

Chapter 2

Hadean and Early Archaean High Grade Metamorphic Terrains

*Who knows for certain
Who shall here declare it
Whence was it born, whence came creation
The Gods are later than this world's formation
Who then can know the origins of the world*

(The Rig Veda, X.129).

Ancient Water / Marble Bar

No one

Was there to hear
The muffled roar of an earthquake,
Nor *anyone* who froze with fear
Of rising cliffs, eclipsed deep lakes
Sparkling comet-lit horizons
Brighter than one thousand suns
That blinded *no one's* vision.

No one

Stood there in awe
Of an angry black coned volcano
Nor *any* pair of eyes that saw
Red streams eject from inferno
Plumes spewing out of Earth
And yellow sulphur clouds
Choking *no one's* breath.

No one

Was numbed by thunder
As jet black storms gathered
Nor *anyone* was struck asunder
By lightning, when rocks shuttered
Engulfed by gushing torrents
That drowned smouldering ashes
Which *no one* was to lament.

In time

Once again an orange star rose
 Above a sleeping archipelago
 Sun rays breaking into blue depth ooze
 Waves rippling sand's ebb and flow
 Receding to submerged twilight worlds
 Where budding algal mats

Declare life

On the young Earth.

A poem by Andrew Glikson

Abstract The oldest terrestrial minerals identified to date are $4,363 \pm 20$ Ma-old detrital zircons from Jack Hills, Western Australia (Valley et al. *Geology* 36:911–912, 2002; Nemchin et al. *Earth Planet Sci Lett* 244:218–233, 2006; Pidgeon and Nemchin, *Precamb Res* 150:201–220, 2006), predating the oldest known rocks – the ~4.0–4.03 Ga-old Acasta Gneiss (Bowring and Williams *Contrib Mineral Petrol* 134:3–16, 1999). The zircon data suggest development of low temperature hydrosphere predated the ~3.8 Ga Isua supracrustal belt of southwest Greenland by some 600 Ma. These greenstone belts contain a wealth of primary textural, mineralogical, geochemical and isotopic features allowing detailed insights into the nature of near Earth surface as well as deep seated plutonic processes. Early Archaean (>3.6 Ga) gneisses underlie approximately 10,000 km² of Earth surface (Van Kranendonk et al., *Paleo-archaeon development of a continental nucleus: the east Pilbara terrain of the Pilbara craton*. In: Van Kranendonk MJ, Smithies RH, Bennett VC (eds) *Earth's oldest rocks. Developments in Precambrian geology* 15. Elsevier, Amsterdam, pp 307–337, 2007a, *Terra Nova* 19:1–38, 2007b). Terrains containing >4.0 Ga (Hadean) detrital and xenocrystic zircons include the Mt Narryer-Jack Hills Terrain (<4404 Ma), Acasta Gneiss (4.03–3.94 Ga) (west Slave Province, northwest Canada) and East Antarctic Gneisses (4.06–3.85 Ga).

Keywords Archaean • Hadean • Zircon • Mount Narryer • Jack hills • Acasta gneiss • Isua belt • Itsaq gneiss

The spatial juxtaposition of the Earth and Moon early in the history of the solar system (Ringwood 1986) requires both have been affected by early meteorite bombardment periods, documented on the Moon at ~3.95–3.85 Ga (Ryder 1990) and earlier periods. However, to date no shock-produced planar deformation features were identified in zircons from the Mt Narryer and other early Archaean terrains. The presence of ~3.85 Ga banded iron formations in southwest Greenland (Appel et al. 1998; Nutman et al. 2010) may signify yet older mafic volcanism with consequent ferrous iron enrichment of the early hydrosphere under unoxidizing conditions of the Archaean atmosphere (Chap. 11). The absence to date in pre-3.75 Ga terrains of un-metamorphosed or low-grade supracrustal rocks retards a search for signature of asteroid impacts. A possibility that terrestrial zircons >4.0 Ga may have been derived from

impact-produced felsic and anorthositic melt sheets, contemporaneous with pre-4.0 Ga lunar mega-impacts such as the South Pole Aitken, requires further examination.

The following sections discuss the principal features of high-grade gneisses and relic zircons in geochronological sequence, with implications to the nature of the Hadean (pre-3.8 Ga) crust.

2.1 Mount Narryer >4.0 Ga Detrital Zircons

The 30,000 km²-large Narryer Terrain, northwestern Yilgarn Craton, Western Australia (Myers 1988; Wilde et al. 2001), consists of granitoids and granitic gneisses ranging in age from early to late Archaean interlayered with banded iron formation, mafic and ultramafic intrusive rocks and metasediments (Williams and Myers 1987; Myers 1988; Kinny et al. 1990). The terrain contains ~3,730 Ma gneiss-hosted zircons and <4,404 Ma detrital zircons hosted by ~3 Ga-old quartzites (Fig. 2.1) (Froude et al. 1983; Wilde et al. 2001; Watson and Harrison 2005; Harrison et al. 2005; Valley et al. 2006; Nemchin et al. 2006; Pidgeon and Nemchin 2006; Cavosie et al. 2004) (Figs. 2.2, 2.3 and 2.4). The gneiss terrain is defined in the west by the Darling Fault, and in the north by the Errabiddy shear zone. Nutman et al. (1993) regards the Narryer Terrain as an allochthonous thrust block over the 3.0–2.92 Ga granites of the Youanmi.

