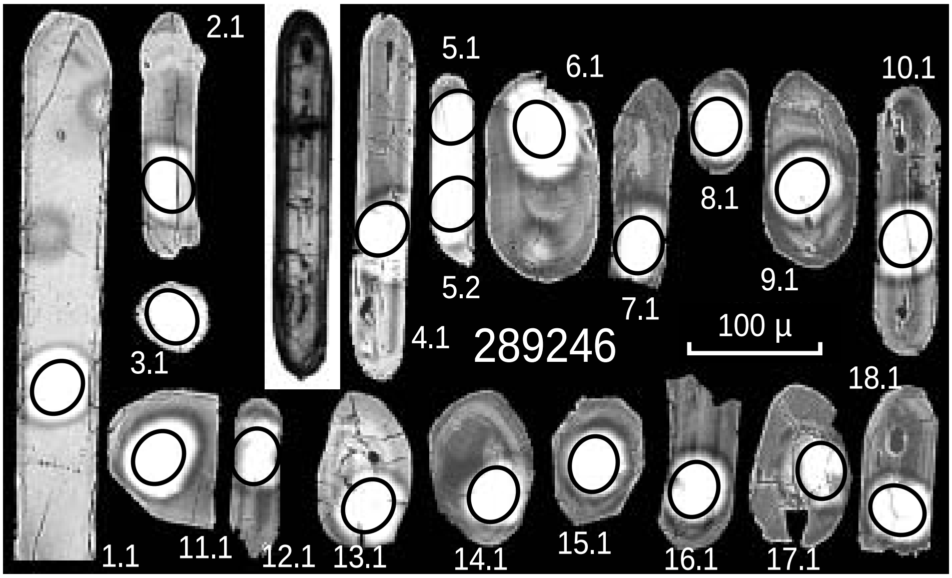



Fig. 6c. Morphology and backscatter imaging of analysed zircons from sample no. 289246, grey retrogressed gneiss, west coast of Qugssuk. The insert on white background is a microphotograph in transmitted light.

gin of the Qeqertaussaq diorite were published by Garde (1997).

*Sample no. 339641, Finnefjeld gneiss.* Previous attempts to date the Finnefjeld gneiss did not result in precise ages; a conventional multi-grain zircon U-Pb analysis yielded 3067 +62 / –42 Ma (Garde 1990), and two Rb-Sr whole rock ages of 3058 ±123 Ma and 3034 ±134 Ma were obtained by S. Moorbath (pers. comm. 1990) and Garde (1997). Marker & Garde (1988) showed that the Finnefjeld gneiss post-dates the Pâkitsoq deformation phase and granulite facies metamorphism in the amphibolite – grey gneiss region to the south-east, and were of the opinion that it also post-dates the retrogression of the grey gneiss. The sample is a typical, homogeneous, little deformed, medium-grained tonalitic member of the Finnefjeld gneiss with finely dispersed biotite typical of un-retrogressed amphibolite facies rocks, collected in the southern part of the pluton (Fig. 2; 65º02′54″N, 52º12′59″W). The sample contains a single morphological population of

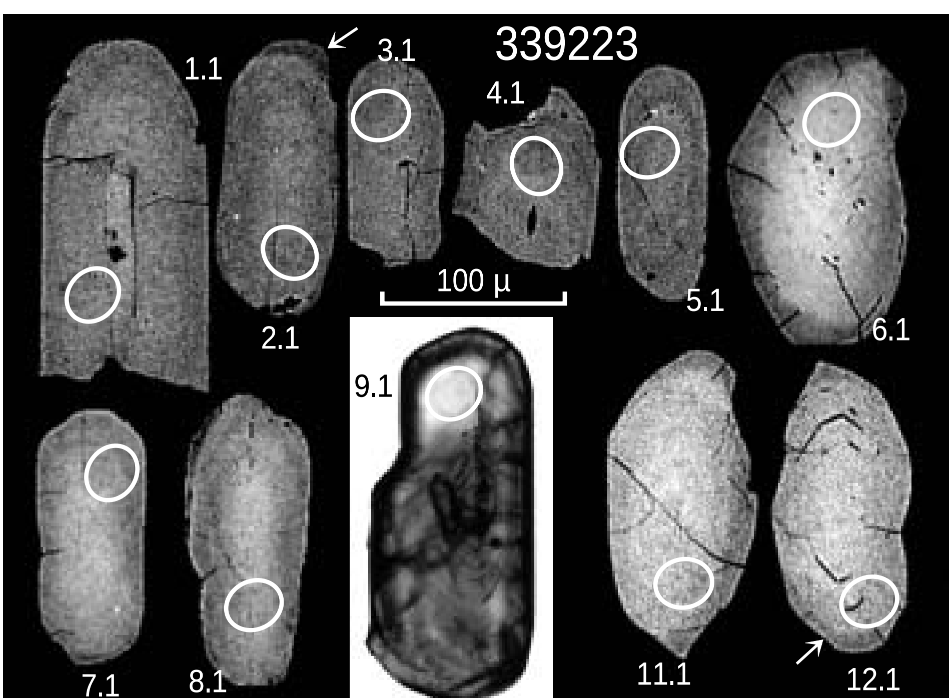



Fig. 6d. Morphology and backscatter imaging of analysed zircons from sample no. 339223, Qeqertaussaq diorite, central Fiskefjord. The insert on white background is a microphotograph in transmitted light. Arrows mark thin overgrowths.

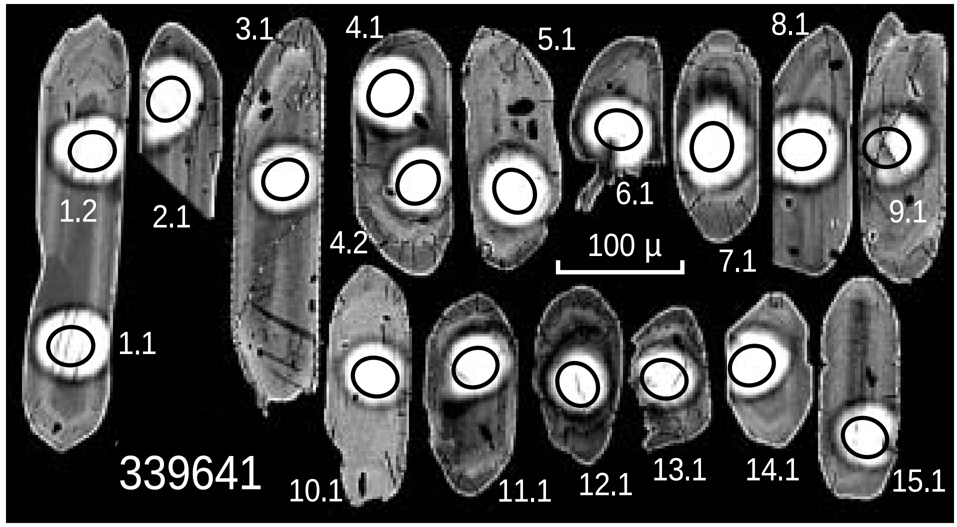



Fig. 6e. Morphology and backscatter imaging of analysed zircons from sample no. 339641, Finnefjeld gneiss, outer coast north of Fiskefjord. Only zoned prismatic grains are present.

