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Clark R L Friend, Allen P. Nutman

Institutions: University of Wollongong

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Clark R L Friend

Allen Phillip Nutman
University of Wollongong, anutman@uow.edu.au

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Abstract

The Itsaq Gneiss Complex of the Nuuk region, southern West Greenland, is dominated by 3850-3690 Ma tonalites intruded into and intercalated with lesser amounts of different ≥3850-3700 Ma supracrustal units. Published wholerock Sr and Nd isotopic studies demonstrate that the tonalites are juvenile crustal additions from a depleted mantle source. From our field studies and SHRIMP U/Pb zircon dating, we argue that this juvenile crustal accretion was spread over ca. 170 m.yr. (≥3850-3690 Ma). Following 3850-3690 Ma juvenile crustal accretion events, the evolution of the Itsaq Gneiss Complex continued with numerous crustal-reworking events between 3670 and 3500 Ma. Examples of these reworking events are as follows: (1) there is intrusion of several generations of geochemically diverse granites (sensu stricto) with subordinate gabbros and diorites; (2) there are superimposed, multiple episodes of amphibolite to granulite facies metamorphism (illustrated with Akilia Island samples by detailed dating of metamorphic zircon overgrowths in several rocks), (3) part of the complex around Amiitsoq and the hills to the north contains the youngest tonalitic gneisses at ca. 3660 Ma, indistinguishable in age from the oldest recognized granites (sensu stricto) elsewhere; and (4) the hills north of Amiitsoq also contain tectonized remnants of volcanosedimentary basins that were still being filled between 3650 and 3600 Ma (from dating youngest detrital zircons) and that had been inverted and metamorphosed by ca. 3570 Ma (dating of oldest in situ metamorphic overgrowths). These 3670-3500 Ma events are interpreted as reflecting a complex orogen (tentatively collisional and/ or strike slip) superimposed on the products of the earlier (3850-3690 Ma) juvenile crustal accretion regimes. Implications for early crustal evolution studies are discussed.

Keywords

3670, 3500, ma, orogenic, episodes, 3690, 3850, complex, between, itsaq, accreted, superimposed, crust, greenland, west, southern, gneiss, juvenile, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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ARTICLES

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Clark R. L. Friend and Allen P. Nutman[1]

45 Stanway Road, Risinghurst, Headington, Oxford OX3 8HU, United Kingdom (e-mail: crlfriend@yahoo.co.uk)

ABSTRACT

The Itsaq Gneiss Complex of the Nuuk region, southern West Greenland, is dominated by 3850–3690 Ma tonalites intruded into and intercalated with lesser amounts of different ≥3850–3700 Ma supracrustal units. Published whole-rock Sr and Nd isotopic studies demonstrate that the tonalites are juvenile crustal additions from a depleted mantle source. From our field studies and SHRIMP U/Pb zircon dating, we argue that this juvenile crustal accretion was spread over ca. 170 m.yr. (≥3850–3690 Ma). Following 3850–3690 Ma juvenile crustal accretion events, the evolution of the Itsaq Gneiss Complex continued with numerous crustal-reworking events between 3670 and 3500 Ma. Examples of these reworking events are as follows: (1) there is intrusion of several generations of geochemically diverse granites (sensu stricto) with subordinate gabbros and diorites; (2) there are superimposed, multiple episodes of amphibolite to granulite facies metamorphism (illustrated with Akilia Island samples by detailed dating of metamorphic zircon overgrowths in several rocks); (3) part of the complex around Amiitsoq and the hills to the north contains the youngest tonalitic gneisses at ca. 3660 Ma, indistinguishable in age from the oldest recognized granites (sensu stricto) elsewhere; and (4) the hills north of Amiitsoq also contain tectonized remnants of volcanosedimentary basins that were still being filled between 3650 and 3600 Ma (from dating youngest detrital zircons) and that had been inverted and metamorphosed by ca. 3570 Ma (dating of oldest in situ metamorphic overgrowths). These 3670–3500 Ma events are interpreted as reflecting a complex orogen (tentatively collisional and/or strike slip) superimposed on the products of the earlier (3850–3690 Ma) juvenile crustal accretion regimes. Implications for early crustal evolution studies are discussed.

Online enhancements: appendix, figures, table.

Introduction

The age of very ancient rocks (e.g., ≥3850 Ma) and the degree to which their chemical systems have remained closed are crucial factors when using geochemical techniques to derive general information on Earth's early evolution. Combined field geology (McGregor 1973); Pb-Pb, Rb-Sr whole-rock dating (e.g., Black et al. 1971; Moorbath et al. 1972, 1973); and bulk zircon dating (Baadsgaard 1973) have demonstrated that the Nuuk region of southern West Greenland (fig. 1) contains some of the world's oldest rocks (≥3600 Ma). The Greenland rocks are predominantly polyphase, banded orthogneisses initially called the "Amîtsoq gneisses" (McGregor 1973; table 1; "Amîtsoq" is the earlier spelling of "Amiitsoq"). The dominant protoliths of the orthogneisses are tonalite-trondhjemite-granodiorite (TTG) suites, although granites (sensu stricto) produced by crustal remelting occur (McGregor 1973, 1979). Also present are smaller amounts of diverse supracrustal rocks, the largest unit of which is the Isua supracrustal belt in the north (e.g., Moorbath et al. 1973; Allaart 1976). Smaller bodies of similar rocks at higher metamorphic grade are collectively

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[1] Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory 0200, Australia.

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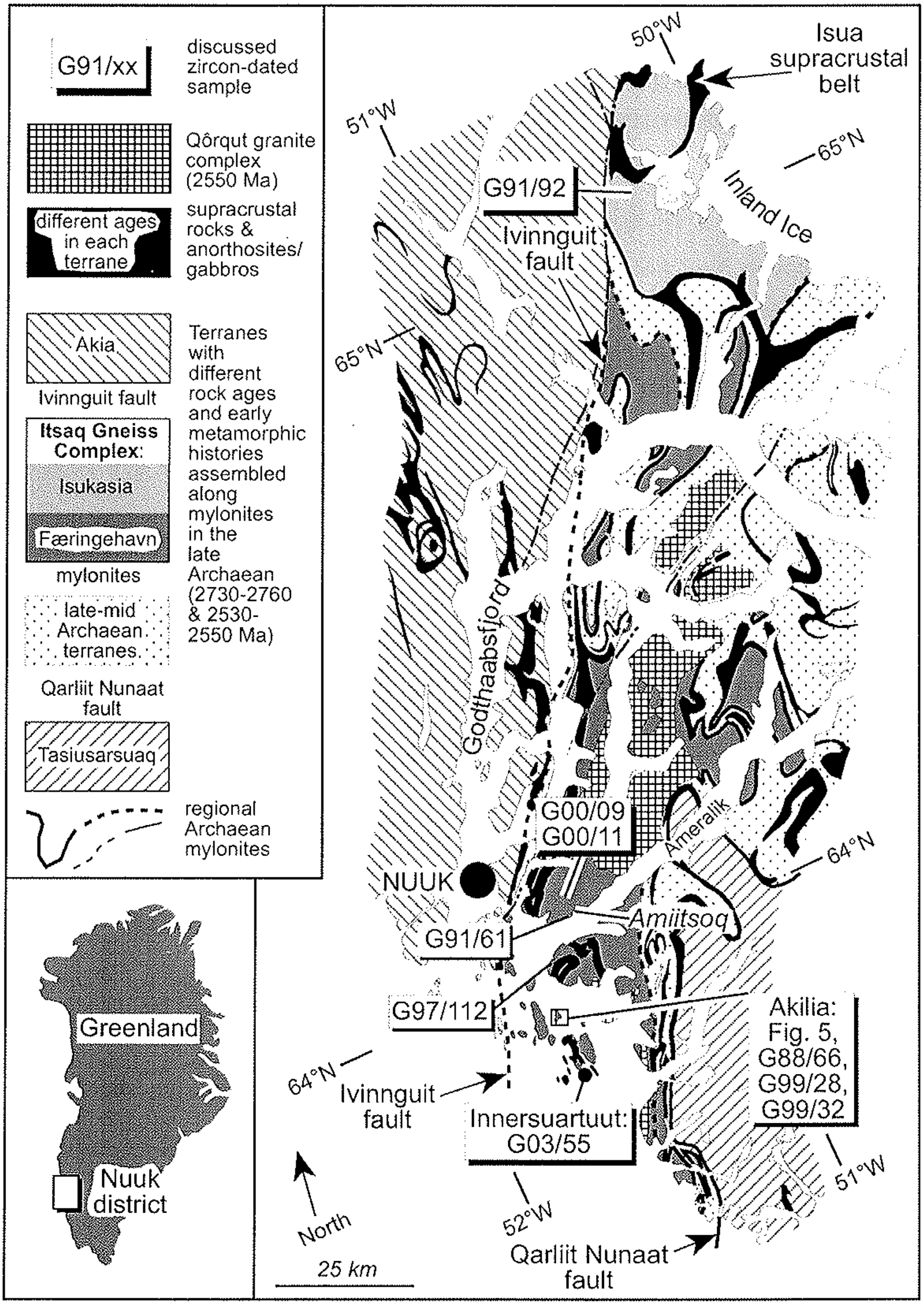


Figure 1. Geological map of the Nuuk district, West Greenland, showing extent of the early Archean Itsaq Gneiss Complex and location of samples studied in this article.

named the "Akilia association" (McGregor and Mason 1977). The Paleoarchean rocks of the Nuuk region present the largest exposed area of varied lithologies for study (Nutman et al. 1996), with domains least affected by later Archean deformation plus domains that escaped granulite facies metamorphism(s) and in situ neosome development (e.g., Bridgwater and McGregor 1974; Nutman et al. 1999, 2000; White et al. 2000*a*; Crowley et al. 2002; Crowley 2003). This study underscores the distinction between juvenile crustal accretion in the Itsaq Gneiss Complex, mostly between 3850 and 3690 Ma and unrelated, superimposed 3670–3500 Ma events, which are the focus of this article. Multiple high-grade metamorphisms and migmatization, intrusion of gabbros coupled with deep crustal melting giving rise to granites (sensu stricto), tectonic intercalation, and deposition of 3650–3600 Ma sediments with detrital zircons derived from a complex hinterland are interpreted as products of an orogen superimposed on TTG-dominated crust generated and assembled appreciably earlier. Implications of this interpretation of the Itsaq Gneiss Complex for early terrestrial studies via radiogenic isotopes are discussed.

Itsaq Gneiss Complex

The Itsaq Gneiss Complex of the Nuuk region comprises gneisses and supracrustal units that contain rocks of considerably different ages (3850–3600 Ma) and origins (Nutman et al. 1996, 2001). The complex is dominated by banded gray orthogneisses, with lenses and pods of mafic and ultramafic material and only rarely unequivocal metasediments such as quartz + magnetite banded iron formation (BIF). Transformation of the originally discordant granitoid intrusions into banded gneisses took place during several episodes of Archean deformation, combined with amphibolite to granulite facies metamorphisms. This process had started by 3850 Ma (Nutman et al. 1999, 2000, 2002*a*; Friend et al. 2002; Crowley 2003) and continued episodically until 2550 Ma (e.g., McGregor 1973; Bridgwater and McGregor 1974; Nutman and Bridgwater 1986; McGregor et al. 1991; Friend et al. 1996, 2002; Myers and Crowley 2000; Crowley 2002). Recently the complex has been interpreted as consisting of two separate tectonic slices: the Faeringehavn terrane in the south and the Isukasia terrane in the north (fig. 1), juxtaposed during Neoarchean tectonic events at ~2950 and 2720 Ma (Friend and Nutman 2004).