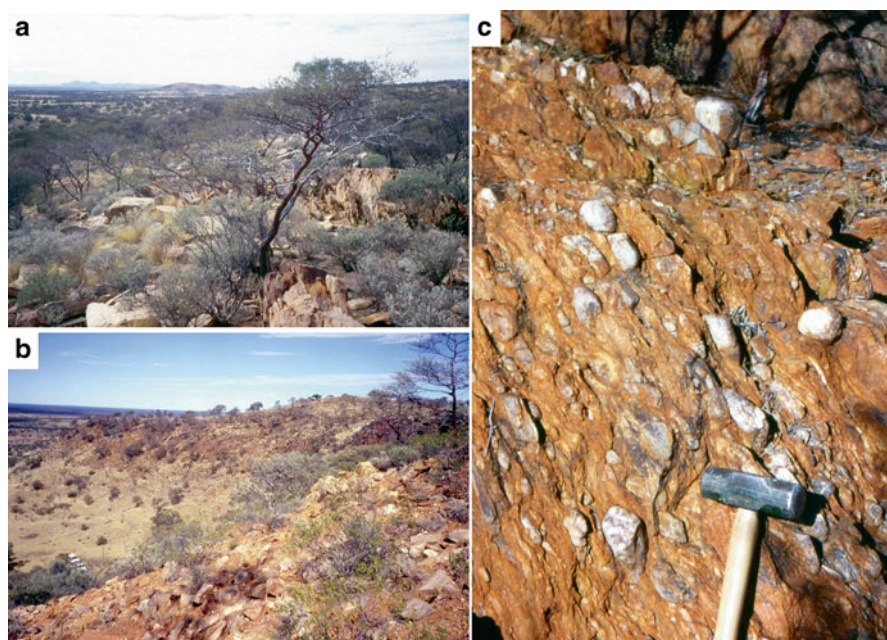


Fig. 2.1 Photographs of quartzite and conglomerate, Jack Hill, northwestern Yilgarn Craton, Western Australia. (a and b) Jack Hills, Western Australia, site of Hadean zircons as old as 4.4 billion years, the oldest known samples of Earth; (c) Outcrop of quartzite pebble-bearing metaconglomerate at Jack Hills. Courtesy John Valley

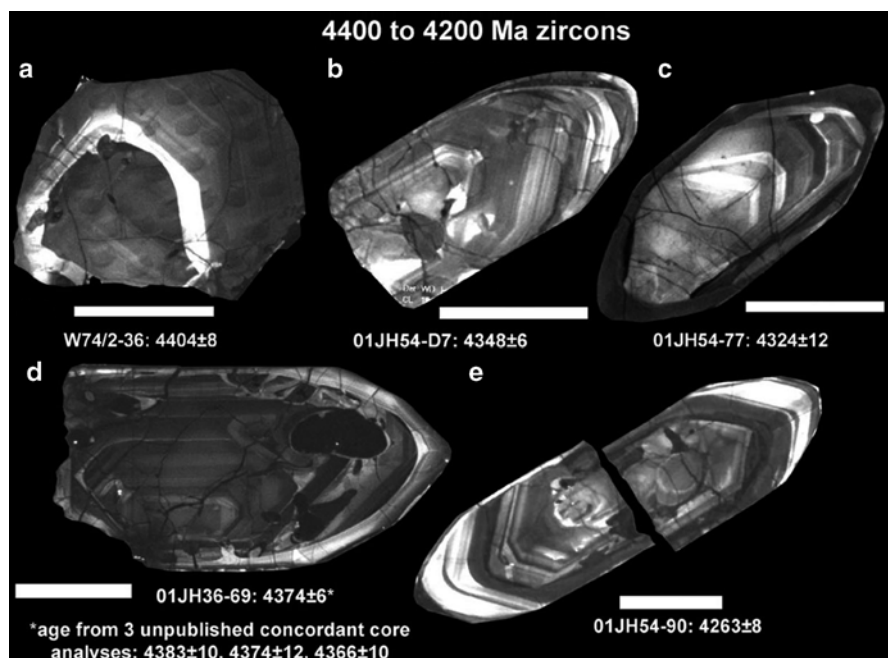


Fig. 2.2 Cathodoluminescence images of five 4,400–4,200 Ma detrital zircons from Jack Hills. Details of these grains are presented in Cavosie et al. (2004, 2005, 2006). Ages are in Million years. Uncertainties in Pb-Pb ages are 2 SD. Scale bars = 100 μ m (From Cavosie et al. 2007; Elsevier, by permission <http://www.sciencedirect.com/science/bookseries/01662635/15>)

Hadean to early Archaean \sim 4.4–3.9 Ga-old ages reported from 251 zircon grains from \sim 3.0 Ga Jack Hills quartzite sediments indicate a peak magmatic activity during \sim 4.2–4.0 Ga. Seventeen grains yielded ages $>$ 4.3 Ga, mostly from a single arenite layer (Cavosie et al. 2004). A 4,352 Ma-old zircon grain measured from Maynard Hills (Wyche et al. 2004) constitutes the oldest terrestrial age record measured to date. The old zircons may display zoned rims representing magmatic overgrowths, some of which dated as \sim 3,360 and \sim 3,690 Ma, consistent with granite ages from the Narryer Terrain, indicating the \sim 4.3 Ga zircons were re-incorporated in granitoid magmas (Cavosie et al. 2004).

Conglomerates of Jack Hills containing early zircons are dominated by quartzite clasts (Fig. 2.1c). To date no granitoid clasts were encountered, which restricts considerations regarding provenance terrains of the zircons. The U-Pb ages, morphology, zoning and geochemistry the zircon population of the Narryer Terrain suggest derivation from heterogeneous sources (Wilde et al. 2001). About 12 % of the zircons yield ages older than 3.9 Ga (Pidgeon and Nemchin 2006). The bulk of the zircons from Mt Narryer and eastern Jack Hills are consistent with granitic provenance similar to adjacent gneisses in terms of age, oscillatory zoning and U-content, whereas zircons from the western Jack Hills are of different composition and origin (Crowley et al. 2005).