zoned, prismatic zircons; the magmatic-type oscillatory zonation is visible both in transmitted light and with BS imaging (Fig. 6e). The U-Pb analyses provide a concordant, relatively well-defined intrusion age of 2975 ±7 Ma (Fig. 8). One grain (2999 Ma) may be inherited, and five grains with lower ages between 2951–2920 Ma were omitted from the calculation. The 2975 ±7 Ma SHRIMP age reported here is in full agreement with the field relationships. An alternative interpretation would be that the youngest grains indicate the true age (2939 ±10 Ma), and that the large majority of the zircons are inherited.

*Sample no. G91-83, tonalite.* This sample was collected on the eastern side of the Ataneq Fault at 64º58′N, 50º21′W, from a unit which appears as early Archaean gneiss on the 1:100 000 scale geological map Ivisârtoq (Chadwick & Coe 1988). However, this interpretation is not supported by the field evidence because the rocks are not cut by discordant amphibo-

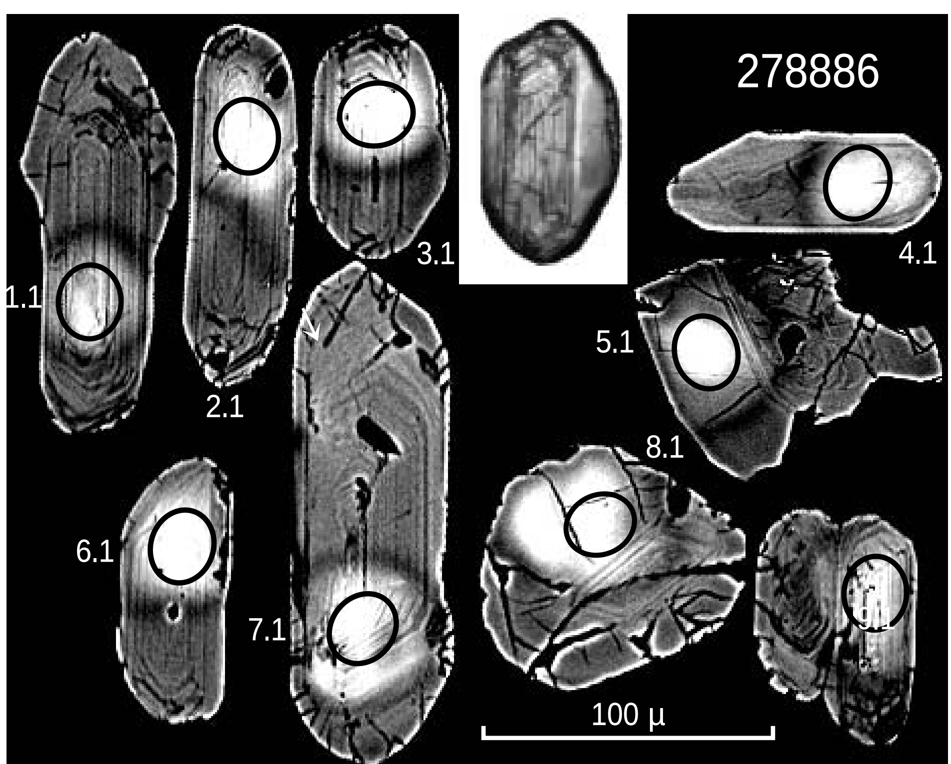



Fig. 6f. Morphology and backscatter imaging of analysed zircons (prismatic grains and crystal fragments) from sample no. 278886, Igánánguit granodiorite north-east of the head of Fiskefjord. The insert on white background is a microphotograph in transmitted light.

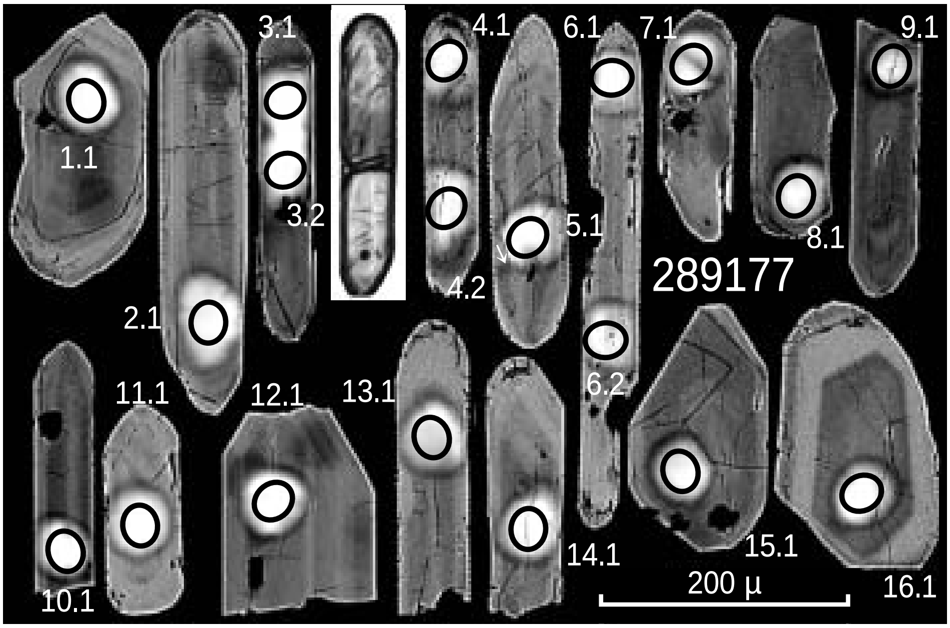



Fig. 6g. Morphology and backscatter imaging of analysed zircons from sample no. 289177, Qugssuk granite north of Qugssuk. A few grains, like 1.1, display older cores. The insert on white background is a microphotograph in transmitted light.