Across most of the complex, strong later Archean tectonothermal overprinting hampers unraveling the correct geochronological framework for early crustal evolution geochemical studies, which instead require an especially strong reliance on U/Pb single-grain geochronology combined with outcrop-scale detailed field-based chronology rather than regional lithological "look-alike" correlations. Despite the generally high Neoarchean strain, there are small domains of lower strain throughout the complex, with larger domains in the north near the Isua supracrustal belt (fig. 1; Bridgwater and McGregor 1974; Nutman 1984; Nutman et al. 1999; White et al. 2000*a*; Crowley et al. 2002). These northern lower strain domains allow detailed intrusion chronologies to be established from crosscutting relationships, providing glimpses of pre-3600 Ma tectonic events (Nutman 1984; Nutman and Bridgwater 1986; Crowley et al. 2002; Friend et al. 2002; Nutman et al. 2002*a*; Crowley 2003).

Juvenile Crustal Accretion in the Itsaq Gneiss Complex between 3850 and 3690 Ma—A Resolved Controversy?

Unradiogenic initial $^{87}Sr/^{86}Sr$ isotopic compositions obtained from best-fit lines through scatters of Rb-Sr whole-rock data from orthogneisses and supracrustal rocks indicate that the Itsaq Gneiss Complex is dominated by Paleoarchean juvenile additions to the crust (e.g., Moorbath 1975, 1985; O'Nions and Pankhurst 1978; Moorbath and Taylor 1981; Moorbath et al. 1981) rather than being the recycled products of much older (primordial) crust. Subsequently, positive initial ε_{Nd} values from similar suites of samples, interpreted as indicating derivation from a depleted mantle source, reinforced this conclusion (e.g., Moorbath et al. 1986). Since then, few have doubted that the TTG materials represent mostly juvenile Paleoarchean continental crust. The slopes of these Rb-Sr and Sm-Nd linear arrays (apart from the Isua supracrustal belt collections; e.g., Moorbath et al. 1973; Kamber and Moorbath 1998, 2001) mostly equate to ages between 3700 and 3600 Ma. However, the scatter in these arrays usually (sometimes substantially) exceeds that satisfying the statistical requirements for isochrons (MSWDs typically >20). Although these isochrons illustrate that the complex is Paleoarchean, it is unlikely that they represent reliable age determination for any of the individual samples used (see Nutman et al. 2000; McGregor 2000).

A considerable body of SHRIMP U/Pb zircon data indicates that ≥3700 Ma rocks dominate the complex (Nutman et al. 1993, 1996, 1999, 2001, 2002*a*). These data differ from the mostly 3700–3600 Ma

Table 1. Summary of the Early Important Contributions to the Geological Understanding of the Itsaq Gneiss Complex of the Nuuk Region, Southern West Greenland

Articles	Contributions	Implications
McGregor 1968, 1973, 1979	Recognition from field relationships of an ancient component in the Archean gneiss complex of the Nuuk district	Archean gneiss complexes could be subdivided using the same field methods as already used to distinguish Proterozoic from Archean rocks and events in younger orogens such as the Nagssugtoquidian belt
	Recognition that most Archean banded gneisses are derived from plutonic rocks of tonalitic to granitic composition rather than being dominated by granitized sediments, as widely thought at the end of the 1960s	Revolution in understanding the dominant rock type in Archean gneiss complexes
	Recognition from field relationships of the structural complexity and lithological diversity of the oldest rocks	Evolution of the oldest rocks complicated and need not have occurred within a single event
Black et al. 1971; Baadsgaard 1973	First whole-rock "isochron" (Pb-Pb) and (bulk) zircon dating of McGregor's old complex; this demonstrated the complex contains >3600 Ma rocks	Recognition that some >3600 Ma rocks from the earliest part of Earth's history are still preserved
Moorbath et al. 1972; Moorbath 1975	Low initial Sr values for the "isochrons" on Rb/Sr suites of the >3600 Ma rocks	Crust grew from juvenile contributions from the mantle throughout the Archean and the development of CADs model (see text)
Bridgwater and McGregor 1974	Recognition from field criteria that the Isua supracrustal belt and the surrounding gneisses also are likely to be early Archean	A better-preserved and more lithologically diverse suite of very ancient rocks available for study
Moorbath et al. 1973; McGregor and Mason 1977	Pb-Pb dating of Isua supracrustal belt banded iron formation as >3700 Ma	Great age of the Isua supracrustal belt, giving evidence that "oceans" have existed since before 3700 Ma
	Field description and geochemistry of the Akilia (supracrustal) association	The Nuuk district contains a more extensive suite of earliest Archean volcanic and sedimentary rocks than just the Isua supracrustal belt
	Field evidence for the oldest recognized early Archean granulite facies metamorphism	Thermal evolution of early Archean gneiss complexes similar to late Archean ones
Michard-Vitrac et al. 1977	First single-zircon dating of an Isua supracrustal rock, giving a precise (and accurate) date of 3769 ± 5 Ma	Opened the door to more detailed studies of the chronology of ancient rocks
O'Nions and Pankhurst 1978	First Sm-Nd determinations on the Isua supracrustal belt rocks	Confirmation of the juvenile sources of these ancient rocks
Griffin et al. 1980	Detailed petrographic studies and first *PT* determinations on early Archean granulites south of Nuuk	Indications of thick crust (>25 km) in early Archean orogens, indicating similarities with younger Archean orogens
	Noted that the Isua supracrustal belt and surrounding gneisses had not experienced the early granulite facies event	Chemistry of the Isua area gneisses should be not so strongly modified by superimposed metamorphism as the granulites south of Nuuk
Compston et al. 1986; Kinny 1986	First SHRIMP U/Pb zircon dating of Isua supracrustal belt rocks	Production of first >3800 Ma ages for a part of Isua supracrustal belt
	First SHRIMP U/Pb zircon dating of Greenland orthogneisses	First indication of Greenland orthogneisses older than the Isua supracrustal belt

Table 1 (*Continued*)

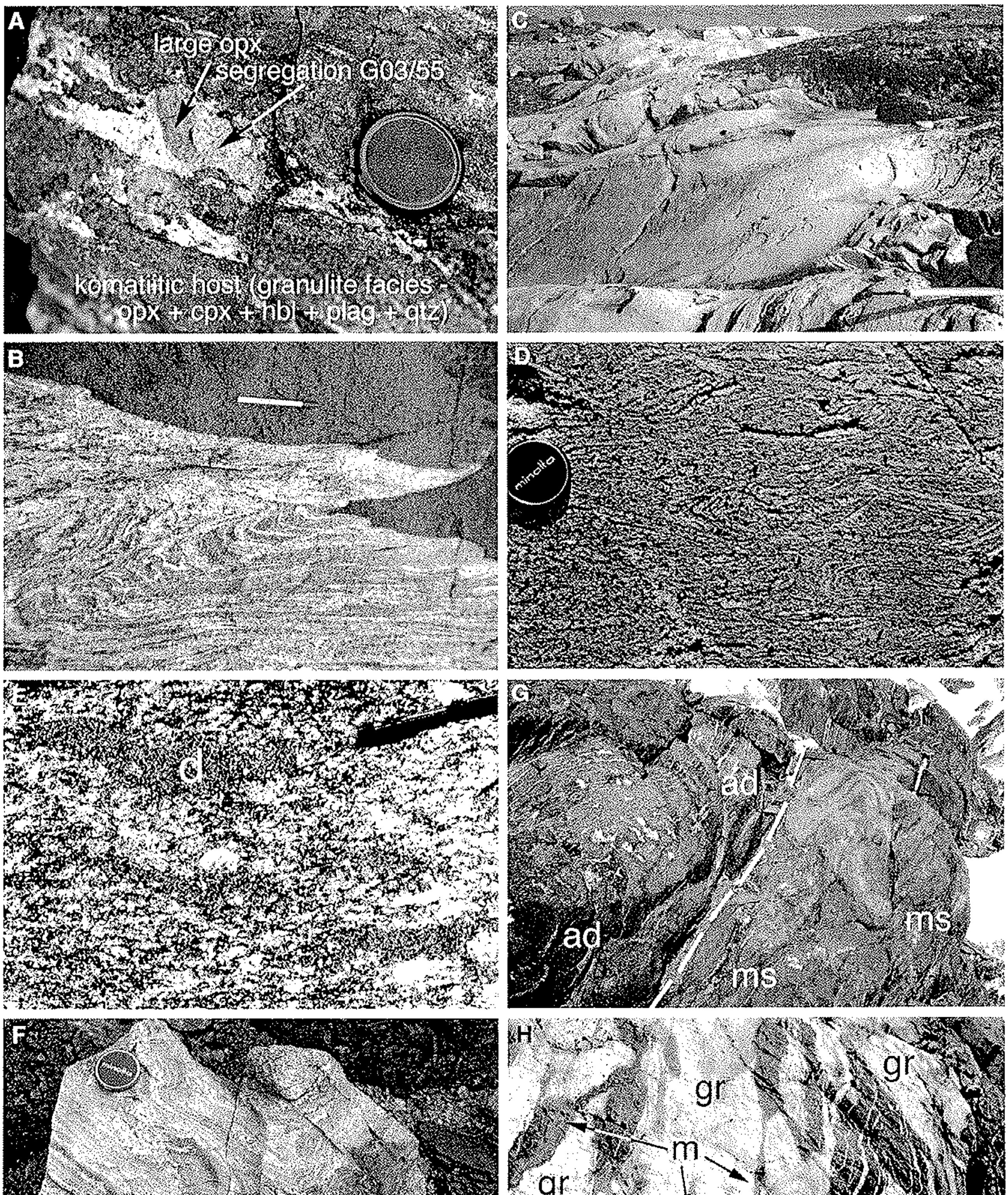
Articles	Contributions	Implications
Gruau et al. 1986; Nutman 1990	Sm-Nd true isochron of 3887 ± 65 Ma from a single body of Akilia association layered gabbro anorthosite; regrettably, this isochron was not favored by Gruau as giving the true age of this gabbro intrusion	Earth's volcanic and sedimentary record extends to >3850 Ma, before the record in the 3700–3800 Ma Isua supracrustal belt; this places the establishment of a retained hydrosphere to >3850 Ma, within the time allotted for the late bombardment
	First suggestion from SHRIMP U/Pb zircon dating that some Akilia association rocks are >3850 Ma old; this controversial result has been replicated by other studies (see text)	
Friend et al. 1987, 1988, 1996	Recognition of tectonic boundaries separating different crustal components and development of the terrane hypothesis; this has been replicated by other studies	A complete reinterpretation of the regional evolution was possible, allowing some of the early controversies between field and isotope geology to be resolved

isochron ages, an age disparity that has stimulated heated debate in the literature (Kamber and Moorbath 1998, 2001; Whitehouse et al. 1999, 2001; vs. Nutman et al. 1996, 2000, 2001, 2002*a*; McGregor 2000). Increasing evidence from independent U/Pb zircon dating studies supports the hypothesis of several significant groups of 3850–3800 Ma tonalitic rocks (Krogh et al. 2002; Mojzsis and Harrison 2002; Crowley 2003; Manning et al. 2003). Thus, there is a growing agreement with our early hypothesis that crustal accretion in the complex had started already started at 3850 Ma (Nutman et al. 1993, 1996) and was not largely concentrated around 3650 Ma.