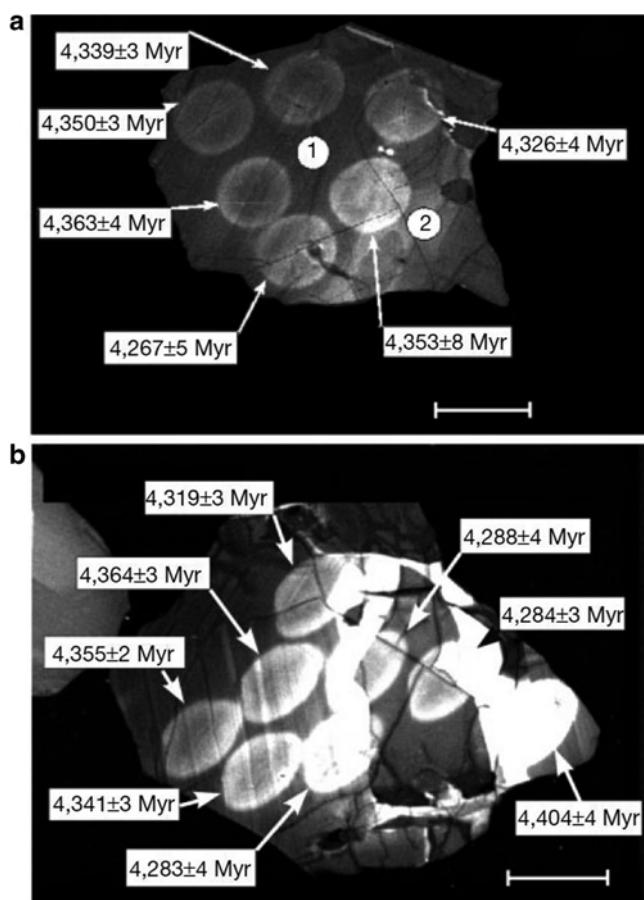


Fig. 2.3 4.4 Ga Zircons Cathodoluminescence and back-scattered electron images of a detrital zircon crystal grain W74/2–36 from Jack Hills. Scale bars are 50 μm ; (a) lighter circular areas are the SHRIMP analytical sites and the values record the $^{207}\text{Pb}/^{206}\text{Pb}$ age of each site. The two white areas (1 and 2) represent the approximate location of the $\delta^{18}\text{O}$ oxygen analytical spots. (b) Cathodoluminescence image showing the sites of analysis and the $^{207}\text{Pb}/^{206}\text{Pb}$ ages for each spot (From Wilde et al. 2001; Nature, by permission)

Palaeo-thermometry studies using Ti levels in zircon and oxygen isotopes support contact with water (Mojzsis et al. 2001; Peck et al. 2001; Wilde et al. 2001; Cavosie et al. 2005; Watson and Harrison 2005). Suggestions of a “cool” early Earth (Valley 2005; Valley et al. 2006) are supported by studies of Ti/zircon of >4.0 Ga-old zircons, inferring temperatures of $\sim 700^\circ\text{C}$ consistent with modern-day geodynamic conditions (Watson and Harrison 2005). From post ~ 2.6 Ga, however, a long term rise in the maximum $^{18}\text{O}/^{16}\text{O}$ ratios indicates further overall cooling of the Earth crust (Figs. 11.2 and 11.3) (Valley 2008). Preferential retention of Lu relative to Hf in the mantle and the low initial $^{176}\text{Hf}/^{177}\text{Hf}$ of most Jack Hills zircons imply derivation

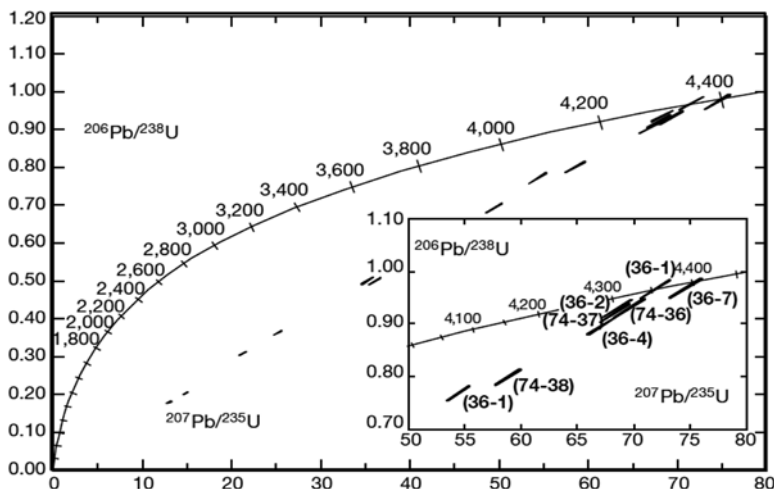


Fig. 2.4 Combined concordia plot for grain W74/2-36 showing the U-Pb results obtained during two analytical sessions. The inset shows the most concordant data points together with their analysis number (From Wilde et al. 2001; Nature, by permission)

by reworking of low Lu/Hf crust. The low $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{18}\text{O}/^{16}\text{O}$ isotope values of the zircons thus suggest that within ~ 100 Ma of its formation Earth had settled into a pattern of crust formation, erosion, and sedimentary cycling similar to that produced during younger periods. Many zircons younger than 3.6 Ga have higher initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, which suggests mantle contributions (Bell et al. 2011).

The assumption of a Hadean continental crust (Harrison et al. 2005) is difficult to reconcile with the likely arrest of the gabbro to eclogite transition under high Archaean and Hadean geotherms, which would have retarded subduction of mafic and production of granitic continental crust (Green 1981). Further, the T_{Zr} values correspond to near-eutectic zirconium saturation temperatures, which could have included equivalents of the Archaean tonalite-trondhjemite-granodiorite (TTG) suite (Chap. 4). Interpretations of zircon populations in terms of the composition of provenance terrains are likely to suffer from a major sampling bias in favor of zircons, as contrasted to a paucity in signatures of labile mafic-ultramafic and other lithic detritus eroded during current reworking. To cite an example, the composition of late Archaean conglomerates, such as in the Moodies Group of the Barberton Greenstone Belt (Chap. 7) or the Lalla Rookh Formation of the Pilbara Craton (Chap. 8), hardly represents the composition of the underlying greenstone-granite terrains.

2.2 Acasta Gneiss and Hadean Zircons

The Acasta Gneiss complex, west Slave Province, northwest Canada, includes relic 4.03–3.94 Ga granitoids and diorites with granitic protoliths indicated as ~ 4.2 Ga-old (Bowring and Williams 1999; Bleeker and Stern 1997; Iizuka et al.