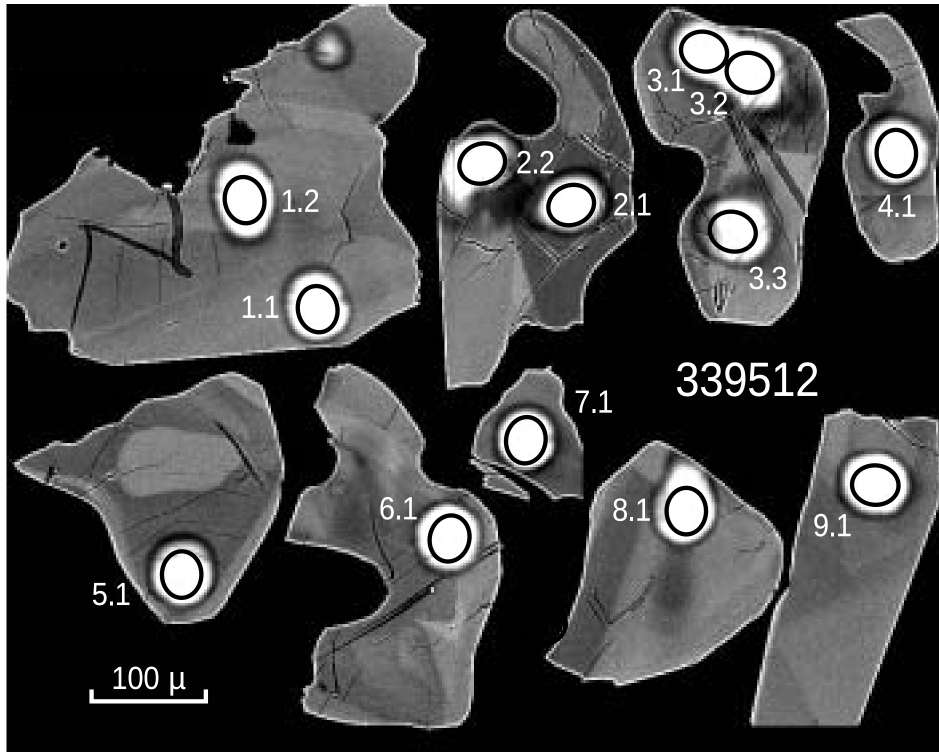
lite sheets *i.e.* remnants of Ameralik dykes, see McGregor (1973). The rock is a medium-grained, homogeneous, weakly foliated, amphibolite facies tonalite and is correlated with the Taserssuaq tonalite complex. The zircons are relatively simple comprising dominantly pale buff to brownish, oscillatory-zoned prisms with a few rounded or ovoid grains and a very few large (*c.* 250 µ) pinkish prisms. Despite the morphological differences, the grains are chemically very similar, with U contents <687 ppm and Th <336 ppm. The data describe the upper portion of a discordia chord (Fig. 8) and are interpreted best as a single population of grains variably disturbed in a later event. The analyses deemed to be the least disturbed provide a $^{207}$Pb/$^{206}$Pb age of 2973 ±8 Ma. If the two analyses of grain 1 (which might be inherited) are ignored, 16 out of the remaining 19 analyses produce a weighted mean $^{207}$Pb/$^{206}$Pb age of 2972 ±12 Ma with a calculated MSWD = 0.9. This is indistinguishable from the selection based on the least disturbed sites.

*Sample no. 278886, Igánánguit granodiorite.* The Igánánguit granodiorite dome, intruded into the border zone between the grey gneiss and the Taserssuaq tonalite complex, post-dates multiple folding of the grey gneiss and must thus be younger than both the grey gneiss, regional deformation and the Taserssuaq tonalite complex, and it bears no signs of former granulite facies metamorphism or retrogression. There is no geographic overlap with the Qugssuk granite, but it is cut by a plug of post-kinematic diorite. The analysed sample was collected within the large composite dome north-east of Fiskefjord (Fig. 2; 65º06′22″N, 51º03′53″W). It is medium grained and almost undeformed and has a granitic texture with dispersed flakes of greenish biotite. The analysed sample contains small, short to long prismatic zircons, commonly displaying dense concentric zonation of igneous type, commonly with thick outer zones (Fig. 6f). Four grains, up to 7% discordant, yielded a rather imprecise age of 2971 ±15 Ma, which we interpret as the intrusion age of the granodiorite (Fig. 8), while two grains with a common age of 3008 ±14 Ma are interpreted as inherited. Many of the zircons extracted from the sample displayed signs of being metamict. Most of the analysed zircons have high U and Th contents, and common lead is a problem in almost all the analysed grains. Three pitted grains with the highest U contents, above 800 ppm, yielded apparently concordant ages of 2900 Ma and younger. These grains are interpreted as having been affected by early lead loss, and the analyses were rejected.

The SHRIMP age is not well defined and only relies on very few analyses. However, it agrees well with the established field relationships and other age determinations. The granodiorite overlaps in age with both the Taserssuaq tonalite complex (conventional zircon U-Pb age 2982 ±7 Ma, sample 289271, Garde *et al.* 1986), the Qugssuk granite, and the post-kinematic diorites (see below).

*Sample no. 289177, Qugssuk granite.* The analysed sample was collected north of Qugssuk (Fig. 2; 64º50′54″N, 51º10′16″W) in an area where granite sheets ranging from few metres to few hundred metres in thickness were emplaced subparallel to the regional NNE-

Fig. 6h. Morphology and back-scatter imaging of analysed zircons from sample no. 339512, post-kinematic diorite south of central Fiskefjord.




trending foliation of grey gneiss interleaved with amphibolite horizons. The rock is medium grained and apparently homogeneous, with granitic texture and evenly dispersed flakes of biotite which display a weak preferred orientation. Its zircons belong to two separate populations (Fig. 6g): nine slender prismatic, zoned grains yielded an age of 2975 ±5 Ma which is interpreted as the intrusion age; an age of 3001 ±6 Ma from six sites in stubby grains and cores of slender grains represents zircon inheritance from a grey gneiss precursor; one discordant stubby grain yielded an age of *c.* 3040 Ma (Fig. 8). Two grains with apparent ages of *c.* 2950 Ma were rejected. The new SHRIMP zircon age is identical to a Rb-Sr whole rock age previously obtained from north of Qugssuk (2969 ±32 Ma, MSWD = 1, Garde *et al.* 1986). The 2975 ±8 Ma zircon age of the Qugssuk granite overlaps with the age of the granulite facies event, 2981 ±8 Ma, obtained from sample 339199 north of outer Fiskefjord. The Qugssuk granite cuts grey gneiss with blebby texture in the western part of its outcrop area, which may mean that it provides a minimum age of the retrogression (see discussion in Garde 1997).