Paleoarchean Granulite Facies Metamorphism(s) in the Faeringehavn Terrane

Early Studies. Early studies of the southern part of the Amîtsoq gneisses (now in the Faeringehavn terrane) recognized that before intrusion of the Ameralik dikes, the rocks had suffered heterogeneous ductile deformation and high-grade metamorphism and preserve granulite facies assemblages in places (Bridgwater et al. 1976; McGregor and Mason 1977). To date, no premetamorphic assemblages have been identified. By contrasting the post-Ameralik dike amphibolite facies assemblages with the metamorphic assemblages and textures of their host rocks, this southern part of the complex was demonstrated to have undergone Paleoarchean (≥3600 Ma) granulite facies metamorphism, whereas the northern part of the complex (near Isua) had not (table 1). The oldest Ameralik dikes have been dated at 3500–3400 Ma (White et al. 2000*b*; Nielsen et al. 2002; Nutman et al. 2004). Salient points present the field context for the zircon geochronology (e.g., Griffin et al. 1980; Nutman et al. 1996, 2000; McGregor 2000) as follows. First, in low-strain zones, there is textural field evidence of pre-Ameralik dike partial melting in equilibrium with orthopyroxene (fig. 2*A*), clearly indicating Paleoarchean high-grade metamorphism (Nutman et al. 1996, 2000; McGregor 2000). Second, in low-strain areas, the partial-melt domains can have "blebby" (McGregor and Friend 1997) hornblende + biotite aggregates. These aggregates pseudomorph orthopyroxene and are unlike amphibole or mica crystals. Locally relict orthopyroxene is preserved in the blebs in the partial-melt domains, partly replaced by hornblende sieved with quartz and hornblende ± biotite. Similar textures and assemblages are observed in retrograde granulite facies transitions where some relict orthopyroxene is still present in Archean rocks elsewhere (e.g., Greenland: McGregor and Friend 1997; NE Labrador: Collerson and Bridgwater 1979). By analogy, this is a strong indication that some Paleoarchean partial melts in the Faeringehavn terrane evolved in equilibrium with orthopyroxene (fig. 2*A*), which was subsequently replaced by hornblende ± biotite ± quartz during hydrous retrogression.

Only rarely have the Paleoarchean granulite facies assemblages escaped significant retrogression. The best domains are a few square meters outcropping in mafic rocks on the southwest of Akilia Island (Nutman et al. 2002*b*) and a total of ~100 m^2 of outcrops in mafic rocks on the eastern side of Innersuartuut Island (Griffin et al. 1980). At


A
large opx
segregation G03/55
komatiitic host (granulite facies - opx + cpx + hbl + plag + qtz)
B
C
D
minolta
E
d
G
ad
ad
ms
ms
F
H
gr
gr
m
gr

both localities, unretrogressed orthopyroxene is most obvious in quartz + plagioclase segregations, which are interpreted as trondhjemitic melts. This in situ arrested partial melting associated with the granulite facies metamorphism(s) resulted in complex, heterogeneous migmatites (Nutman et al. 1996, 2000, 2002*a*; McGregor 2000). A migmatite demonstrating relatively little post-Ameralik dike strain (fig. 2*B*) can, with stronger postdike deformation, be mistaken for "homogeneous" rocks (fig. 2*C*) unless closely scrutinized (fig. 2*D*). This may account for divergent interpretations of the zircon geochronology on these rocks (see Nutman et al. 2000, 2002*a* vs. Whitehouse et al. 1999, 2001). This early migmatization is typical for the TTG gneisses in the Faeringehavn terrane, but detailed fieldwork (Nutman et al. 2000, 2002*b*) has discovered small vestiges of nonmigmatized TTG up to 3850 m.yr. old.

Granulite Facies Partial Melt G03/55—Innersuartuut. High-Mg mafic rocks with compositional affinity to komatiites (e.g., analysis GGU131477; table 2) dominate the eastern side of Innersuartuut (G03/55 locality, fig. 1). These mafic rocks range from hornblende + plagioclase amphibolites to two pyroxene + hornblende assemblages. Textural relationships (growth of a second generation of hornblende by breakdown of pyroxenes) indicate that the hornblende amphibolites are the products of retrogression of the two pyroxene-bearing assemblages. Segregation G03/55, of trondhjemitic composition and containing large (up to 15 mm long) orthopyroxenes (fig. 2*A*), was used to obtain a U/Pb zircon age (table 3 in the online edition of the *Journal of Geology* and also available from the *Journal*'s Data Depository in the *Journal of Geology* office upon request) of the granulite facies segregation-forming event. This was probably by partial melting at 3–4 GPa (e.g., Rapp et al. 2003). The segregation is within orthopyroxene + clinopyroxene + hornblende + plagioclase mafic granulites and the parts illustrated (fig. 2*A*) are essentially unretrogressed. However, other parts of the same segregation show some breakdown of orthopyroxene to produce hornblende. The host mafic rocks were avoided as much as possible in the dated material, as were the large orthopyroxenes. Thus, the sample (ca. 200 g) used for zircon separation was dominated by trondhjemitic melt.

Of the 35 zircons recovered, most were small (50–100 μm), multifaceted equant to anhedral in habit (fig. 3). This low yield is in keeping with the small sample size and the <15-ppm Zr content of the host rocks (e.g., GGU131477; table 2). They are structureless or display sector zoning in cathodoluminescence (CL) images and contain cores (of higher-U zircon) that appear dark in CL images. Also present are a few large ($\geq$200 μm) prismatic grains that are darker in CL images (higher U) and display vestiges of zoning (fig. 3). These large grains form perhaps one-third of the volume of zircon from the sample. Using SHRIMP U/Pb zircon dating (for analytical method and data assessment, see appendix in the online edition of the *Journal of Geology* and also available from the *Journal*'s Data Depository in the *Journal of Geology* office upon request) all analyzed sites yielded close to concordant dates (ta-

Figure 2. Itsaq Gneiss Complex rocks. *A*, Segregation consisting of plagioclase + quartz and large orthopyroxenes in metakomatiites, east side of Innersuartuut, an extremely rare example that escaped total retrogression during later Archean amphibolite facies metamorphisms. The segregation (zircon date is 3669 ± 8 Ma; see text) is interpreted as a trondhjemitic melt grown in equilibrium with orthopyroxene during dehydration melting. *B*, Small domain in the southern end of the complex that suffered less deformation than usual since intrusion of the mid-Archean Ameralik dikes (*dark gray, top right*). This domain reveals evidence that the rocks have suffered early Archean migmatization and deformation, to give banded metatexites that were further disrupted by the accumulation of melt patches. *C*, *D*, Gneiss outcrop in southern end of the complex. In general view (*C*), the gneisses appear homogeneous and potential candidates for geochemical study. However, upon close view assisted by wetting of the outcrop (*D*), a fine-scale folded migmatitic structure is revealed. Such rocks will yield complex zircon age spectra (Nutman et al. 2000). Clearly, the closest scrutiny in the field is required. *E*, Low-strain area within granitic augen gneisses (*pen for scale at top right*). Finer-grained, gray lenses (*d*) are interpreted as having been derived from coeval dioritic magma. *F*, Enclave of polyphase banded gneiss (*under lens cap*) within augen gneisses (*bottom of block*) from western Qilaangarssuit (lat 63°52.35′N long 51°39.01′W and lat 63°52.91′N long 51°41.34′W). Block was displaced about a meter from outcrop, to ease photography and sampling. *G*, Metasediment inclusion G00/11 within banded gneisses north of Amiitsoq, consisting of interlayered mica schist (*ms*) and siliceous rocks that had already been folded (*center right*) before intrusion of an Ameralik dike (*ad*). *H*, G97/92 locality, south of the Isua supracrustal belt. Granite/pegmatite (*gr*) contains blocks and blobs of mafic material traversed by lobate-margined mafic sheets (*m*), an indication of mingling of mafic and felsic magmas.

Table 2. Whole-Rock Major and Trace Element Geochemistry Analyses of Samples from the Itsaq Gneiss Complex

Detail	Analysis						
Sample number	131477	G97/94	248022	155820	201404	162475	G91/61
Latitude (N)	63°50.26′	65°03.50′	64°0.6′	64°0.6′	63°48.33′	64°1.75′	64°06.42′
Longitude (W)	51°40.88′	50°10.18′	51°39.0′	51°39.0′	51°47.00′	51°36.00′	51°27.14′
Lithology	Meta-kom	Um	Gabbro	Diorite	Augen	Augen	TTG
Source	Nutman 1986	...	Nutman et al. 1984	Lambert and Holland 1976	Nutman et al. 1984	Nutman et al. 1984	...
Date (Ma)	*>3670*	3661	3640	3640	3630–3640	3630–3640	3659
SiO_2	45.00	51.39	52.95	59.45	58.92	61.56	66.94
TiO_2	.32	.52	2.39	1.94	1.85	1.32	.58
Al_2O_3	3.08	5.45	13.37	12.42	14.27	13.89	15.60
Fe_2O_3	...	9.81	3.78	12.56	3.33	...	4.73
FeO	11.03	...	11.28	...	7.72	8.19	...
MnO	.25	.18	.22	.16	.21	.10	.08
MgO	26.82	17.35	3.29	1.86	1.97	1.38	1.55
CaO	9.31	12.74	7.69	6.22	5.29	4.26	4.21
Na_2O	.31	.64	3.17	3.02	2.75	3.26	4.39
K_2O	.22	.29	.89	1.52	2.55	2.87	1.48
P_2O_5	.04	.04	.24	.74	.5	.50	.11
Loss	...	...	1.34	...	.52	.43	...
Total	96.38	98.41	100.61	99.89	99.88	97.76	99.67
#Mg	...	.73	...	.65	.67	.68	...
Rb	...	6	...	32	31	40	99
Sr	...	44	...	72	55	51	226
Ba	...	36	...	122	53	58	239
Y	...	8	...	11	15	12	21.5
Zr	...	25	...	56	53	55	163
Nb	...	...	...	2	2	2	7.4
Ni	...	1294	...	585	607	599	...
Cr	...	4017	...	2630	2645	2669	...
La	...	2.248	...	8.683	...	...	12.3
Ce	...	5.351	...	16.157	...	...	26.9
Pr	...	...	...	...	...	...	...
Nd	...	2.530	...	6.195	...	...	16.4
Sm	...	.788	...	1.691	...	...	3.77
Eu	...	.214	...	.413	...	...	1.00
Gd	...	...	...	...	...	...	3.73
Tb	...	.156	...	.325	...	...	...
Dy	...	...	...	...	...	...	3.82
Ho	...	...	...	...	...	...	.82
Er	...	...	...	...	...	...	2.22
Yb	...	.594	...	1.062	...	...	2.26

Note. Sample numbers: six-digit numbers are property of Geological Survey of Denmark and Greenland (GEUS; and G*xx*/*yy* numbers are property of Australian National University. Lithologies: augen = granitic augen gneiss; diorite = metadiorite; gabbro = metagabbro; meta-kom = metkomatiite; TTG = tonalite-trondhjemite-granodiorite; um = ultramafic dike. Ellipses = previously unpublished data. Date: roman type = U/Pb zircon date on unit; italic type = geological correlation of dated unit.

ble 3; fig. 4). Seven analyses of two large prisms plus a dark core in a more equant grain yielded Paleoarchean dates, with the four oldest sites agreeing within error with a weighted mean $^{207}Pb/^{206}Pb$ date of 3669 ± 8 Ma (95% confidence). Most of the sector-zoned equant/multifaceted and anhedral grains yielded dates of ca. 2720 Ma, with lower Th/U than the Paleoarchean grains. A lesser number of such grains yielded dates of 3300–3400 Ma. Because the segregation definitely formed in situ and the host rocks have a depleted komatiite composition, it is highly unlikely that the Paleoarchean zircons were inherited from country rocks. Rather, they most likely grew when the segregation formed during granulite-facies metamorphism. Laser ablation inductively coupled mass spectrometry analysis of the orthopyroxene grown in equilibrium with the segregation shown in figure 2*A* indicates a Zr content of ca. 0.5 ppm, whereas nearby clinopyroxenes and hornblendes have ca. 21 and 31 ppm, respectively, values agreeing well with the bulk analyses for these minerals in host mafic rock (table 2). Therefore, it is likely that further zircon growth at ca. 3300–3400 and 2720 Ma during retrogression required some Zr addition via influx of a hydrous fluid.