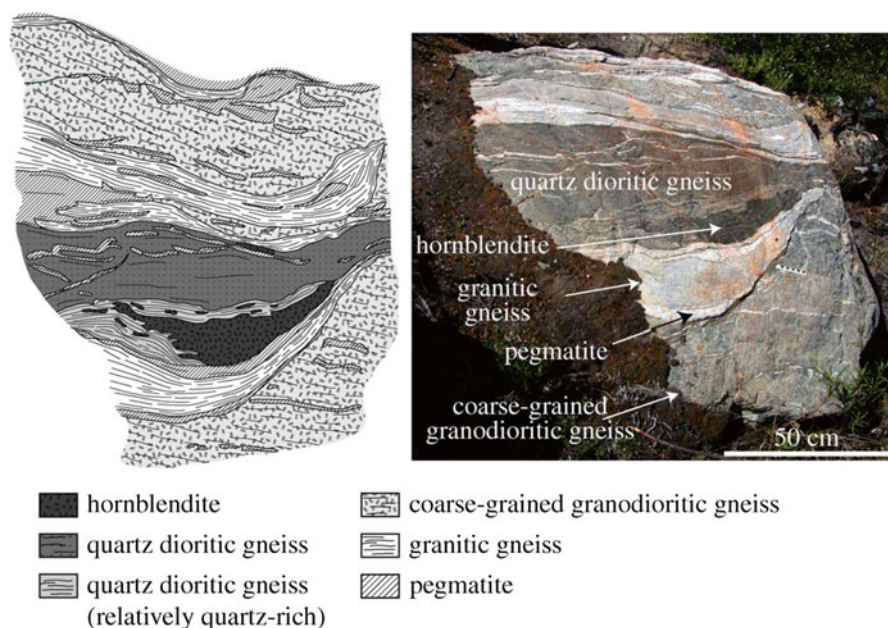
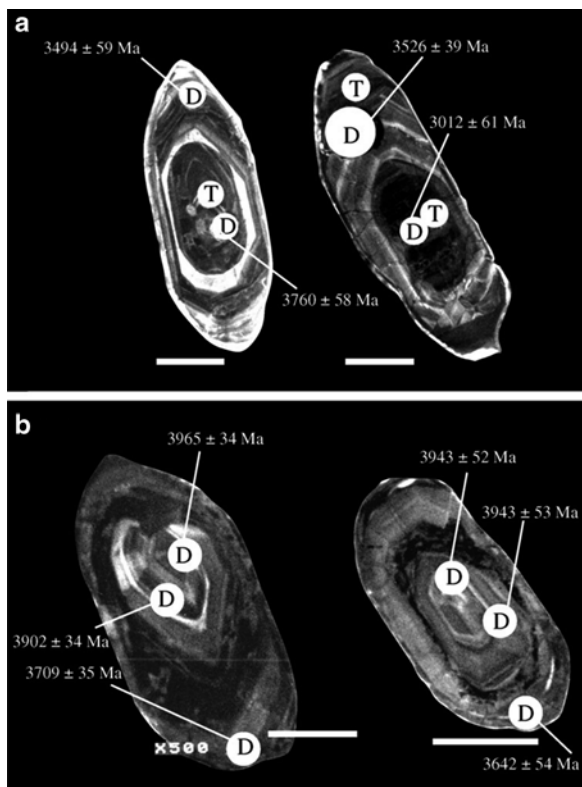


Fig. 2.5 Sketch map and photo of outcrop of quartz dioritic, coarse-grained granodioritic and granitic gneisses, with minor pegmatite and hornblendite layers. The outcrop displays granitic gneiss intruding quartz dioritic and coarse-grained granodiorite gneisses. The quartz diorite gneiss differentiated into relatively quartz-rich quartz diorite gneiss leucosome and residual layers of hornblendite, indicating anatexis of the quartz diorite by intrusion of granitic magmas (From Iizuka et al. 2007; Elsevier, by permission)

2007) (Fig. 2.5). The un-radiogenic Hf isotopic composition and the geochemical and mineralogical properties of the ~4.2 Ga zircon xenocrysts suggest crystallization in granitic magmas derived by reworking of older Hadean felsic crustal rocks (Iizuka et al. 2007). Calculations based on $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of the ~4.2 Ga zircons and juvenile magma of chondritic Hf isotopic composition allow estimates of mixing ratios and metamorphic reworking, suggesting that about half of the samples have a reworking index higher than 50 % and implying extensive reworking of Hadean granitoid crust (Iizuka et al. 2007). Zircon zonation patterns (Fig. 2.6) include evidence for metamorphic overgrowth of ~3.66 Ga zones around ~3.96 Ga cores, likely associated with intrusion of granites. Younger magmatic events include ~3.74–3.72 Ga granitoids, >3.6–3.59 Ga diorites and granitoids (Iizuka et al. 2007). ~4.2 Ga ages are obtained from model Hf zircon data and ^{40}Ar – ^{39}Ar ages of ~4.3 Ga within banded iron formation, also obtained in the Isua supracrustal belt (Kamber et al. 2003) (Sect. 2.5). U–Pb zircon data indicates mafic magmatic activity at ~4.0 and ~3.6 Ga. Evidence for younger magmatic events in the West Acasta terrain includes ~3.36, ~2.9, ~2.6 and ~1.9–1.8 Ga felsic magmatism and related anatexis and metamorphism associated with the Wopmay orogeny

Fig. 2.6 Cathod-luminescence images of zircons: (a) from granitic gneiss AC458 with a protolith age of 3.59 Ga, showing that some zircons contain xenocrystic cores; (b) from granitic gneiss AC584 with a protolith age of 3.94 Ga, showing the overgrowth of oscillatory-zoned zircon during recrystallization/anatexis at 3.66 Ga, which is coincident with the protolith age of an adjacent tonalitic gneiss. Scale bars are 50 μm . Values record 207Pb/206Pb ages (2σ). “D” and “T” represent analytical spots of LA-ICPMS dating and LA-ICPMS trace element analysis, respectively (Iizuka et al. 2007; Elsevier, by permission)



(Hodges et al. 1995; Sano et al. 1999), followed by ~ 1.26 Ga MacKenzie mafic dyking event (LeCheminant and Heaman 1989; Bleeker and Stern 1997).