*Sample no. 339512, post-kinematic diorite***.** The sample was collected from one of several small intrusions emplaced into retrogressed grey gneiss south of central Fiskefjord (Fig. 2; 64°48′14″N, 51°47′11″W) and is granular with dispersed hornblende and biotite, and minor blue-green amphibole. The zircon morphology is quite different from the prismatic zircon populations found in the grey gneiss, Finnefjeld gneiss complex and younger granitoids: the grains are significantly larger (200µ and larger), and none are prismatic. Most grains are equant with irregular and locally concave surfaces (Fig. 6h); this type of igneous zircon habit is common in some diorites and most mafic rocks. The zircons are interpreted as late crystallisates (in some cases with inherited cores) with shapes controlled by the surrounding, pre-existing minerals. Three dark brown zircon cores, interpreted as inherited from grey gneiss, yielded an age 3016 ±23 Ma (Fig. 8); overgrowth on the inherited cores seems to have begun already at 3006 ±13 Ma (five sites along dark brown margins). Pale margins and small pale grains (five sites) yielded an age of 2976 ±13 Ma, which is interpreted as dating the final emplacement.

The SHRIMP age data agree with field relationships and other age data. The emplacement age (2976 ±13 Ma) is younger than, but overlaps with the age of zircons interpreted as dating the granulite facies metamorphism (2981 ±8 Ma), and also overlaps with the 2971 ±15 and 2975 ±5 Ma ages of the post-granulite facies Igánánguit granodiorite and Qugssuk granite which are both intruded by post-kinematic diorites.

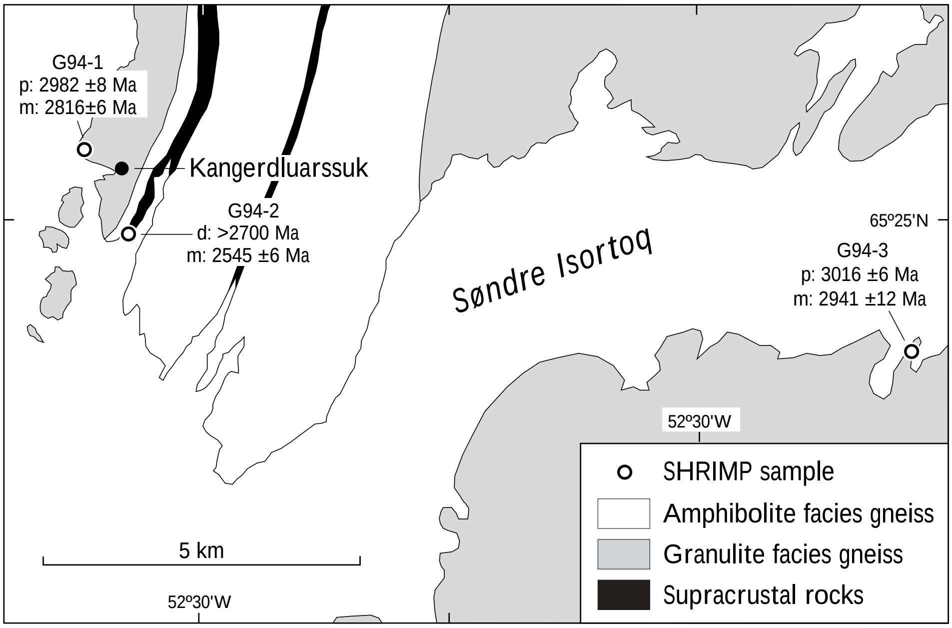



Fig. 9. Geological sketch map of the area around outer Søndre Isortoq, with locations of samples used for SHRIMP geochronology. p: protolith age, d: detrital age, m: metamorphic age.

## Northern Akia terrane

Three dated samples come from the northern side of the Akia terrane. They were taken in an attempt to locate either the edge of the Akia terrane, or the boundary between the *c.* 3000 Ma granulite facies event and that dated at *c.* 2740 Ma (Friend & Nutman 1992). Two samples (G94–1 and G94–3), both at granulites facies, represent the main grey gneiss complex whilst one sample (G94–2) is from an amphibolite facies unit of metasediments flanked by granulite facies gneisses. A geological sketch map with sample locations is shown in Fig. 9, and U-Pb concordia diagrams are shown in Fig. 10.

*Sample no. G94–3, grey granulite facies gneiss.* This, the southernmost sample comes from the south shore of Søndre Isortoq (Fig. 9; 65º24′12″N, 52º14′42″W) where the rocks are largely at granulite facies with some patchy retrogression and appear to be structurally continuous with the Akia terrane further south. The sample itself is not retrogressed and has orthopyroxene and amphibole in equilibrium. It was thus expected that this sample might provide a date for the metamorphism and an indication of the age of protolith. The zircons are all large, around 250 μ, with a variety of shapes from prismatic to equant. Many have little visible internal structure. Based on their shape and colour the grains can be divided into two groups: (1) brownish, broadly prismatic grains including some with faint oscillatory zones, though not of the very fine scale typical of igneous grains; (2) larger, pinkish or buff-coloured grains with more ovoid and equant shapes. In terms of U and Th chemistry, there are also two groups, but these do not coincide with the morphological groups. The first of these has high U and low Th contents (642–2073 ppm U, Table 2) and Th / U ratios less than 0.26. The second group has 30–500 ppm U and Th / U ratios greater than 0.25. Some sites have very low Th / U ratios (<0.02) that might indicate a metamorphic origin, e.g. spot 7.2, Th / U = 0.1 (Table 2) at the tip of a prismatic grain. However, the $^{207}Pb/^{206}Pb$ age of 2997 ±11 Ma for spot 7.2 is identical to that of the dark, poorly luminescing core (7.3, 2997 ±13 Ma).

The entire data set forms a smear close to concordia and can be treated in two ways: (1) all the grains may form a single, disturbed igneous population; (2) some of the protolith grains are variably disturbed and overgrown by metamorphic zircon. Still younger ancient disturbance is also possible, as indicated by analysis 14.1. This provided an extremely young concordant $^{207}Pb/^{206}Pb$ date of 2742 ±25 Ma (Table 2); no event of this age is known from the Akia terrane, but the date does equate with the age of the granulite facies event in the next block to the north (Friend & Nutman 1994).