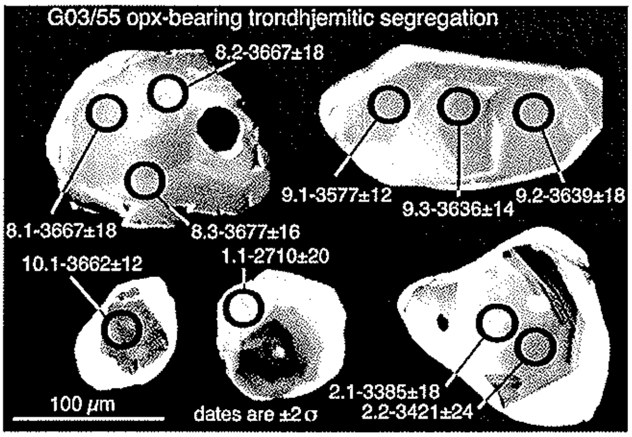


Figure 3. Cathodoluminescence images from zircons from trondhjemitic partial melt segregation The G03/55. $^{207}Pb/^{206}Pb$ dates (Ma) are given at 2σ uncertainty.

Multiple Superimposed 3660–3540 Ma High-Grade Metamorphisms—An Example from Akilia Island, Faeringehavn Terrane

We have published dates on different Paleoarchean metamorphic events from across the whole complex (Nutman et al. 2000, 2002*a*, 2002*b*). Here, a single locality, Akilia Island (fig. 5), was chosen to test whether several such Paleoarchean events were superimposed upon each other.

Banded Gneiss G88/66. On the southwestern tip of Akilia Island is a >100-m-wide composite body of mafic, ultramafic, and siliceous rocks, in contact on its eastern side with banded gneisses that suffered their last strong deformation in the Neoarchean (e.g., Friend et al. 1996; Myers and Crowley 2000; Nutman et al. 2002*b*). Along the eastern contact of the supracrustal enclave is a dark gray pegmatite-banded gneiss with schlieren and pods of hornblendite (Nutman et al. 2000, their fig. 9*a*). Nutman et al. (1996, 1997*a*, 1997*b*) suggested that the igneous protolith(s) of the gneiss was originally intrusive into the supracrustal rocks. Sample G88/66 (table 3) yielded abundant, large (typically 200–400-μm) prismatic zircons. Transmitted light microscopy revealed core-overgrowth relationships on some grains. Low Th/U rims gave dates of ca. 2720 and 3650 Ma (interpreted as metamorphic ages), whereas cores and other apparently whole grains of prismatic zircon with some oscillatory zoning formed at ca. 3850 Ma (interpreted as the protolith age; Nutman 1990; Nutman et al. 1996). This SHRIMP U/Pb zircon dating was undertaken in 1989, before CL became widely available for choosing sites within zircons for ion-microprobe analysis (e.g., Friend and Kinny 1995). Retrospective (post-SHRIMP analysis) CL images in an article by Nutman et al. (2000) indicated overgrowths were more extensive and complex than previously thought from transmitted light microscopy alone. While oscillatory-zoned ≥3850 Ma zircon still dominates the cores, grains devoid of or with limited overgrowth are rare. The oscillatory-zoned zircon is embayed by structureless recrystallization domains, commonly moderate to brightly luminescent (low U) in CL images (fig. 6). The ≥3850 Ma zircon is also often partly sheathed or replaced by homogeneous zircon appearing dark (higher U) in CL images. Outside of this are broad rims, in cases exceeding 100 μm across on the pyramidal terminations. These generally show weak, oscillatory to sector zoning and may show division into inner and outer cores plus have recrystallization domains. The terminations of most grains have outermost growth shells that appear homogeneous and generally rather dark in CL images (fig. 6).

There are 37 SHRIMP U/Pb analyses on the overgrowths and 14 on discrete recrystallization areas. Most of these analyses were CL guided, but a minority of the original 1989 data set are included,

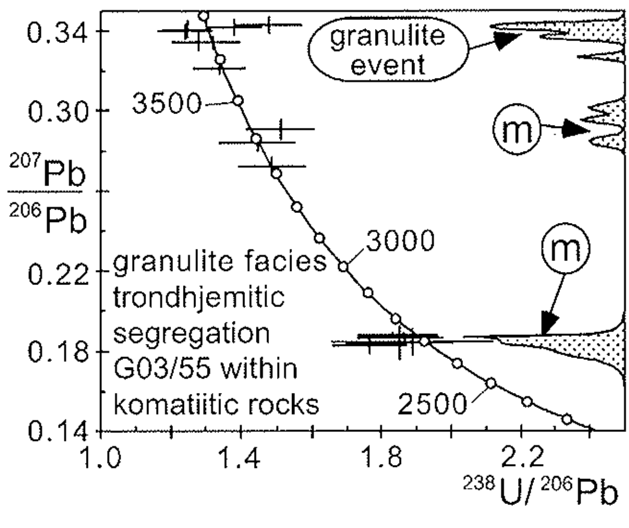


Figure 4. The $^{238}U/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ Tera-Wasserburg plot for trondhjemitic partial melt segregation G03/55. Errors are depicted at the 1σ level and have been corrected for (minor) common Pb based on measured $^{204}Pb/^{206}Pb$. Shaded area on right-hand side of each plot is the relative probability of the SHRIMP (common Pb corrected) $^{207}Pb/^{206}Pb$ ratios with their measured analytical error. *m* = metamorphism.

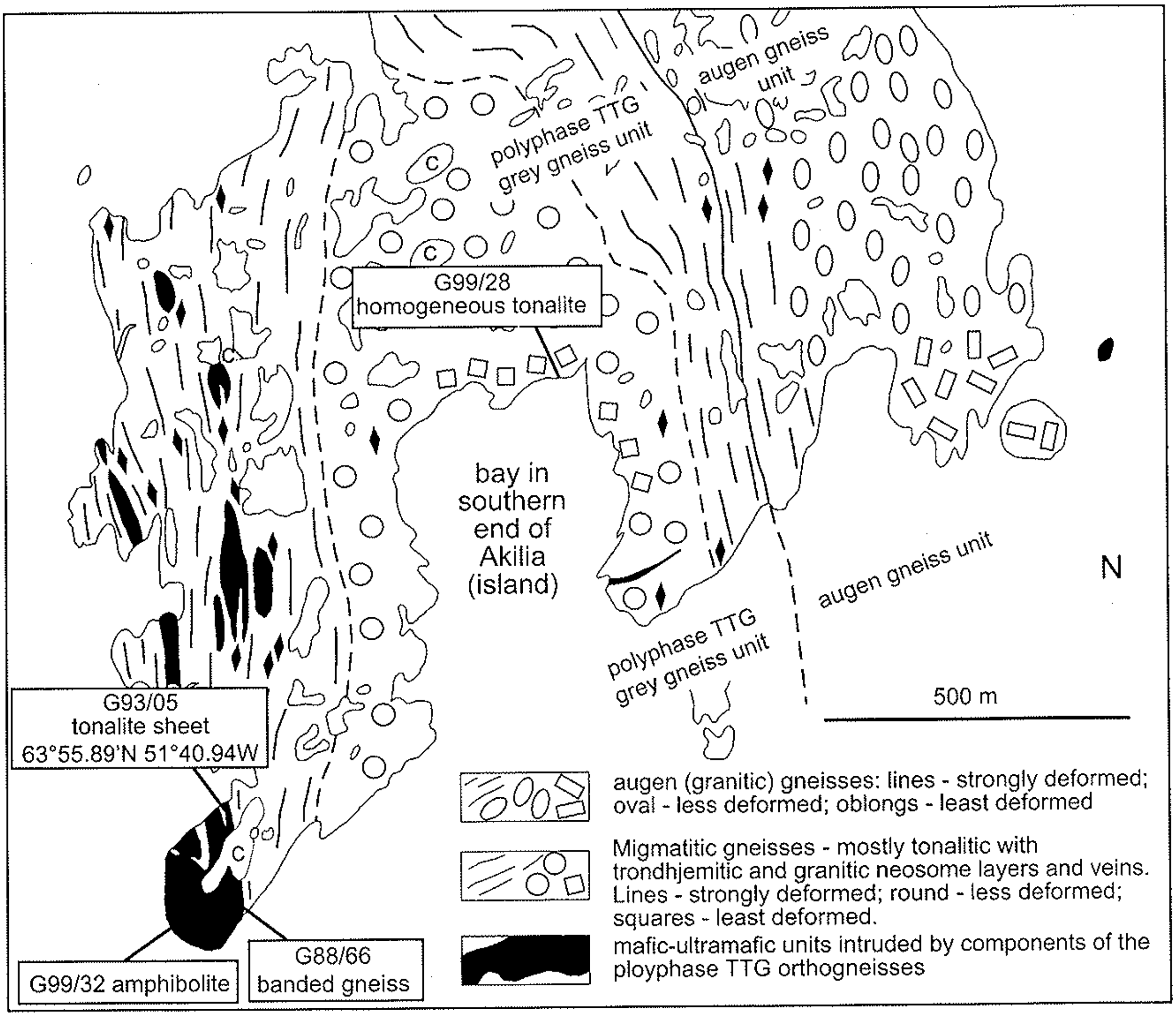


Figure 5. Sketch geological map of the southern half of Akilia showing sampling localities. See Nutman et al. (2002*b*; fig. 2) for a more detailed color map.

and where the retrospective CL images indicate, they are solely of single-component, post-3850 Ma zircon. These display a complex array of Paleoarchean ages (fig. 7) plus ca. 2720 Ma ages (not discussed further). Multiple age determinations (up to nine) were done on some grains to explore the complexity seen in CL images. Most if not all grains have a substantial core of high Th/U, ≥3850 Ma oscillatory-zoned zircon that shows discrete recrystallization domains with low Th/U and ages up to ca. 3730 Ma (fig. 6). Broad rims over the ≥3850 Ma cores generally show ages of 3670–3620 Ma (fig. 6). Multiple analyses of these broad rims show that much of this zircon crystallized at 3670–3660 Ma and that younger ages are due to recrystallization with some Pb loss (fig. 6). Generally narrow, incomplete, outermost rims yielded ages of ca. 3460 Ma or more commonly ca. 2720 Ma.

Homogeneous Metatonalite G99/28. A few hundred meters to the east of the G88/66 locality, there are areas of much lower strain at the head of the bay on the southern end of the island (fig. 5). In this low-strain zone, the gneisses are isotropic to weakly banded, medium-grained, pale tonalite, containing inclusions of finer-grained darker, sometimes pegmatite-banded, tonalitic gneiss, which themselves locally contain lenses of amphibolite and hornblendite. Veins and patches of pre-Ameralik dike (i.e., Paleoarchean) blebby-textured pegmatite traverse the tonalitic gneisses,

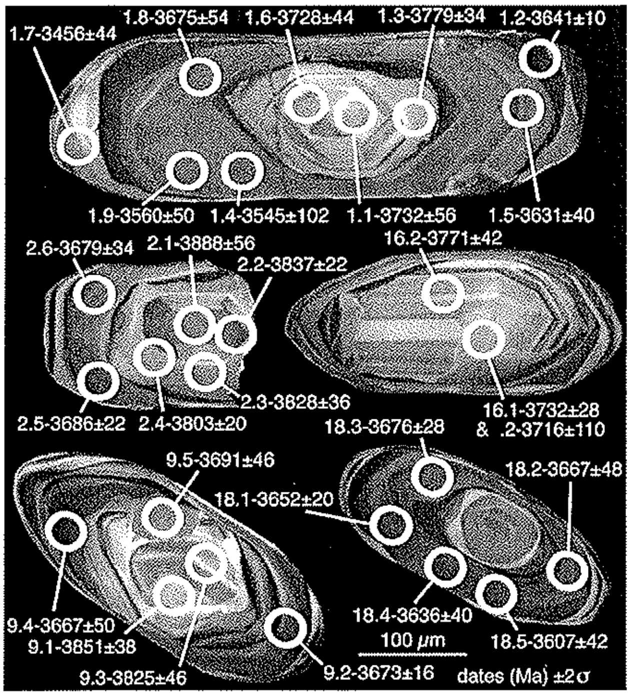


Figure 6. Cathodoluminescence images of zircons from banded gneiss G88/66. The $^{207}Pb/^{206}Pb$ dates (Ma) are given at 2σ uncertainty.

showing some early in situ partial melting, probably under granulite facies conditions.