2.3 Northeastern Superior Province Gneisses

The Nuvvuagittuq (or Porpoise Cove) greenstone belt, located on the eastern coast of Hudson Bay, Northeastern Superior Province, Canada, dated at 3.8 Ga, is composed of Archaean plutonic suites containing 1–10 km-wide belts of amphibolite and granulite-facies greenstones traced up to 150 km along strike (Percival and Card 1994; Percival et al. 1992; Leclair et al. 2006). The terrain includes one of the world’s oldest known mantle-derived assemblages (O’Neill et al. 2007), comprising both Al-depleted and Al-undepleted komatiite volcanics and isotopic positive ϵNd values indicating long-term preceding mantle-type high $^{147}\text{Sm}/^{144}\text{Nd}$ ratios and depletion in the light rare earth elements (LREE). U-Pb age determinations define younger 3.8–1.9 Ga domains spatially defined by aeromagnetic anomalies (Leclair et al. 2006). Two principal age terrains are identified, including (A) The east Arnaud

River terrain consisting of <2.88 Ga rocks with Nd depleted-mantle model ages (T_{DM}) <3.0 Ga, and (B) The west Hudson Bay terrain including the Nuvvuagittuq greenstone belt which contain ~3.8 Ga inherited zircons (Stevenson et al. 2006). Mafic components of the gneisses include cummingtonite amphibole with positive Eu and Y anomalies, similar to those of Algoma-type banded iron formations of marine exhalite origin and seawater signature (Fryer 1977; Graf 1978; Fryer et al. 1979). Banded iron formation associated with the greenstone belts display heavy Fe isotopic composition (0.1–0.5‰ amu) relative to those of associated gneisses and amphibolites, indicating origin as marine chemical precipitates, by analogy with heavy Fe isotopic composition of the Akilia banded iron formation, southwest Greenland. The origin of banded iron formations includes interpretations in terms of precipitation of marine exhalations (Jacobsen and Pimentel-Klose 1988; Olivarez and Owen 1991), oxidation of Fe^{+2} derived from deep ocean basins and deposition under anoxic conditions (Holland 2005) and anaerobic microbial activity (Konhauser et al. 2002). The REE and Y profiles and the Fe isotopic compositions of Nuvvuagittuq's BIF confirm their origin as marine exhalites (O'Neill et al. 2007).

2.4 Wyoming Gneisses

The northwestern Wyoming Craton and the Granite Mountain region of central Wyoming include outcrops of 3.4–3.2 Ga rocks (Mueller and Frost 2006) and evidence from Nd and Pb isotopic indices suggesting 3.6–4.0 Ga precursor source terrains (Wooden and Mueller 1988; Frost and Frost 1993; Mueller and Frost 2006; Chamberlain et al. 2003). The Archaean rocks are exposed in the cores of Laramide (Cretaceous) uplifts, bordering Proterozoic terrains and late Archaean ~2.67 Ga terrain of the Teton and Wind River Ranges (O'Neill and Lopez 1985; Mueller et al. 2002; Frost et al. 2006). Other late Archaean terrains occur in the North Snowy Block, southwestern Montana and in south-central Wyoming (Chamberlain et al. 2003).

Detrital zircons from 3.3 to 2.7 Ga quartzite of the eastern Bearooth Mountains, western Bearooth Mountains and Tobacco Root Mountains and Hellroaring plateau are dominated by 3.3–3.4 Ga grains and also include >3.6 Ga zircons, including grains 3.9–4.0 Ga-old (Mueller and Frost 2006). Lu-Hf model ages of 3.3–3.4 Ga from bulk zircon samples in quartzites suggest derivation from a relatively juvenile magmatic event (Stevenson and Patchett 1990). Early Archaean zircons also occur in the northwest part of the Wyoming Craton, which contains extensive pelitic, quartzitic and carbonate metasediments interleaved with gneisses (Mogk et al. 1992, 2004). Zircon xenocrysts from these meta-sediments yield ages of ~3.3 Ga from trondhjemite from the northern Madison Range and up to 3.93 Ga from the Tobacco Root Mountains. Tonalitic orthogneiss with magmatic ages of ~3.3 Ga east of the Granite Mountain contains early Archaean xenocrystic zircon cores mostly yielding ages of about ~3.3 Ga with some grains yielding ages of ~3.42, ~3.48, ~3.59 and ~3.80 Ga (Kruckenberg et al. 2001). Cores of xenocrystic zircons from the

southwest Wind River Range include 3.8–3.65 Ga internal domains with low U (34 and 25 ppm) and high Th/U (0.70 and 0.74) values, suggesting crystallization in mafic or high grade metamorphic rocks.

Chamberlain and Mueller interpreted the evidence in terms of the pre-existence of a major ~3.3 Ga craton extending from the Oregon Trail belt in south-central Wyoming to the Great Falls Tectonic zone and Dakotan segment of the Trans-Hudson Orogen. Prevalence of 3.3–3.4 Ga detrital zircons in the eastern Beartooth Mountains suggests proximal sources of terrains of this age. Elevated isotopic $^{207}\text{Pb}/^{204}\text{Pb}$ ratios in upper Archaean rocks suggest derivation from high- μ Hadean-aged basaltic proto-crust and mantle. Nd isotopic data vary widely, in part suggesting mantle-derivation and in part incorporation of 3.8–3.6 Ga components in the sources of younger magmatic events (Kamber et al. 2003). Chamberlain and Mueller interpreted the evidence in terms of combination of erosion of early Archaean cratons and subduction of basaltic crust including craton-derived sediments into the mantle. Cratonization of the Wyoming Craton about ~3.5, ~3.3 and 3.0–2.85 Ga was associated with multiple intrusions of tonalite-trondhjemite-granodiorite and K-granites in the Beartooth-Bighorn Magmatic Zone, forming broad plutonic blooms rather than arc trench-type linear belts (Frost et al. 2006; Mueller and Frost 2006). Evidence of modern-style lateral accretion and arc magmatism is suggested at 2.67–2.63 Ga in the southern part of the craton. Possible geophysical evidence for buried equivalents of the ~3.3 Ga craton is provided by a, at least 100,000 km² large, 15–25 km thick and seismically-fast lower crustal layer imaged beneath the Bighorn subprovince by the Deep Probe experiment (Nelson 1999; Gorman et al. 2002; Chamberlain et al. 2003), imaged north to the Great Falls tectonic zone and much of central and eastern Montana.