In conclusion we prefer to interpret the bulk of the analyses from G94–3 as a protolith population disturbed by granulite facies metamorphism. The buff coloured zircon, usually with relatively high U contents, yielding a $^{207}Pb/^{206}Pb$ age of 3016 ±5 Ma, is interpreted as dating the protolith. The pinkish to colourless, commonly low-U and low Th / U zircon yielding a $^{207}Pb/^{206}Pb$ age of 2941 ±12 Ma is interpreted to date a subsequent high-grade metamorphic event. The two events are relatively close together and, with the lack of definition of different zircon types, resolu-

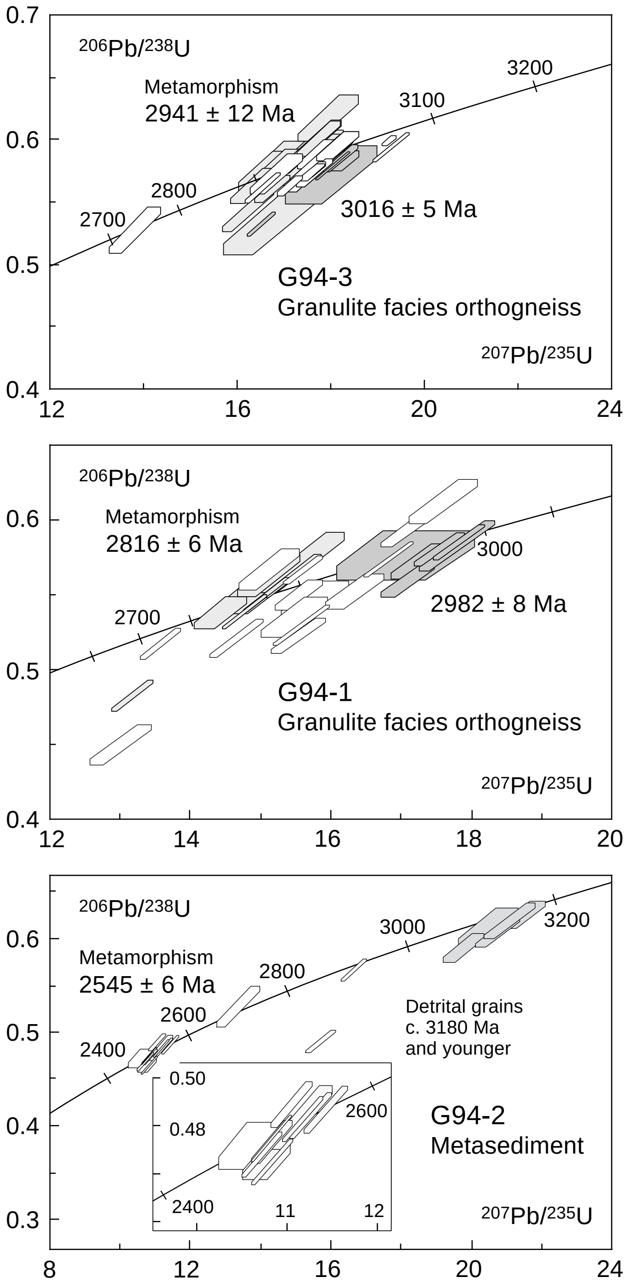



Fig. 10. U-Pb concordia diagrams displaying SHRIMP zircon geochronology of samples from the northern part of the Akia terrane.

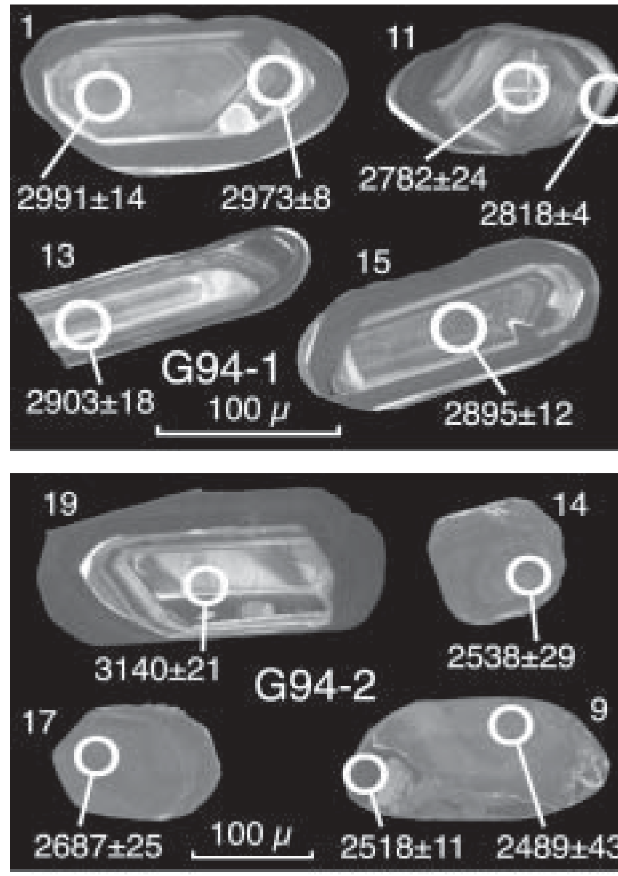



Fig. 11. Morphology and cathode luminescence imaging of typical analysed zircons from samples G94-1 and G94-2 from the northern part of the Akia terrane.

tion is consequently difficult.

*Sample no. G94–1, grey granulite facies gneiss.* This weakly retrogressed, granulite-facies sample of tonalitic composition came from west of the settlement Kangerdluarssuk (Fig. 9; 65º25′30″N, 52º32′ 24″W) and to the north-west of the belt of amphibolite facies metasediments which could possibly represent the north-western boundary of the Akia terrane. The zircons are brownish or buff-coloured, rounded prisms or equant grains commonly with rounded terminations. Optical inspection shows that some of the more acicular grains have oscillatory zones, whilst the equant to ovoid grains may or may not show internal zoning. CL imagery (Fig. 11a) displays a variety of internal zoning patterns, where brightly luminescing zones are poorly represented; a few grains appear to have cores, although no obvious truncations were found. The analytical points were divided into two groups. The first group, generally with U contents above 300 ppm, shows a degree of scatter along concordia that is considered to reflect metamorphic disturbance (Fig. 10). From this scatter a group of six statistically indistinguishable grains yielded an age of 2982 ±8 Ma which is interpreted as a minimum age for the protolith. The second group, mostly with lower U contents, gave an age of 2816 ±6 Ma interpreted to reflect a metamorphic event. One slightly discordant grain (7.1) gave a younger date of 2745 ±7 Ma and, like the youngest point on G94–3, could reflect the age of the granulite facies event known from further north.