Sample G99/28 is a pale tonalite from the low-strain zone (fig. 5), where, by careful sampling, all pegmatite veins and patches were avoided. The G99/28 zircons are predominantly 200–300-μm prisms. The CL images show common micron-scale oscillatory zoning parallel to grain exteriors (fig. 8). The best-preserved sites on the G99/28 oscillatory-zoned prismatic zircon yield a date of 3744 ± 17 Ma (MSWD = 1.8; Nutman et al. 2000). Most grains have overgrowths that appear bright in the images. The structure of these rims can be complex, with several layers of overgrowths (fig. 8). None of these overgrowths show fine-scale oscillatory zoning, lessening the likelihood that they grew out of melt. This is in keeping with the lack of pegmatite veins and in situ partial-melt segregations. Twenty-three analyses on the overgrowths and recrystallization areas (table 3) show generally low U, giving poor precision on $^{207}Pb/^{206}Pb$ measurements. In many grains, the narrowness of separate overgrowth domains hampers resolution of different ages of growth in the rims. The mixture modeling results suggest that three or more episodes of zircon growth may be recorded in these rims between ca. 3660 and 3400 Ma (fig. 7).

Homogeneous Amphibolite G99/32. The amphibolites that dominate the enclave of supracrustal rocks on southwestern Akilia show patchy development of pre-Ameralik dike blebby-textured pegmatite (McGregor 2000; Nutman et al. 2001). On the western coast of the island, layered amphibolites locally preserve orthopyroxene in felsic metamorphic segregations, clear evidence of granulite facies metamorphism (Nutman et al. 2002*a*). Sample G99/32, from homogeneous amphibolite adjacent to these segregations, yielded equant to stubby

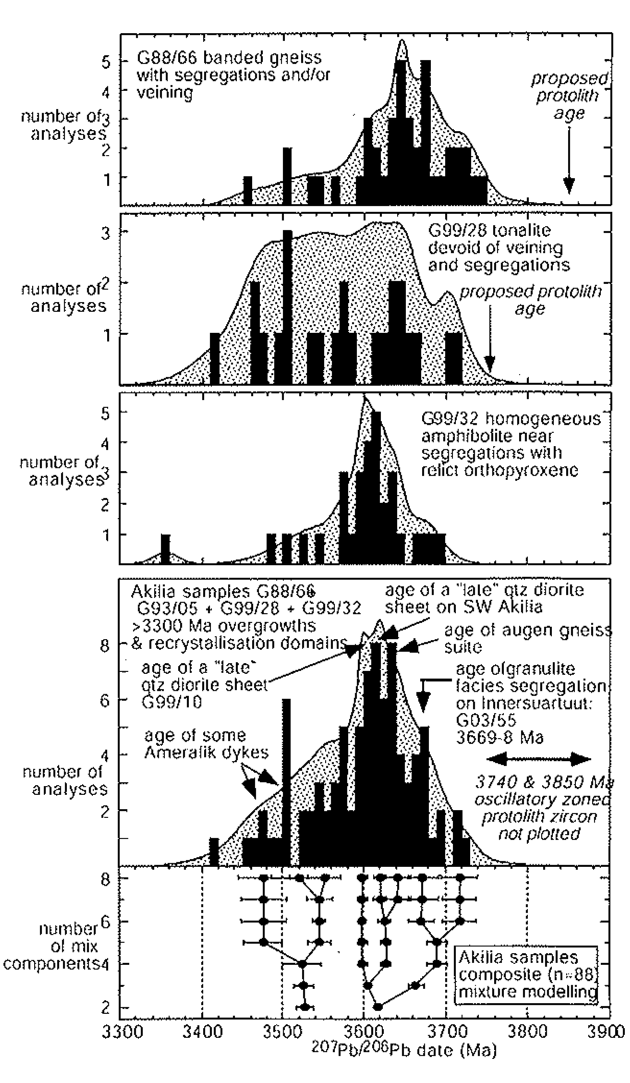


Figure 7. The $^{207}Pb/^{206}Pb$ dates (Ma) spectra for post-protolith, pre-3400 Ma zircon concordant analyses in Akilia Island samples. Top three frames show separate data for samples G88/66, G99/28, and G99/32. In the bottom frame, data for these samples are combined along with "postprotolith" zircon in G93/05 (from Nutman et al. 2002*b*), and the result from the mixture modeling is shown.

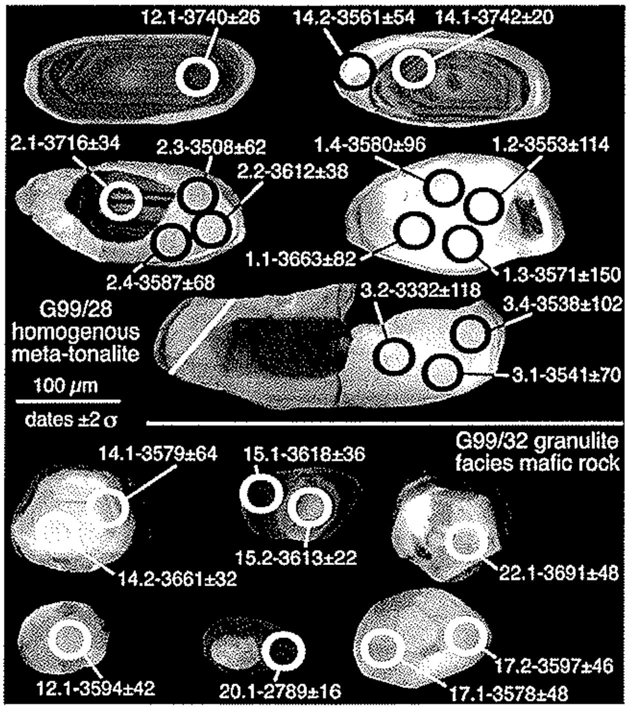


Figure 8. Cathodoluminescence images of zircons from homogeneous tonalite G99/28 and amphibolite G99/32. $^{207}Pb/^{206}Pb$ dates (Ma) are given at 2σ uncertainty.

prismatic zircons, up to 200 μm long but typically 100–50 μm across (fig. 8). They range from dark to bright in CL images and are homogeneous to sector zoned, with no indications of fine-scale oscillatory zoning. Some zircons display cores and rims and recrystallization domains, suggesting complex growth histories, most likely under subsolidus conditions in several metamorphic events. Thirty-one analyses on 26 grains (table 3) gave dates between ca. 3700 and 3500 Ma, indicating several phases of possible metamorphism (fig. 7). One Neoarchean overgrowth was located (analysis 20.1; table 3).

Multiple High-Grade Paleoarchean Events on Akilia. Structural complexities of Akilia Island zircons revealed in CL images (figs. 6, 8; Whitehouse et al. 1999; Nutman et al. 2000) point to many superimposed Paleoarchean zircon recrystallization/regrowth events. To create a large data set to enhance resolution of these events, 88 $^{207}Pb/^{206}Pb$ >3400 Ma dates on nonprotolith zircon (corrected for minor common Pb using measured ^{204}Pb) from G88/66, G99/28, and G99/32 plus that for a similar zircon in tonalite sheet G93/05 (Nutman et al. 2000) have been pooled. The pooled data indicates a multiply spiked probability distribution for the $^{207}Pb/^{206}Pb$ dates (fig. 7). Mixture modeling (Sambridge and Compston 1994) recovered eight age components from the distribution: 3718 ± 22, 3673 ± 18, 3642 ± 16, 3621 ± 8, 3599 ± 6, 3552 ± 20, 3521 ± 36, and 3476 ± 32 Ma (fig. 7). Although the veracity of any one of these components might be debated, the complex age spectrum clearly shows repeated zircon regrowth/recrystallization, pointing to many superimposed events between 3730 and 3400 Ma on Akilia. We interpret that the complex pattern of partial zircon recrystallization and regrowth (figs. 6, 8) was superimposed on zircons formed in rocks before 3800 Ma high-temperature conditions coupled with repeated heterogeneous strain and /or fluid movements onto natural zircons with variable degrees of lattice damage. Beyond this, there are two more detailed ways in which these results could be interpreted. The first would be that a main granulite facies thermal event (ca. 800°C) at ca. 3660 Ma was followed by very slow cooling over the next 200 m.yr., such that detectable Pb diffusion out of the margins of crystals could generate the spread in $^{207}Pb/^{206}Pb$ dates from the overgrowths and the recrystallization domains. Recently, a diffusion model has been proposed to explain the 80-m.yr. spread in U/Pb ages from igneous zircon in a Neoproterozoic anorthosite from Madagascar (Ashwal et al. 1999). In this case, zircon grain size, U/Pb age relationships, and application of recently determined diffusion parameters (Lee et al. 1997) were compatible with very slow cooling rates of 1–2°C $m.yr.^{-1}$ or less. The studied anorthosites are very coarse grained (up to 10 cm), with abundant relicts of the igneous mineralogy, indicating that they have not been completely reworked/recrystallized by subsequent or coeval tectonic events.

A slow-cooling-rate model might be considered for the Akilia data, but we consider there are three points that mitigate against it. (1) The Akilia data have been obtained on rims, and recrystallization domains have been developed on and within much older igneous zircon rather than on variably recrystallized igneous zircon. Different ages can show up between samples, which we attribute to local variations in strain and fluid movement throughout the 3660–3460 Ma period. (2) There is diverse tectonic activity involving both thrusting and likely extension in the Itsaq Gneiss Complex during the 3660–3550 Ma period (e.g., Nutman et al. 2002*a*; this article) to which a slow-cooling-rate, Pb-diffusion model might be applied. This tectonically active setting is unlikely to maintain a stable crust with an undisturbed slow-cooling rate following the start of high crustal temperatures at ca. 3660 Ma. (3) Matches of many of the age events identified by mixture modeling on zircon overgrowths and recrystallization domains from Akilia rocks can be found in dated igneous activity in the Faeringehavn terrane. Two examples are as follows: ca. 3640 Ma is the age of the augen gneiss within-plate granite suite (Nutman et al. 1996, 2000; Whitehouse et al. 1999; this article) and, south of Nuuk, some Ameralik dikes were intruded at 3510–3470 Ma (Nutman et al. 2004). Figure 7 shows the full comparison of the mixture modeling results and dating of intrusions in the Færingehavn terrane, around the Akilia locality. Therefore, we interpret the Akilia data to indicate complex zircon recrystallization and extra growth within a 200-m.yr. period with elevated crustal temperature, sporadic tectonic activity, and emplacement of intrusions of several ages.

The 3640 Ma Metagabbro/Diorite and Granite Augen Gneiss Suite, Faeringehavn Terrane—Evidence of a High Heat Flow, Extensional Regime?