2.5 Itsaq Gneisses and Supracrustals, Southwest Greenland

The Itsaq Gneiss Complex contains tonalitic, granitic, minor quartz-dioritic and ferro-gabbro gneisses dated as ~3,870 and 3,620 Ma, associated with amphibolite, chemical sediments, minor felsic volcanics, gabbro-anorthosite suites and slivers of >3,600 Ma peridotite. Intrusive tonalites are compared to the Archaean tonalite-trondhjemite-granodiorite suite in terms of their geochemistry, including Sr and Nd isotopic mantle-derived signatures and are interpreted in terms of partial melting of hydrated basalt converted into eclogite (Nutman et al. 1993, 2007). The northern part of the Itsaq gneiss complex contains the 35 km-long Isua supracrustal belt (Fig. 2.7), originally dated as ~3,700 Ma (Moorbath 1977), 3,800 Ma (Baadsgaard et al. 1984) and 3,710 Ma (Nutman et al. 2007), including meta-volcanic amphibolite and banded iron formations. The primary volcanic and sedimentary textures are mostly overprinted by penetrative deformation, leaving only small low-strain least-deformed structural windows where original features such as pillow lava in amphibolite are observed (Komiya et al. 1999; Nutman et al. 2007). The chemical

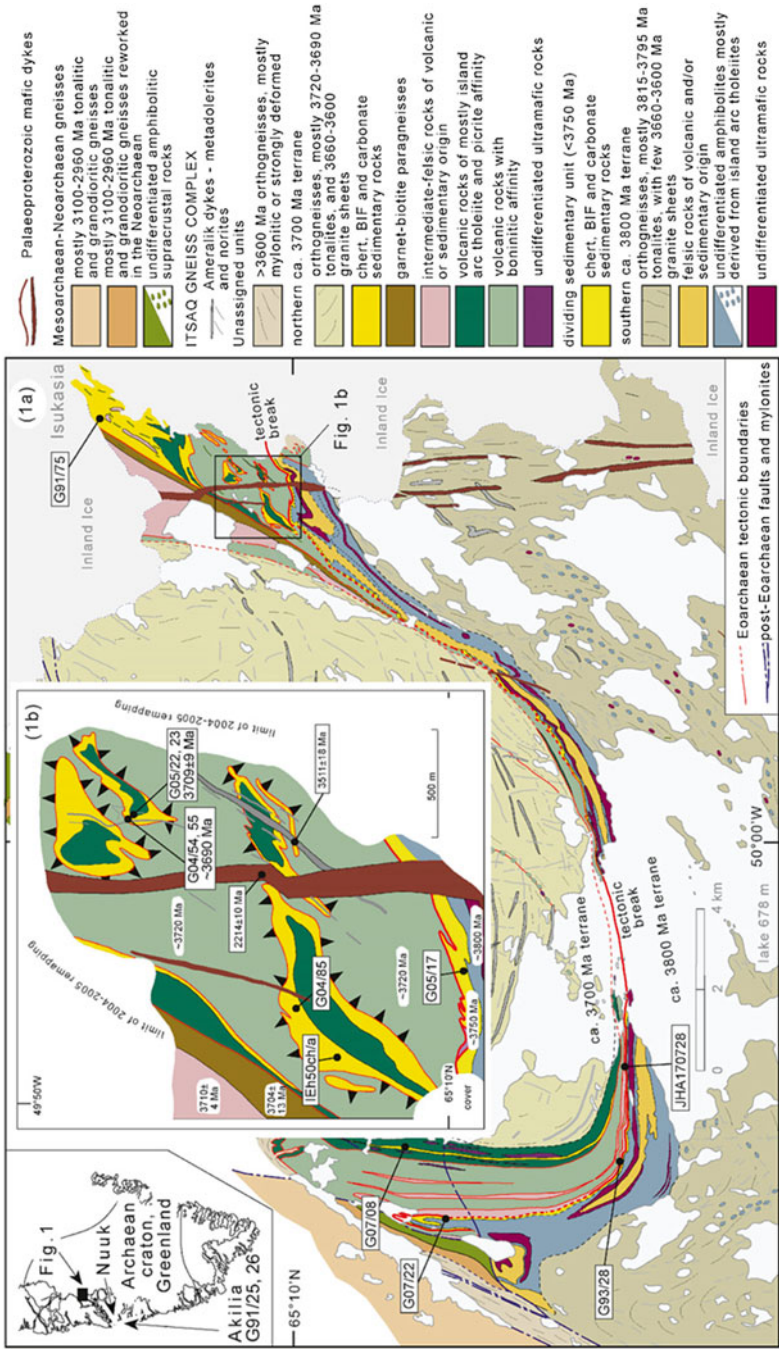


Fig. 2.7 Isua supracrustal belt, southwestern Greenland: (a) Map of the Isua supracrustal belt showing location of samples; (b) map of a small part of the eastern part of the Isua supracrustal belt, showing the geological relationships between altered intermediate basaltic-andesite(?), pillowed volcanic rocks, chemical sedimentary rocks and an overlying thrust sheet of boninitic amphibolites. The rocks were deformed prior to intrusion of Ameralik dykes ~3,510 Ma (From Nutman et al. 2010; Elsevier, by permission)