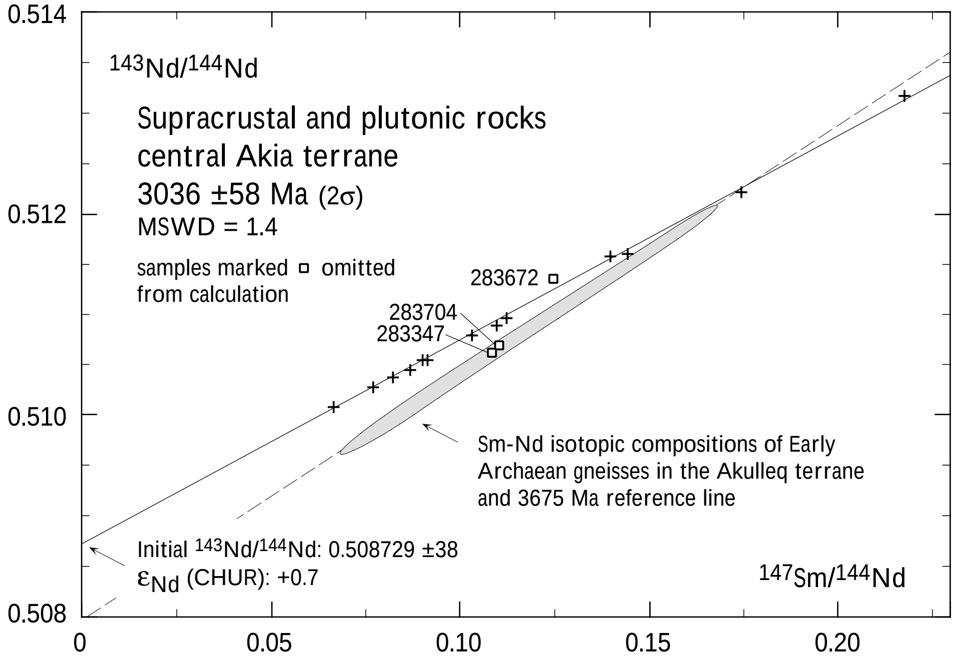



Fig. 12. Sm-Nd isochron plot of supracrustal and plutonic rocks from the central part of the Akia terrane. Lithology, Sm-Nd data and location of each sample are given in Table 3. See the main text for discussion.

*Sample no. G94–2, amphibolite facies metasediment*. This sample collected south-east of Kangerdluarssuk (65º24′48″N, 52º31′24″W) comes from a narrow, approximately NNE-striking belt of metasediments within a zone of amphibolite facies gneisses (Fig. 9). The high metamorphic grade recorded in the mineral assemblages – anthophyllite, garnet ±aluminium silicate, rutile, cordierite and staurolite, suggests that the metamorphic event is of Archaean rather than Proterozoic age; hence the supracrustal rocks at Kangerluarssuk might represent the north-western edge of the Akia terrane.

The sample was taken in an attempt to determine the age(s) present in the source region and the age of the high-grade metamorphism. The zircons vary from colourless to dark brown or red and have a large range of high U and low Th concentrations, for the most part giving very low Th / U ratios (Table 2). Most are rounded or equant consistent with them representing detrital grains; also some elongate grains are present. Some grains have pinkish or reddish cores with distinct buff to brownish overgrowths, but these were rarely observed in CL imagery because the majority of the grains are non-luminescent due to their high U contents. However, grain 19 showed a brightly luminescing core (Fig. 11b).

Most of the analysed grains fall into two groups (Figs 10, 11b). First, a group comprising rounded grains and cores that are interpreted as detrital grains gave a range of ages from *c.* 2700–3180 Ma. Second, a group including some homogeneous grains and overgrowths yielded an date of 2545 ±6 Ma, which is interpreted to reflect the age of a metamorphic event. Three points between these two age groups comprise discordant analyses or mixtures. Grain 9 (Fig. 11b) has a pale pink core (9.1) with 662 ppm U and a concordant $^{207}$Pb / $^{206}$Pb age of 2489 ±43 Ma, overgrown on one side by a pale buff partial rim (9.2) with 7138 ppm U, yielding a likewise concordant $^{207}$Pb / $^{206}$Pb age of 2518 ±11 Ma. The core analysis has a younger age than the rim but large error, and the grain is best interpreted as being disturbed and so ignored. A few younger grains are statistically separate and could either reflect disturbance or indicate a second metamorphic event.

# Sm-Nd isotopic data

Sm-Nd analyses were performed on 16 representative rock samples from the central part of the Akia terrane, including seven of the samples used for zircon geochronology. Information about lithologies, geographical coordinates and Sm-Nd data are given in Table 3. Besides grey gneiss and granitic rocks, the data include three samples of supracrustal amphibolite and a sample of pelitic metasediment intercalated with amphibolite and ultrabasic rocks, which is thought to have been derived from erosion of basic volcanic protoliths.

Thirteen of the 16 analyses plot along an errorchron (Fig. 12) with a slope corresponding to an age of 3036 ±58 Ma (2σ) and MSWD = 1.4, initial $^{143}$Nd / $^{144}$Nd =

Table 3. Sm-Nd whole-rock data from the central part of the Akia terrane.

| No | Lithology | Locality | | $^{147}Sm/^{144}Nd^{\dagger}$ | $^{143}Nd/^{144}Nd^{\S}$ |
|---|---|---|---|---|---|
| **Supracrustal rocks** | | | | | |
| 278792 | Leuco-amphibolite, amphibolite facies | 64º53′22″N | 51º05′08″W | 0.1126 | 0.510973 ±08 |
| 289141 | Amphibolite, partially retrogressed | 64º52′15″N | 51º26′30″W | 0.1746 | 0.512224 ±06 |
| 289189 | Amphibolite, granulite facies | 64º50′18″N | 51º10′18″W | 0.2176 | 0.513168 ±06 |
| 339573 | Pelitie, garnet-biotite-sillimanite bearing | 64º58′25″N | 52º10′07″W | 0.1400 | 0.511566 ±07 |
| **Dioritic gneiss** | | | | | |
| 283672* | Nordlandet dioritic gneiss, granulite facies | 64º34′48″N | 51º39′21″W | 0.1249 | 0.511366 ±08 |
| 289151 | Dioritic gneiss, granulite facies | 64º45′28″N | 51º42′42″W | 0.1442 | 0.511600 ±06 |
| 339223* | Qeqertaussaq diorite, retrogressed | 64º53′53″N | 51º36′38″W | 0.1034 | 0.510792 ±09 |
| **Grey TTG gneiss** | | | | | |
| 283347 | Grey gneiss, amphibolite facies | 64º40′05″N | 51º09′15″W | 0.1101 | 0.510685 ±05 |
| 289274 | Grey gneiss, amphibolite facies | 64º40′20″N | 51º11′22″W | 0.1096 | 0.510885 ±10 |
| 289280 | Grey granitic gneiss, amphibolite facies | 64º40′20″N | 51º11′22″W | 0.0914 | 0.510539 ±06 |
| 289246* | Grey gneiss, retrogressed | 64º43′28″N | 51º17′22″W | 0.0822 | 0.510370 ±06 |
| **Late plutonic rocks** | | | | | |
| 289171 | Taserssuaq tonalite | 65º02′N | 50º45′W | 0.0867 | 0.510462 ±06 |
| 339641* | Finnefjeld gneiss | 65º02′54″N | 52º12′59″W | 0.0903 | 0.510556 ±07 |
| 278886* | Igánánguit granodiorite | 65º06′22″N | 51º03′53″W | 0.0772 | 0.510277 ±06 |
| 289177* | Qugssuk granite | 64º50′54″N | 51º10′16″W | 0.0665 | 0.510091 ±06 |
| 283704 | Post-kinematic diorite (=339512*) | 64º48′14″N | 51º47′11″W | 0.1082 | 0.510629 ±06 |