The K-feldspar-phyric, high-Fe granitoids with subordinate amounts of gabbro/diorite, known as the augen gneisses (McGregor 1973, 1979; Nutman et al. 1984), form ~20% of the Itsaq Gneiss Complex south of Ameralik (fig. 1). In (rare) lowest-strain zones, small, lobate-margined inclusions of fine-grained gabbro/diorite are seen in the augen gneisses (fig. 2*E*). This suggests that mafic and granitic liquids were coeval and mingling. Despite the generally high strain, there are also rare examples preserved of banded TTG gneiss inclusions in the augen gneisses near Faeringehavn (Friend et al. 1987) and on the island Qilanngaarsuit (fig. 2*F*). This shows that coeval augen gneiss granitic and mafic magmas were emplaced into older, already deformed sialic crust.

Gabbro/Diorite G97/112. A >100-m broad granitic augen gneiss unit on the west of the Narsaq peninsula, south of Ameralik (fig. 1), contains lenses of gabbro/mafic-diorite. An ~50 × >100-m-long lens exposed on the coast was sampled for zircon dating. The unit is a generally homogeneous hornblende + plagioclase ± garnet + quartz amphibolite (see table 2 for whole-rock analyses of equivalent samples 155820 and 248022 from the same unit). Locally, it has color-index layering, interpreted as tectonically modified igneous layering, and is interpreted as a ferro-gabbro/diorite intrusion.

Sample G97/112 yielded many large (250–350 μm long) prismatic to more rarely jagged, anhedral zircons. In CL images (figs. 11–13 in the online edition of the *Journal of Geology* and also available from the *Journal*'s Data Depository in the *Journal of Geology* office upon request), most grains show domains of oscillatory zoning parallel to grain exteriors, although many grains have partial, narrow (<30 μm) overgrowths of homogeneous zircon concentrated on their pyramidal terminations. Homogeneous recrystallization domains disrupt the oscillatory zoning. Nineteen analyses were undertaken on 16 zircons. Twelve analyses were of oscillatory-zoned domains, seven were recrystallization domains, but none were of the overgrowths (table 3; fig. 9). All analyses yielded close to concordant dates and show generally low U abundance and high Th/U. All oscillatory-zoned zircon analyses gave a weighted mean $^{207}Pb/^{206}Pb$ date of 3640 ± 11 Ma (95% confidence; MSWD = 0.6). Six analyses of postmagmatic recrystallization domains gave a weighted mean $^{207}Pb/^{206}Pb$ date of 3584 ± 15 Ma (95% confidence; MSWD = 1.0). An anomalous recrystallization domain in grain 15 gave an older date, within error of the pooled age obtained on the oscillatory-zoned sites. These results suggest the gabbroic magma was emplaced and crystallized at 3640 ± 11 Ma (date of oscillatory-zoned domains), and subsequently there was a thermal event at 3584 ± 15 Ma recorded by the recrystallization domains.

A-Type/Within-Plate Granite Suite Affinity of the Augen Gneisses. That the date for diorite/gabbro G97/112, 3640 ± 11 Ma, is within error of the ion-microprobe U/Pb zircon dates for granitic rocks from the same augen gneiss unit (3638 ± 6 Ma: Whitehouse et al. 1999; 3633 ± 5 Ma: Nutman et al. 2000) supports an interpretation as coeval with the emplacement of the granitic rocks of augen gneiss suite (Nutman et al. 1984). These ca. 3640 Ma diorites/gabbros display high Fe/Fe + Mg, high Ti, LREE, and LIL and are probably the product of combined deep crustal fractionation of basaltic liquids and some crustal contamination (Nutman et al. 1984; analyses 155820 and 248022 in table 2). The augen gneiss suite granitoids (granodiorites, granites, and quartz monzonites) have elevated Fe/Fe + Mg ratios and a high abundance of Zr, Nb, Y, LREE, and strong negative Eu anomalies (analyses 201404 and 162475 in table 2; Nutman et al. 1984, 1996). In these respects, the augen gneiss suite resembles A-type/within-plate granites/rhyolites from younger epochs (Anderson 1983; Emslie 1991; Hildreth et al. 1991; Frost and Frost 1997), which along with mafic magmas were emplaced into older sialic material in anorogenic/extensional settings. By analogy with these younger suites, a similar high heat flow and extensional setting

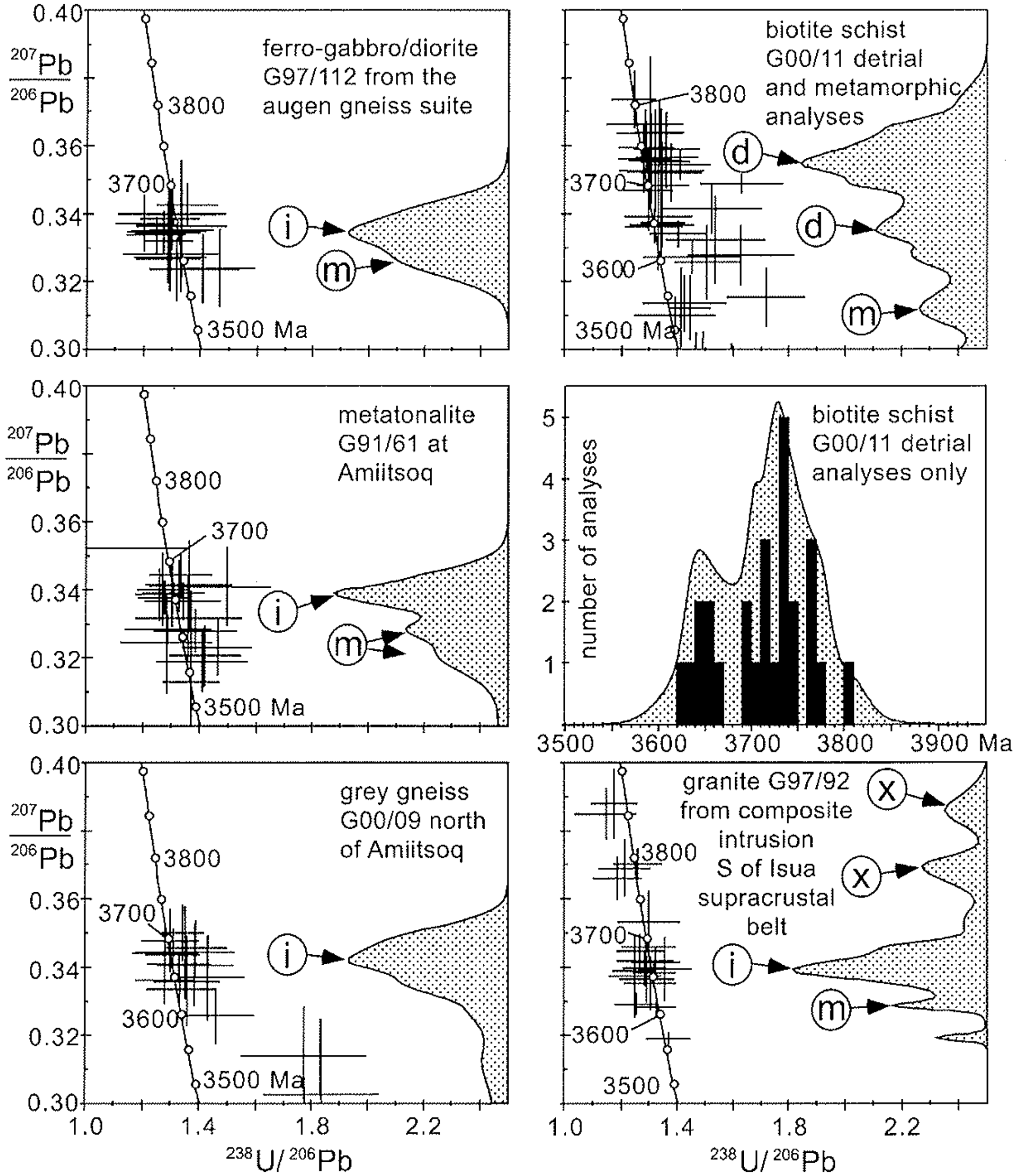


Figure 9. The $^{238}U/^{206}Pb$ versus $^{207}Pb/^{206}Pb$ "Tera-Wasserburg" concordia plot for zircon analyses of G97/112, G91/61, G00/09, G00/11, and G97/92, plus $^{207}Pb/^{206}Pb$ dates (Ma) spectrum for detrital zircon in G00/11. Errors are depicted at the 1σ level and have been corrected for (minor) common Pb based on measured $^{204}Pb/^{206}Pb$. Shaded areas on right-hand side of each plot are the relative probability of the SHRIMP (common Pb corrected) $^{207}Pb/^{206}Pb$ ratios with their measured analytical error. d = detrital; i = igneous; m = metamorphism; x = recrystallization.

would be possible for the ca. 3640 Ma augen gneiss suite diorites/gabbros and granitic rocks.

The Youngest Tonalites (3680–3660 Ma) and Clastic Metasediments (3650–3600 Ma), Outer Ameralik, Faeringehavn Terrane

Around Amiitsoq (fig. 1; the type locality for the Amîtsoq gneisses), on the northern coast of outer Ameralik, the Itsaq Gneiss Complex is dominated by pegmatite-banded orthogneisses (McGregor 1973, 1979). The best domain of lower strain in these gneisses lies just west of Amiitsoq. Unlike most other parts of the Faeringehavn terrane, the Amiitsoq lower-strain domain reveals isotropic tonalitic rocks devoid of both blebby texture and in situ segregations. In the mountains north of Amiitsoq, gneisses in other lower-strain domains also lack blebby textures. This suggests there is a domain covering ~100 km^2 in outer Ameralik (the "new block" of Nutman et al. 1993) that escaped Paleoarchean granulite facies metamorphism. Although there is no textural evidence for early granulite facies metamorphism in these rocks, abundant pre-Ameralik dike granitic pegmatite layering in these gneisses points to veining under probable amphibolite facies conditions in the Paleoarchean.

The western areas of these gneisses contain up to 200-m-long and 50-m-wide lenses of garnet + biotite ± graphite metaquartzite and garnet ± graphite mica schist metapelite. These are anomalous, rare lithologies for the Itsaq Gneiss Complex. To the east, up to the contact of the Neoarchean Qôrqut Granite Complex (fig. 1), these gneisses contain lenses of quartz + magnetite BIF and variegated amphibolite-ultramafic rocks. The BIF units are up to 5 m across, whereas the mafic-ultramafic units are up to 500 m across and up to 1 km long. The metasediments, mafic-ultramafic rocks, and BIF are Paleoarchean in age because dated mafic bodies cut them (Nutman et al. 2004) and their contacts are traversed by pre-Ameralik dike pegmatites. However, everywhere their relationship with the regional tonalitic gneisses is ambiguous because of high strain leading to concordance of contacts and compositional layering on either side.

Previous studies that performed zircon dating on the gneisses at and around Amiitsoq were reconnaissance studies (Nutman et al. 1993) that indicated ages of ≤3650 Ma, making them the youngest recognized TTG components in the complex. Nutman et al. (1996) presented more detailed dating of a banded orthogneiss (G91/58) from north of Amiitsoq and a nearby garnet + biotite + graphite metasediment (G91/55). Both these samples were dated using SHRIMP in the early 1990s, without CL imaging for choosing sites. The gneiss G91/58 was interpreted to be 3567 ± 6 Ma old, with inherited zircon back to >3600 Ma. With the benefit of retrospective CL imaging of analyzed sites together with revisiting the sample locality in 2000, we now reinterpret this sample as neosome-rich banded gneiss with a probable protolith age of ca. 3650 Ma and abundant ca. 3570 Ma veining. The metasediment G91/55 was interpreted to contain ca. 3600–3800 Ma detrital components, plus first metamorphic overgrowths by ca. 3570 Ma. Retrospective CL imaging of the analyzed sites supports this first interpretation. These results point to late development of the crust in this part of the complex plus the presence of rare ca. 3600 Ma detrital metasediments. Here we study this part of the complex in more detail, by presenting SHRIMP U/Pb zircon dating from tonalite G91/61 near Amiitsoq and tonalitic gneiss G00/09 and metapelite G00/11 from the hills to the north.