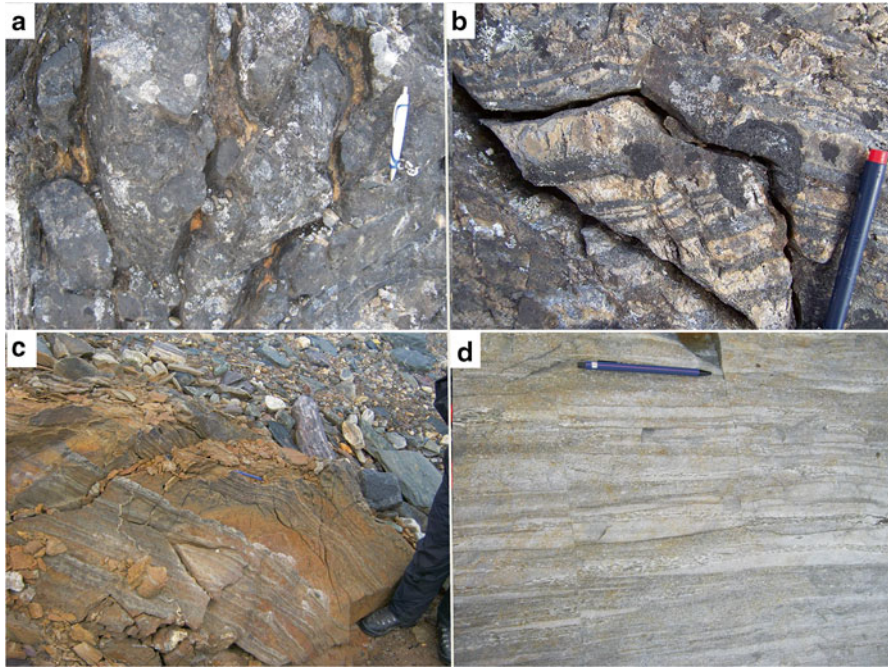


Fig. 2.8 Isua supracrustal belt: (a) Relict pillows in amphibolite facies ~3.8 Ga meta-basalts of arc-tholeiite to picrite compositions from the southern flank of the Isua Belt; (b) Low strain zone in ~3.760 Ma Isua banded iron formations. Note the grading of the layering and the layering on a cm-scale; (c) Agglomerate clasts in a ~3.7 Ga felsic intermediate unit from the eastern end of the Isua belt; (d) Original layering preserved in quartz + dolomite + biotite +/- hyalophane (Na-Ba feldspar) metasediments, likely derived from marl and evaporites (Courtesy Allen Nutman)

composition of the amphibolites compares with arc basalts (Polat et al. 2002; Jenner et al. 2006). Pillow basalt (Fig. 2.8a) and felsic meta-volcanic schist (Fig. 2.8c) preserving pre-deformation layering and graded volcanic breccia and conglomerate, containing 3,710 Ma zircons (Nutman et al. 1997). Relic banded iron formations (Moorbath et al. 1973; Dymek and Klein 1988) and likely sedimentary calc-silicate are mostly deformed, displaying transposed layering, where local primary sedimentary banding is reserved (Fig. 2.8b–d). The supracrustal relics are tectonically intercalated with the tonalites and are separated by ~3.6 Ga mylonite shear zones.

The Isua metasediments display low Al_2O_3 (<0.5 %) and TiO_2 (<0.05 %) levels and the Ca-Mg-Fe ratios correspond to those of ferroan dolomite – siderite – Fe-oxide sediments, with the sedimentary origin corroborated by shale-normalized REE + Y profiles showing La, Ce, Eu and Y positive anomalies (Fig. 2.9) which correspond to the signature of sea water (Bolhar et al. 2004). Evidence for early life in Isua sediments and in quartz + tremolite + calcite interstices of pillow lava emerges from Chap. (11):

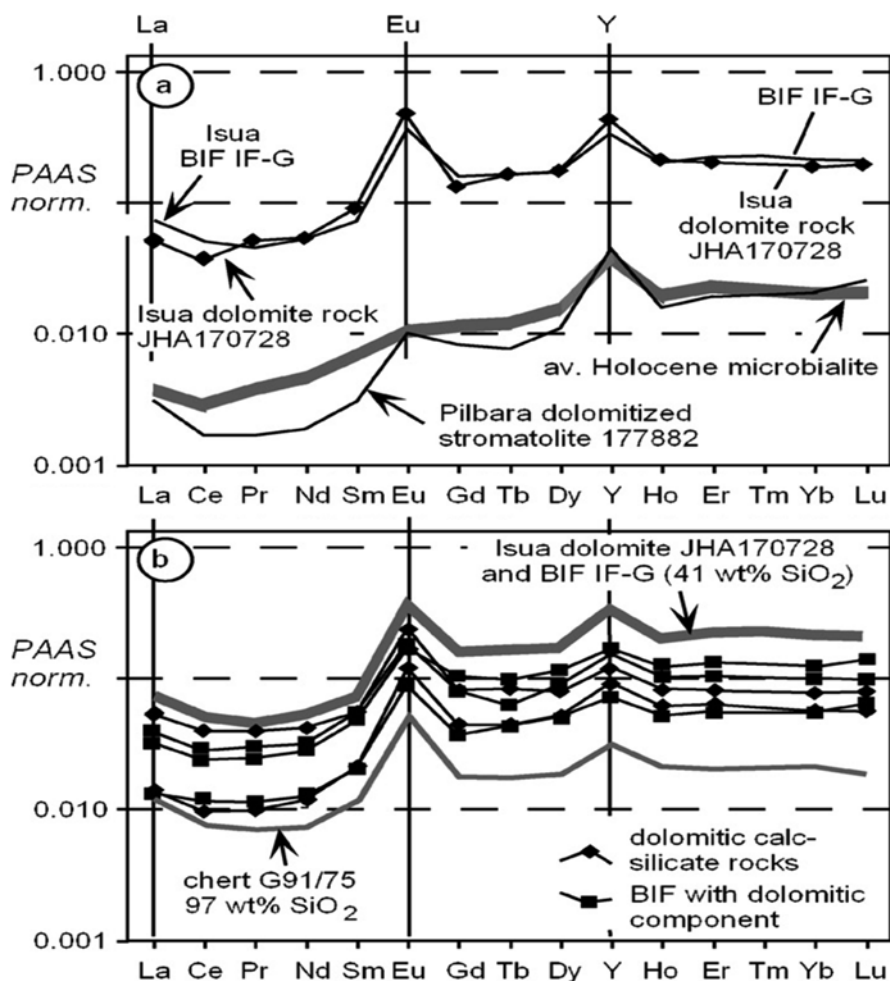


Fig. 2.9 REE+Y patterns normalized to Post-Archaean-Australian-Shale (PAAS). (a) IF-G Isua Banded iron formation and metamorphosed dolomite (JHA170728), modern Mg-calcite microbialite from Heron Island, Great Barrier Reef and a Warrawoona ~3.45 Ga low-temperature dolomitized stromatolite; (b) Isua dolomitic calc-silicate rocks and BIF with a dolomitic component (From Nutman et al. 2010; Elsevier, by permission)

- (A) Experimental evidence for anoxic microbial origin low-temperature dolomites (Nutman et al. 2010; Vasconcelos et al. 1995; Roberts et al. 2004), and
- (B) The likely precipitation of banded iron formations either by microbial oxidation of iron or by photolysis by ultraviolet radiation under the ozone-poor or ozone-free Archaean atmosphere (Konhauser et al. 2002).