Sm-Nd analysis at the Geological Institute, University of Copenhagen, normalised to the La Jolla standard (accepted value of $^{143}Nd/^{144}Nd$ = 0.511860). Mean of 10 standard measurements during analysis period = 0.511849 ±0.000006 (2σ).
†Errors estimated to ± 2% (2σ).
§Analytical errors (2σ) used for isochron calculation (Fig. 11).
*Sample also used for SHRIMP U-Pb zircon geochronology.

0.508729 ±0.000038 ($\varepsilon_{Nd(CHUR)}$ = +0.7 at 3036 Ma). Three samples were omitted from the isochron calculation: one sample, Nordlandet dioritic gneiss 283672 with a SHRIMP zircon U-Pb protolith age of 3221 ±13 Ma, plots above the line. Of the two samples plotting below the line, 283704 is a post-kinematic diorite (same locality as 339512 used for SHRIMP zircon geochronology) derived from ultrabasic magma contaminated with continental crust (Garde 1991, 1997). The other sample, 283347, is a grey tonalitic orthogneiss.

The bulk of the Sm-Nd data (omitting the *c.* 3220 Ma Nordlandet diorite, the post-kinematic diorite and one of the grey gneiss samples) are best interpreted as indicating extraction from a mildly depleted mantle source at around 3050 Ma. The compositional field of 75 Early Archaean gneisses and metagabbros from the adjacent Akulleq terrane in the Godthåbsfjord area (Bennett, written communication, 1999 and previously published data by A.P. Nutman and coworkers) and a 3675 Ma reference line are included in the Sm-Nd diagram for comparison.

## Interpretation and discussion

It has gradually become accepted that Archaean crustal accretion was largely governed by plate-tectonic processes not unlike those operating today, although it is still debated (e.g. Martin 1994) if Archaean continental crust was largely generated by partial melting of the upper mantle above the subducted slab, or if Archaean TTG magmas were derived from hot, hydrated basaltic oceanic crust undergoing subduction.

The accretionary history of the central part of the Akia terrane is summarised in Table 1. Four populations of igneous zircons in grey gneiss range from *c.* 3050–3020 Ma in age. During this period, which may have extended to *c.* 3000 Ma as suggested by inherited zircons in the Qugssuk granite, new continental crust was accreted into and around the older (3220 Ma) Nordlandet dioritic gneiss. Numerous diorite and tonalite sheets were intercalated with supracrustal rocks of oceanic affinity by intrusion, thrusting and folding in a convergent (island arc) plate-tectonic setting (Garde 1997). The small quantity of available age data is insufficient to demonstrate if the magmatic accretion was a continuous process, or if it took place in several shorter pulses; the N-S orientation of Smalledal phase isoclinal fold axes suggests that E-W orientated compressional forces predominated in the later part of the period.

The Sm-Nd data from both supracrustal associations and plutonic quartzo-feldspathic rocks in the central part of the Akia terrane indicate that the protoliths which eventually differentiated into the grey gneiss and younger tonalites, granodiorites and granites may have been extracted from a mildly depleted mantle source at around 3050 Ma, without any significant contribution from early Archaean crust. This interpretation is in close agreement with other lines of evidence (see Garde 1997 and references therein) that the grey gneiss – now known to have zircon ages between *c.* 3050–3020 Ma – was probably derived from partial melting of hydrated oceanic crust in a convergent plate-tectonic environment, which had a short crustal residence time and was therefore hotter than modern oceanic crust when it was subducted; at least in the central part of the Akia terrane there is no evidence of middle Archaean komatiitic rocks or other signs of mantle plume activity, which would be an alternative way of extracting new crust from the mantle.

Sm-Nd data from type Nûk gneisses in the vicinity of Nuuk at the southern margin of the Akia terrane reported by Duke (1993) contrast with the Sm-Nd results obtained from the central part of the terrane. The data set of Duke (1993) plots with considerable scatter on a Sm-Nd isochron diagram: a fitted errorchron (Duke, 1993) has a slope corresponding to an age of 2786 ±120 Ma and initial $^{143}Nd/^{144}Nd$ = 0.50889 ±0.00008, corresponding to an $e_{Nd(CHUR)}$ = –2.6. This suggests that older continental crust was involved in the crust formation, and that the Sm-Nd isotope system showed open system behaviour, perhaps in connection with intense late Archaean ductile deformation along the terrane margin.

The age of metamorphic zircons in grey gneiss 339199 show that the granulite facies conditions around central Fiskefjord were reached at *c.* 2980 Ma; at this time the new crust appears to have reached its maximum thickness and become partially dehydrated and less ductile. Recumbent isoclinal folding ceased, and the continuously E-W orientated stress field now resulted in upright, N-S trending folds of the Påkitsoq phase. The upright folding was contemporaneous with, or succeeded by localised steep to vertical, N- to NE-trending, ductile high strain zones, which were initiated while granulite facies conditions still persisted; no evidence of a subsequent extensional phase due to gravitational collapse of thick crust has yet been recorded.

Friend & Nutman (1994) reported a slightly older SHRIMP age (2999 ±4 Ma) from low-U zircons in a metasediment from central Nordlandet, which probably dates the same metamorphic event, and sample G94-3 from the northern part of the terrane described in this paper yielded a metamorphic age of 2947 ±12 Ma. It is therefore possible that the granulite facies event was diachronous, with the thermal maximum moving from the southern to the northern part of the terrane between *c.* 3000 and 2950 Ma, but more age data are required to confirm this.

The metamorphic maximum was followed within a few million years by the emplacement of two large, broadly dome-shaped tonalite complexes. At around this time (*c.* 2975 Ma), both the production of new continental crust and regional penetrative deformation ceased, and it therefore seems reasonable to assume that also plate-tectonic convergence was coming to an end.