Metatonalite G91/61 Near Amiitsoq. Metatonalite G91/61 (table 3) is a homogeneous, single-phase rock with a biotite foliation and is devoid of partial melt patches and pegmatite veins. It is medium grained with an "oatmeal" texture given by slightly larger plagioclases that is interpreted as a modified, recrystallized igneous texture. The sample yielded 100–150-μm-long prismatic zircons. In CL images (see figs. 11–13) most grains display oscillatory zoning parallel to grain exteriors that is commonly disrupted by recrystallization domains, plus there are some thin rims, which mostly appear dark on CL images. A few analyses yielded strongly discordant SHRIMP U/Pb dates and are considered no further here. Two analyses of prismatic grain 11 yielded the lowest $^{207}Pb/^{206}Pb$ dates and together with a rim analysis on grain 13 gave a weighted mean $^{207}Pb/^{206}Pb$ date of 3575 ± 23 Ma (95% confidence; MSWD = 0.3). These grains indicate some post-3600 Ma disturbance of the sample by some new zircon growth. Other concordant analyses are all of variably recrystallized oscillatory-zoned zircon and gave a spread of older ages, interpreted to be due to ancient Pb loss from a single population (fig. 9). Using the ancient Pb loss interpretation, the 12 "oldest" sites yield a weighted mean $^{207}Pb/^{206}Pb$ date of 3659 ± 8 Ma (95% confidence; MSWD = 0.5), interpreted as the age of tonalite crystallization.

Tonalitic Gneiss G00/09. Tonalitic gneiss G00/09 (table 3) comes from north of Amiitsoq. The sample is from a ca. 20-cm fine- to medium-grained gray layer from pegmatite-banded gneiss. About 10 m to the east, these gneisses are in sharp concordant contact with the paragneiss unit from which mica schist G01/11 (below) was taken. Sample G00/09 yielded 100–150-μm prismatic zircons. The CL imaging (see figs. 11–13) shows that most grains have a thin, structureless dark rim (10–20 μm) over oscillatory-zoned zircon. Four analyses of structureless rims all have moderate to high U (>350 ppm) combined with low Th/U of <0.1. The rim on grain 8 gave a $^{207}Pb/^{206}Pb$ date of 3665 Ma, indistinguishable from the date obtained on the oscillatory-zoned zircon (below). Three other rims (on grains 13, 14, 15) yielded $^{207}Pb/^{206}Pb$ dates down to 2710 Ma, indicating Neoarchean disturbance. The CL imaging shows that the interiors of the grains show an unusually high degree of recrystallization. However, it does appear that the grains were characterized by oscillatory zircon parallel with the grain exteriors. Analyses of relict oscillatory zoning yielded $^{207}Pb/^{206}Pb$ ages mostly between 3700 and 3650 Ma and scatter beyond analytical error. Repeat analyses on several of the grains suggest variable degrees of ancient Pb loss have taken place (table 3). Using this ancient Pb loss interpretation, nine out of the 11 analyses of oscillatory-zoned zircon yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 3676 ± 11 Ma (95% confidence; MSWD = 1.0). This is interpreted as the age of intrusion of the tonalitic protolith of G00/09.

Metapelite G00/11. At the same locality as tonalitic gneiss G00/09, there is a >20-m-wide body of paragneisses, forming part of a >1-km-long train of paragneiss lenses. Dominant lithologies are biotite ± garnet ± graphite schist and garnetiferous quartzite. These rocks show complex folding cut by Ameralik dikes (fig. 2*G*). This demonstrates their Paleoarchean age and that they had undergone early deformation. Metapelite G00/11 yielded prismatic to ovoid zircons, mostly 150–50 μm across. The CL imaging (see figs. 11–13) shows that dark (high-U), structureless zircon forms entire grains, particularly those of ovoid habit. A minority of the grains, particularly those of prismatic habit, contain a core of oscillatory-zoned zircon within a broad rim of dark, structureless zircon. The SHRIMP analyses were concentrated on the cores, with only five analyses of rims and structureless grains attempted (table 3). The edge of homogeneous ovoid grain 13 was discordant with a $^{207}Pb/^{206}Pb$ age of ca. 3590 Ma, whereas four other analyses gave more concordant ages around ca. 3530 and 3460 Ma. These results are consistent with more extensive age determinations of 3577 ± 9 to 3455 ± 10 Ma for metamorphic zircon overgrowths in metasediment G91/55 <1 km away and VM90/10 on the south side of Ameralik (Nutman et al. 1996; Nutman 2001). These results show that these sediments had undergone their first metamorphism by 3550 Ma. Thirty SHRIMP analyses were undertaken on G00/11 zircon cores of probable detrital origin. After rejection of four >10% discordant and one duplicate analysis, the remaining 25 analyses showed a spread of $^{207}Pb/^{206}Pb$ age from 3650–3600 to ca. 3800 Ma (fig. 9). This suggests detritus was derived from a complex terrane and that deposition took place after ca. 3650 Ma.

The 3660–3600 Ma Granites, Mafic-Ultramafic Intrusions, and Mylonites around the Isua Supracrustal Belt—Multiple Tectonothermal Events in the Northern End of the Itsaq Gneiss Complex

The northern end of the Itsaq Gneiss Complex, the Isukasia terrane, differs from the southern end in two very important respects. First, it displays little or no indication of Paleoarchean (pre-Ameralik dike) in situ arrested partial melting (Nutman 1984; Nutman et al. 1996, 2000). Second, in the Neoarchean it suffered low amphibolite facies metamorphism and less deformation (e.g., Bridgwater and McGregor 1974; Nutman et al. 1996), greatly assisting in understanding its Paleoarchean evolution. That there is no early granulite facies metamorphism in the complex's northern end shows that the Paleoarchean metamorphism(s) there peaked at lower pressures and temperatures than in the southern portion. Nonetheless, the northern part of the complex displays a complicated early tectonothermal history, which from 3660 Ma onward involved intrusion of dioritic to ultramafic dikes and many generations of granite and pegmatite sheets. This complex history examined here was superimposed on crust dominated by 3810 and 3690 Ma tonalites (Nutman et al. 1996, 1999, 2000; Crowley et al. 2002; Crowley 2003).

Inaluk (Ultramafic-Dioritic) Dikes—Evidence for 3660 Ma High Heat Flow and Extension. In the domain of low Neoarchean strain north of the Isua supracrustal belt (fig. 1), tonalitic gneisses are intruded by the ultramafic to dioritic Inaluk dikes, with some coeval pegmatite. The Inaluk dikes from the northern part of the Itsaq Gneiss Complex (fig. 1) were introduced by Nutman (1986) and Nutman and Bridgwater (1986, p. 139) as "mafic, biotite and hornblende bearing, dioritic intrusions. … They intrude the grey (tonalitic) gneisses but are cut by the white (granitic) gneisses." These bodies are a volumetrically minor component of the Itsaq Gneiss Complex. One of these yielded a date of 3659 ±

2 Ma (Crowley et al. 2002). Further, Crowley (2003) has presented a date of 3658 ± 1 Ma for a likely Inaluk dike just south of the Isua supracrustal belt.

About 3 km south of the southwestern bend in the Isua supracrustal belt, Paleoarchean tonalitic gneisses contain a tract of mafic-ultramafic bodies within pegmatite and leucogranite, cut by Ameralik dikes (Nutman 1986). At the G97/92 site (fig. 1) these mafic-ultramafic rocks occur as both lobate margined dikes cutting, and as globular inclusions within, leucogranite and pegmatite (fig. 2*H*). The composition of a fine-grained "pillow" of homogeneous mafic rock G97/94 (~17% MgO) in leucogranite is given in table 2.

Sample G97/92 (table 3) of granitic pegmatite containing rounded/lobate, fine-grained hornblendite bodies yielded mostly light brown prismatic zircon, some of which contain less-colored structural cores. Cores of grains have generally the lowest U abundance and mostly have $^{207}Pb/^{206}Pb$ dates of ≥3700 Ma (fig. 9). The dominant prismatic zircon that forms whole grains and also the rims to ≥3700 Ma cores has locally well-preserved oscillatory zoning parallel to grain boundaries. The U content of these grains is moderate to high, with the exteriors generally having the highest concentrations. All analyses of this type of zircon yielded a weighted mean $^{207}Pb/^{206}Pb$ date of 3661 ± 7 Ma (95% confidence; MSWD = 1.0), which is interpreted as the magmatic age of the leucogranite and hence the age of the comagmatic gabbros and ultramafic rocks. Pre-3660 Ma inherited zircon cores were derived from partially melted older country rocks.

This association of 3660 Ma ultramafic to dioritic dikes with coeval crustally derived pegmatite and leucogranite points to emplacement of mafic liquids deep in the older continental crust, triggering partial melting at greater depths than presently exposed. This phenomenon points to a ca. 3660 Ma high heat flow regime, possibly coupled with extension, in juvenile crust that was formed up to ca. 150 m.yr. earlier.

The 3650–3600 Ma Granite Sheets and Mylonites—Melting of the Crust at Depth and Tectonic Intercalation. In the low-strain zone north of the Isua supracrustal belt, tonalites and 3660 Ma Inaluk dikes are cut by voluminous swarms of gently inclined leucogranite sheets, produced by melting of older tonalitic crust (Baadsgaard et al. 1986*a*; Nutman and Bridgwater 1986). The SHRIMP U/Pb ages for the granite sheets are 3648 ± 2 and 3646 ± 3 Ma and 3702 ± 4 to 3686 ± 6 Ma for the host tonalites (Nutman et al. 1993, 1996, 2000). Crowley et al. (2002) provided a more detailed sequence of post-Inaluk dike intrusion and deformation events, obtaining ages of 3653 ± 2, 3649 ± 4, and 3644 ± 3 Ma for granite and pegmatite sheets.

Nutman et al. (2002*a*) dated pegmatite and granite sheets coeval with movement on pre-Ameralik dike shear zones. South of the Isua supracrustal belt at lat 65°0.85′N long 50°12.28′W, a granite lithon in a mylonite zone yielded a zircon date of ca. 3630 Ma, whereas a deformed but not mylonitized granite sheet intruded along the same mylonite yielded a zircon date of 3607 ± 5 Ma. North of the Isua supracrustal belt at lat 65°10.66′N long 50°1.25′W, a flaser pegmatite restricted to a mylonite zone marked by lenses of mafic and supracrustal rocks yielded a zircon date of 3633 ± 6 Ma. The mylonites marking the northern edge of the Isua supra-

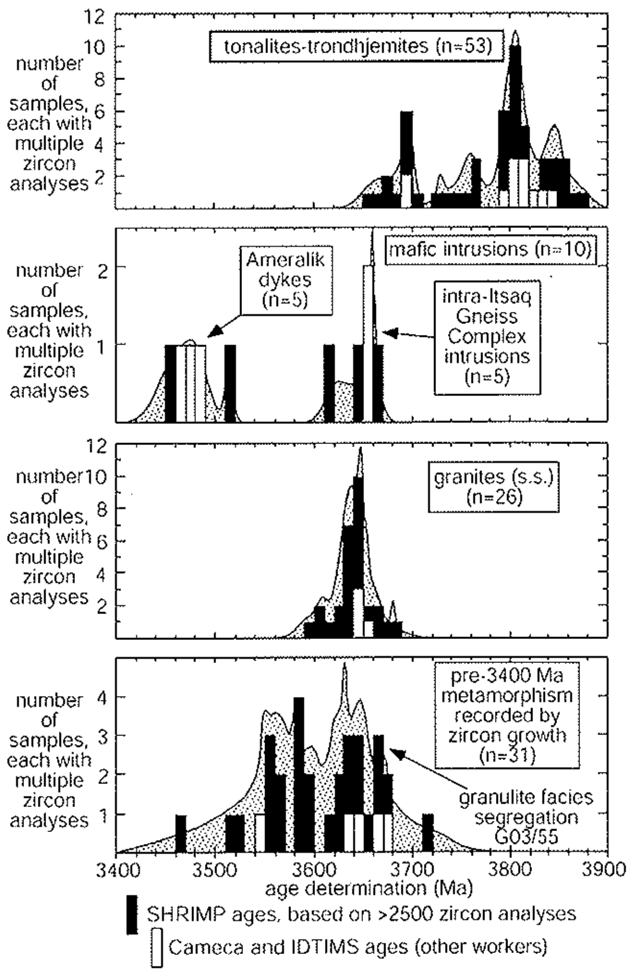


Figure 10. Summary histograms and relative probability plots (in background) for zircon U/Pb dating of tonalite-trondhjemite-granodiorite, mafic intrusions, granites (sensu stricto), and early high-grade metamorphism from the Itsaq Gneiss Complex.

crustal belt (Nutman 1984) had formed by 3600 Ma (Crowley et al. 2002; Hanmer et al. 2002).