Granulite facies banded iron formations and calc-silicates observed in the ~3,850 Ma Akilia terrain, southwest Greenland, displaying similar compositions as

reported from the Isua supracrustal belt, suggest early traces of microbial life at the end of the late heavy Bombardment defined about 3.95–3.85 Ga (Ryder 1990, 1991, 1997) (Chap. 11).

2.6 Siberian Gneisses

The Aldan Shield of the Siberian Craton north of Lake Baikal is dominated by the Olekma granite–greenstone terrain and gneisses and granitoids of the tonalite–trondhjemite–granodiorite series (TTG). The gneisses yield T_{NdDM} ages of 3.69–3.49 Ga and are intruded by gabbro at 3.1–3.0 Ga (Rosen and Turkina 2007). The terrain includes mafic–ultramafic and felsic volcanics, dated as 3.2–3.0 Ga, as well as granulite–gneiss suites. The terrains have been interpreted as micro–continents amalgamated during 2.8–2.6 and 2.0–1.7 Ga. Mid-Archaean 3.57–3.51 Ga granitic crust in the Onot and Bulun granite–greenstone domains displays evidence of reworking, recycling, and magma intrusion at 3.41–3.28 Ga. 3.22–3.0 Ga crust in the Sutam granulite–gneiss terrain and 3.4–3.3 Ga of the Sharyzhgaysky granulite–gneiss domain display overlap (Rosen and Turkina 2007). The Anabar Shield in the northeast Siberian Craton includes granulite–gneiss terrain dominated by 3.35–3.32 Ga metamorphosed calc–alkaline volcanics, TTG and mafic gneisses, followed by 3.16 Ga enderbites derived by partial melting of mafic source and reworked at 3.1–3.0 Ga. Derived sediments have T_{NdDM} model ages of 3.19–3.00 Ga (Rosen and Turkina 2007). Granite–greenstone terrains include the Onot and Bulun belts which include TTG plutons with mafic enclaves dated by Sm–Nd (T_{NdDM}) as 3.57 Ga and 3.51 Ga. U–Pb zircon ages of 3.41–3.28 Ga represent metamorphism and contamination. Paleo–pressure and temperature estimates suggest an origin of TTG gneiss under pressures of ~10 kb. The Irkut and Kitoy granulite–gneiss domains contain intermediate and felsic granulites with zircon cores ~3.4–3.3 Ga–old and Nd model ages of 3.4–3.1 Ga. These rocks have undergone high–pressure metamorphism at 2.5–2.4 Ga and granulite facies metamorphism at ~2.0–1.85 Ga. Meta–sedimentary enclaves associated with the gneisses yield model Nd_{DM} ages of 3.6–2.8 Ga. A derivation by erosion of 3.64–3.46 Ga tonalitic gneisses is likely. Diorite gneisses and granites have generally younger ages of 3.2–3.0 Ga. The eastern part of the Aldan shield contains Late Archaean and paleo–Proterozoic rocks.

2.7 North China Craton

The Anshan region of the northern China craton, northeastern China, contains extensive >3.6 Ga gneisses, including some ~3.8 Ga components: (1) Baijiafen mylonitized trondhjemitic rocks; (2) Dongshan banded trondhjemitic rocks, and (3) Dongshan meta–quartz diorite (Song et al. 1996; Liu et al. 1992). Associated

younger Archaean rocks include 3.3 Ga Chentaigou supracrustal rocks, ~3.3 Ga Chentaigou granite, ~3.1 Ga Lishan trondhjemite, ~3.0 Ga Donganshan granite, ~3.0 Tiejiaoshan granite, ~2.5 Ga Anshan Group supracrustal rocks, and ~2.5 Ga Qidashan granite (Liu et al. 1992; Wan et al. 2005). The Archaean blocks are rimmed by paleo-Proterozoic collisional orogenic belt extending through Wutai and Hengshan in Shanxi province to Kaifeng and Lushan in Henan province, separating the North China Craton into an eastern and a western block, the latter including meta-sedimentary rocks (Zhao et al. 2005). Tectono-metamorphic events in the North China Craton are manifest by a concentration of zircon ages at 2.55–2.5 Ga (Shen et al. 2005), constituting about 85 % of the North China Craton. Minor age frequency peaks occur at ~2.7, ~1.85 and ~2.15 Ga. Linear granite-greenstone terrains about ~2.5 Ga in age are widespread, including the western Liaoning province. Volcanic geochemical features correlate with island arc basalts (Wan et al. 2005). ~2.5 Ga greenstones and TTG plutonic rocks were metamorphosed within short periods following their formation (Kröner et al. 1996).

2.8 Antarctic Gneisses

The East Antarctic Shield contains 4.06–3.85 Ga-old high-grade metamorphic blocks and 1,400–910 Ma-old Proterozoic and younger formations which were amalgamated in the Cambrian (Cawood 2005; Harley and Kelly 2007). 3,850–3,400 Ga-old suites are dominated by tonalites, granodiorites and granites in terrains located in Gondwana reconstructions south of India, including the Rayner Province and Prydz Belt, and are superposed and overprinted by younger metamorphic belts. Similar early Archaean events are recorded in the Napier Complex and Rayner Province in Kemp Land where an anatexis/metamorphic event at ca. 3,450–3,420 Ma is locally preserved. Harley and Kelly (2007) suggest that much of the geological terrain covered by the East Antarctic ice cap consists of Archaean crust. Major thermal events have been dated as <2,840 Ma to >2,480 Ma, 2,200–1,700 Ma, 1,400–910 Ma and 600–500 Ma (pan-African Orogeny) (Harley 2003). Originally the Archaean blocks were juxtaposed with Gondwanaland crustal segments including Africa, India and Australia (Tingey 1991; Dalziel 1991; Fitzsimons 2000; Harley 2003).

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