Then followed high-grade retrogression (closely linked to the preceding granulite facies event), emplacement of late-tectonic granitic rocks generated by partial melting and remobilisation of grey gneiss, and emplacement of post-kinematic diorites, while the Akia terrane cooled and stabilised. The zircon geochronology (Table 1) shows that all these events succeeded each other very rapidly at around 2975 Ma. Whereas a relative chronology is firmly established from field observations, the SHRIMP and conventional zircon ages of all the late plutonic rocks are statistically unresolvable from each other.

In conclusion, currently available zircon U-Pb and whole-rock Sm-Nd geochronological data combined with previously reported field observations, major and trace element geochemistry and isotope geochemistry suggest that the *c.* 3000 Ma accretional history of the central part of the Akia terrane may have begun with separation from the mantle at around 3050 Ma. The magmatic accretion of grey gneiss, presumably by partial melting during subduction of hydrated, young and therefore relatively hot oceanic crust, consisted of a relatively protracted accumulative stage which prevailed for *c.* 50 Ma, a thermal maximum which lasted around 10–15 Ma, and a short stage of maturation and stabilisation which lasted only 5–10 Ma. The currently available age data may indicate that the thermal maximum was diachronous within the terrane and lasted until *c.* 2950 Ma in its northern part. The Akia terrane then remained passive until the final terrane assembly in the Godthåbsfjord region at around 2720 Ma. In the intervening period of *c.* 250 Ma, the locus or loci of plate-tectonic convergence shifted to other sites in the region, including the adjacent Akulleq and Tasiusarsuaq terranes.

The present study has demonstrated that complicated magmatic, tectonic and metamorphic events followed each other very rapidly in the Akia terrane towards the end of its mid-Archaean accretion. A modern example of comparable complexity is provided by the Fiji region (Hathway 1993; Lagbrielle, Goslin, Martin, Thirot & Auzende 1997).

Another dimension of this study, the delineation of the northern boundary of the Akia terrane, has been advanced only a little by this work. Rocks with the protolith and metamorphic geochronological characters of Akia terrane are now known to exist up to the southern shore of Søndre Isortoq (Figs 2, 10), whereas the geochronological evidence from the remaining samples collected further north is ambiguous. Granulite facies tonalite G94–1 has the protolith age character of Akia terrane, but the inferred metamorphic age, presumed to reflect the granulite facies event, is neither that seen in Akia, nor to the north (Friend & Nutman 1994). Maybe the 2786 Ma age is not meaningful. Alternatively, the boundary of the Akia terrane may be located still further to the north, towards Maniitsoq. In this case, these rocks represent a granulite facies event at around 2786 Ma which has not been recorded elsewhere. Besides, the few analyses providing *c.* 2740 Ma ages may reflect the effects of the Maniitsoq granulite facies event (dated at 2738 ±6 Ma by Friend & Nutman 1994) in the vicinity of Søndre Isortoq (Fig. 9).

The problems of interpretation are compounded by the amphibolite facies metasediment G94–2. This records a detrital history that includes grains with ages akin to the Akia terrane to the south, implying that the sediment itself must be younger. Whilst some grains have dates similar to those of the Akia terrane, many grains are younger, with a completely different chemistry, and thus cannot have been derived locally. The belt also clearly records an apparently restricted amphibolite facies metamorphic event at *c.* 2550 Ma, as older granulite facies rocks are present on both sides. The record of such a young event in this limited area might be explained as simply representing another of the many late Archaean retrogression events that are known from elsewhere to the south. This is certainly possible as by this time the Akia terrane had docked with the rest of the Nuuk region (Friend et al. 1996). Several episodes of crustal reworking around this time are known from the southern side of the Akia terrane, and crustal readjustment could have created a zone of strong retrogression and deformation inside the Akia terrane. Alternatively, it may be that rocks of Akia age extend further north but are overprinted and disturbed by younger high-grade metamorphic events. It still remains possible, however, that the intense deformation zone along Kangerdluarssuk represents a boundary along which two blocks with similar protolith ages but different metamorphic histories have been juxtaposed. This problem can only be resolved with further geochronological work.

## Acknowledgements

We thank Feiko Kalsbeek, Geological Survey of Denmark and Greenland, for constructive comments and suggestions during preparation of the manuscript, J. Barling, University of Copenhagen, for Sm-Nd isotope analyses, and P. Venslev, University of Copenhagen, for zircon separations. We also thank F. Corfu and S. Moorbath for constructive reviews; some disagreement with the reviewers on the interpretation of complex zircon age data, including the role of inherited zircons, still remains. This paper is published with permission of the Geological Survey of Denmark and Greenland.

## Dansk sammendrag

Nye ionsonde U-Pb analyser af zirkoner fra 12 prøver af orthognejs, granit og post-kinematisk diorit fra Akia terrænet i det sydlige Vestgrønland giver sammen med tidligere publiceret materiale detaljerede oplysninger om, hvordan den midtarkæiske kontinentale skorpetilvækst foregik, og viser, at differentiation, modning og stabilisering af den nydannede skorpe skete meget hurtigt. Aldrene af magmatiske zirkoner i grå gnejs og arvede zirkoner i granitter opsmeltet fra den grå gnejs viser, at den magmatiske tilvækst af ny kontinental skorpe foregik for mellem ca. 3050 og 3000 mill. år siden. Processen var domineret af tonalitisk magma og foregik i et konvergent pladetektonisk øbue-miljø omkring en lidt ældre, ca. 3220 mill. år gammel kontinental kerne af dioritisk gnejs. Tonalitterne blev indplaceret som lag i ældre suprakrustale bjergarter ved intrusion, overskydning og isoklinal foldning under Midterhøj og Smalledal deformationsfaserne, som oprindeligt blev opstillet af Berthelsen (1960). Den vedvarende intrusion af tonalitisk magma førte til et thermalt maksimum med granulit facies metamorfose samtidig med dannelsen af stående, angulære folder under Pâkitsoq deformationsfasen, som nu er dateret ved hjælp af metamorfe zirkoner til 2980 mill. år. Allerede få millioner år senere fandt en delvis retrogradering sted under høj til mellem amfibolitfacies tryk- og temperaturbetingelser. Samtidig hermed blev to store intrusive komplekser af tonalit og granodiorit dannet, der blev remobiliseret granitsmelter fra de grå gnejser, og postkinematiske 'plugs' af diorit blev intruderet. Aldersbestemmelser med ionsonde af zirkoner fra alle disse forskellige enheder, hvis relative indbyrdes aldre er kendt fra tidligere feltundersøgelser, giver sammenfaldende resultater på omkring 2975 mill. år.

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