From previous studies (Nutman et al. 1996, 2000, 2002*a*; Crowley et al. 2002; Hanmer et al. 2002; Hanmer and Greene 2002; Crowley 2003) plus new results presented here, it is clear that the northern part of the complex around the Isua supracrustal belt experienced a complicated tectonothermal history plus intrusion of granite (sensu stricto) and pegmatite, some of which was coeval with mafic intrusions. This tectonic history included intercalation and imbrication of unrelated packages of rocks between 3650 and 3600 Ma (Hanmer and Greene 2002; Nutman et al. 2002*a*).

Discussion

Multiple 3660–3550 Ma Orogenic Episodes Superimposed on 3850–3690 Ma Juvenile Crust. Modern U/Pb zircon dates from across the Itsaq Gneiss Complex are collated in figure 10. This is an extensive data set arising from >2500 zircon spot measurements on more than 70 rocks undertaken on SHRIMP instruments in the Australian National University, Curtin University of Technology, Hiroshima University, and the National Polar Institute in Tokyo. Additionally, a smaller amount of other data (Cameca ion probe: Whitehouse et al. 1999; Mojzsis and Harrison 2002; Manning et al. 2003; Whitehouse and Kamber 2003; modern small-sample isotope dilution thermal ionization mass spectrometry data: White et al. 2000*b*; Crowley et al. 2002; Krogh et al. 2002; Crowley 2003). The following paragraphs reveal several fundamental characteristics of those parts of the Itsaq Gneiss Complex that have been dated.

First, the TTG rocks that dominate the complex are mostly ≥3690 m.yr. old. Numerous whole-rock isotopic studies (e.g., Moorbath et al. 1972) demonstrated these to be juvenile crustal components. This compilation (>50 samples) indicates several pulses of TTG formation: 3850, 3810, 3760, and 3690 Ma (fig. 10). The TTG are associated with belts and enclaves of ≥3700 Ma metabasalts, metagabbros, ultramafic rocks, and chemical sediments, the largest of which comprises the composite ca. 3800 and 3700 Ma (Nutman et al. 1997*a*) units of the Isua supracrustal belt. These supracrustal belts contain only limited recycled crustal material. Another striking aspect of the pre-3680 Ma history is the lack of granites (sensu stricto), evidence of widespread high-grade metamorphism via in situ migmatization and any extensive growth of metamorphic zircon (fig. 10), suggesting that pre-3680 Ma crust preserved in the Itsaq Gneiss Complex was largely pristine. Thus, up to ca. 3680 Ma, the complex is interpreted as displaying growth of new crust by successive emplacement of isotopically juvenile tonalites into imbricated piles of ≥3700 Ma supracrustal rocks (arcs?) dominated by mafic volcanics and with intercalated depleted peridotites (Nutman and Collerson 1991; Friend et al. 2002).

Second, post-3670 Ma, the geological evolution of the Itsaq Gneiss Complex is one of reworking. There were multiple episodes of crustally derived granites (sensu stricto) and small amounts of mantle-derived mafic intrusions (e.g., Nutman et al. 1984, 2001; Nutman and Bridgwater 1986; Crowley et al. 2002); tonalites of this age are rare. In this period, zircon geochronology records several high-grade metamorphic events (Nutman et al. 2000). Via results from Akilia, at any one locality, many Paleoarchean tectonothermal events are superimposed upon each other. The crustal anatexis events in this period were accompanied by intrusion of mafic to dioritic rocks (fig. 10). Within-plate granite chemistry has been determined for the ca. 3640 Ma augen gneiss suite (Nutman et al. 1996). In younger epochs, granitoids of such chemistry are largely restricted to extensional or anorogenic settings. In the volcanosedimentary rocks on the north side of Ameralik (Nutman et al. 1996, 2002*b*; this article), the youngest detrital grains are 3650–3600 Ma, whereas the oldest in situ metamorphic overgrowths are ≥3550 Ma. This suggests the presence of sedimentary sequences (now tectonically dismembered) still being deposited at 3650 Ma; by 3550 Ma, these had undergone high-grade metamorphism. In the northern parts of the complex in and around the Isua supracrustal belt, several researchers contend that there is juxtaposition and repetition of units along 3650–3600 Ma mylonites (Nutman et al. 1997*a*, 2002*a*; Myers 2001; Crowley et al. 2002; Hanmer and Greene 2002). The repetition of lithological units suggests thrusting might have occurred, indicating contractional episodes. We interpret the 3660–3540 Ma events as reflecting "reworking" superimposed onto the 3850–3690 Ma juvenile crustal components. This period of reworking involved emplacement of mafic intrusions, TTG melting to give true granites, repeated metamorphism (generally highest grade in the southern end of the complex), extension and contraction, plus development of sedimentary sequences active up to 3650–3600 Ma. These events are interpreted to be the products of an orogen superimposed on TTG crust accreted in distinctly older events (fig. 10). Because of the now-limited extent (ca. 3000 km^2) of the complex, plus its generally severe reworking by Neoarchean tectonothermal events, the nature of this orogen is unclear.

Third, following ca. 3540 Ma, thermal activity continued. The first Ameralik dikes were intruded between 3510 and 3450 Ma (White et al. 2000*b*; Nutman et al. 2004), with enough thermal impact to cause the sporadic growth of new metamorphic zircon across the complex (e.g., sample G97/87 from the Isua supracrustal belt: Nutman et al. 2002*a*; sample VM90/10 in Ameralik: Nutman 2001).

Evolution of the Itsaq Gneiss Complex. Moorbath and coworkers' groundbreaking 1970s work and the first zircon results of Baadsgaard (1973) in the Itsaq Gneiss Complex were the first demonstrations of extremely ancient rocks at the earth's surface. Their revolutionary studies demonstrated that Paleoarchean TTG gneiss complexes are dominated by juvenile crustal components (Moorbath et al. 1972; Moorbath 1975, 1985). They also developed the continental accretion-differentiation superevents (CADs) model (Moorbath 1975, 1985; Moorbath and Taylor 1981) whereby large volumes of Archean crust were formed and underwent internal differentiation in a single process. The CADs model clearly differs from that proposed by us, where formation and internal evolution of a crustal segment takes place by several separate, unrelated, events punctuating 300 m.yr. (Nutman et al. 1993; Bennett et al. 1993 and onward).

Both our interpretation of the Itsaq Gneiss Complex and that of Moorbath and coworkers stress the importance of 3700–3600 Ma events. Guided by our combined field geology and zircon geochronology, we regard this period to be marked predominantly by repeated remobilization superimposed on mostly older crust. Reworking includes polymetamorphism up to granulite facies and in situ melting (fig. 2*A*, 2*B*), granite intrusion (fig. 2*E*, 2*G*), and polyphase ductile deformation (fig. 2*B*, 2*D*), plus minor emplacement of tonalites (fig. 10).

A Global Perspective on Paleoarchean Tonalites, Granites, and Metamorphism—Implications for Reading the Isotopic Signatures of Ancient Rocks. The Itsaq Gneiss Complex is argued to represent juvenile crustal production dominated by tonalite emplacement that occurred between 3850 and 3690 Ma and followed by repeated granite emplacement and high-grade metamorphism between 3670 and 3540 Ma in superimposed orogenic events (fig. 10). In the Uivak Gneiss Complex of northeastern Labrador (e.g., Bridgwater et al. 1978), a lesser amount of SHRIMP zircon dating indicates emplacement of granitoids (mostly TTG) between ca. 3920 and 3720 Ma, followed by migmatization and/or granite emplacement at ca. 3620 Ma (Schiøtte et al. 1989; Collerson et al. 1992). The Narryer Gneiss Complex of Western Australia, however, is dominated by granitic gneisses and migmatites, with only minor amounts of tonalite (Myers 1988; Kinny and Nutman 1996). Rare tonalites have yielded dates of ca. 3730 Ma (Nutman et al. 1991), and ca. 30 SHRIMP U/Pb zircon age determinations on mostly granitic gneisses and migmatites yielded ages clustered at 3670, 3620, 3600, 3460, 3380, and 3300 Ma (Kinny and Nutman 1996). In the Acasta gneisses of northern Canada, early 4020–3800 Ma components were overprinted by migmatization and granite injection at ca. 3620 Ma (Bowring et al. 1989; Stern and Bleeker 1997; Bowring and Williams 1999). In the Sino-Korean Craton in northeastern China, very rare ca. 3800 Ma tonalite enclaves in younger Archean granitoids record their first migmatization at ca. 3300 Ma (Song et al. 1996). In the Napier Complex of Antarctica, ≥3800 Ma tonalitic protoliths were overprinted by high-grade events at ca. 3070, 2900, and 2460 Ma (Williams et al. 1984; Black et al. 1986; Harley and Black 1997).

These earliest surviving Paleoarchean crustal segments dispersed around the world show that juvenile TTG components typically formed before the first recorded high-grade metamorphism and granite emplacement. Particularly noteworthy in several complexes is the importance of 3650–3600 Ma migmatization, deformation, and granite emplacement. These processes will potentially modify the geochemical signatures of the protoliths. On the whole-rock scale, each element will respond differently. Unfortunately, an element particularly prone to mobility in quartzofeldspathic rocks is Pb, whose isotopic system is used extensively for modeling early terrestrial evolution (Gancarz and Wasserburg 1977 to Kamber and Moorbath 1998; Kamber et al. 2003; Tera 2003). Even in the best-preserved Paleoarchean rocks around the Isua supracrustal belt, whole-rock + feldspar Pb isotopic work indicates significant postmagmatic mobility (Baadsgaard et al. 1986*b*; Kamber et al. 2003). Moreover, very different interpretations can be reached even when the same Pb-Pb data set is used (Kamber and Moorbath 1998 vs. Tera 2003), illustrating the unconstrained degree of freedom there is in modeling terrestrial evolution using such scattered data sets.

Most Archean TTG terrains show evidence of reworking and consequent isotopic disturbance. Consequently, isotopic studies of these difficult terrains increasingly concentrate on robust minerals, zircon (e.g., Vervoort et al. 1996; Wilde et al. 2001;

Honda et al. 2003), spinel (Bennett et al. 2002), and galena (Appel et al. 1978; Frei and Rosing 2001) from geological contexts where they have suffered the least recrystallization in superimposed tectonothermal events.

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