# Crust of the Hadean Earth

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High temperatures in the interior of the young Earth led to the initiation of melting at great depths in the mantle (>150 km) and the production of large volumes of magma that erupted to form a >40 km thick basaltic crust. The ubiquitous presence of this crust dominated Archaean tectonics. Granitoid rocks, the source for >4 Ga Western Australian zircons, formed by partial melting at the base of the crust during the first 600 Ma of Earth history, but were always subordinate to basalt. The lunar record provides evidence that both the Moon and Earth experienced major impacting during this period. The impacts mixed granitoid with mantle-derived basalt to produce a composite granitoid-basalt layer with isotopic compositions close to bulk-Earth values. No record of its existence was retained in the oldest extant continents which formed ~ 3.9 Ga ago, after major impacting had ceased.

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During a Workshop on the Growth of Continental Crust (Ashwal 1988), Bill Hartmann was asked whether it was merely coincidence that the maximum age of extant rocks in the lunar highlands and on the Earth coincides with the cessation of major meteorite impacting. Hartmann had no answer at that time, but the question certainly is one that deserves further attention. The role of impacting during the evolution of the Hadean (4.5– ~ 3.9 Ga) Earth has been debated ever since the timing and the intensity of the early bombardment became known through investigations of the cratering record on the Moon and terrestial planets. The roles assigned to impacting are various, and range from intense brecciation (Taylor 1989) or "brecciation, melting and tectonic revitilization" leading to the destruction of ancient continental crust (Warren 1989), to constructive processes such as the formation of greenstone belts (Green 1972), proto-ocean basins (Frey 1980; Lowman 1976) and proto-continental crust (Goodwin 1976; Grieve 1980; Grieve & Parmentier 1984). Two recent developments allow the role of major impacting and the overall tectonic situation on the early Earth to be re-evaluated: (a) the discovery of >4 Ga zircons in metasediments from Western Australia, and (b) the recognition that higher temperatures in the Archaean mantle would have resulted in the formation of a thick, global layer of basaltic crust. The aim of this paper is to incorporate these developments in a description of tectonic processes and the nature of the Hadean Earth.

## Constraints on models for the Hadean Earth

(a) The oldest minerals on Earth are 4.2–4.3 Ga old zircons in ~ 3.1 Ga old metaquartzites from the Mt Narryer and Jack Hills areas of Western Australia (Froude *et al.* 1983; Compston & Pidgeon 1986). These are the only known pre-4.0 Ga terrestial minerals, and other early Archaean metasediments appear devoid of such old minerals. However, in the Australian examples, the old zircons are relatively abundant, making up 2% or more of the zircon population. The compositions of the old zircons are unremarkable in most respects. REE and most other trace elements are indistinguishable from those of zircons in modern continental crustal rocks (Maas *et al.* in prep.). Thorium and U contents of the Jack Hills zircons are low, but not inordinately so, and those from Mt Narryer plot together with zircons from modern continental environments (Fig. 1). The Jack Hills zircons may have come from pyroxene granulite (Compston & Pidgeon 1986), but the most likely source of the Mt Narryer zircons are normal granitoid rocks (Froude *et al.* 1983; Maas *et al.* in prep.). The diversity of zircon populations suggests a heterogeneous source; the inferred

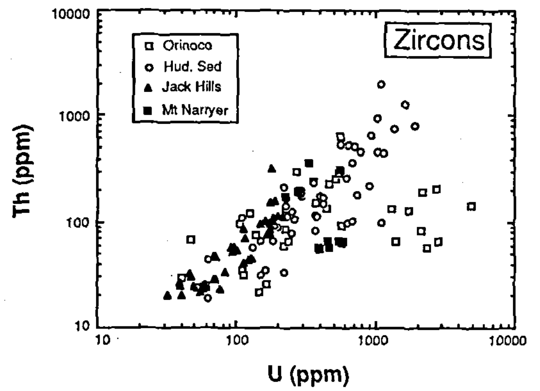


Fig. 1. U and Th contents of >4 Ga zircons from Mt Narryer and Jack Hills orthoquartzites (data from Froude *et al.* (1983) and Compston & Pidgeon (1986)), compared with compositions of younger detrital zircons in Hudsonian (1.9) Ga metasediments from Saskatchewan and from sand from the Orinoco River in Venezuela (ion microprobe analyses of N.T. Arndt, unpublished data).

granulitic component suggests a significant crustal thickness. The fact that such old zircons constitute 2% of the zircon population in a sediment deposited some 1 Ga after they formed is astonishing: either there was a remarkable preservation mechanism that enabled these zircons to survive for a billion years at the surface of an unstable early Earth, or the source of the old zircons was abundant and voluminous. Since the most likely platform that could have preserved the zircons is buoyant, low density, felsic crust, the very existence of old zircons is strong evidence that voluminous felsic material in one form or other existed on the Hadean Earth.

(b) The oldest rocks in extant outcrop are ~ 3.96 Ga old Acasta granitoid gneisses from the Slave Province, Canada (Bowring *et al.* 1989a, b). Other pre-3.8 Ga rocks survive in Antarctica (Black *et al.* 1986), Labrador (Schiøtte *et al.* 1989), and Greenland (Baadsgaard *et al.* 1984; Compston *et al.* 1986; Kinny 1986), but with the possible exception of the Acusta region, where more work is being done, these areas are small and isolated. Together they make up far less than 1% of exposed continental crust.

(c) Although the Acasta gneiss has a low $\varepsilon_{Nd}$ value (-2) consistent with it having formed from a ~ 4.1 Ga old granitoid precursor, all other pre-3.5 Ga granitoids have Nd and Sr isotopic compositions similar to those inferred for the early mantle and show no record of significantly older granitoid crust. This observation, together with the rarity of older rocks, is the basis of arguments that little or no granitoid continental granitoid crust existed prior to about 3.9 Ga (e.g. Moorbath *et al.* 1986).

(d) The isotopic compositions of mantle-derived mafic and ultramafic rocks in greenstone belts provide evidence that portions of the mantle were depleted as early as 3.7 Ga ago (Fig. 2). Some ~ 3.4 Ga old regions of the mantle beneath greenstone belts apparently had Nd isotopic compositions close to chondritic (Barberton greenstone belt; Hamilton *et al.* 1979; Gruau *et al.* 1990) while other parts were strongly depleted (Pilbara block; Gruau *et al.* 1987). 2.7 Ga ago, depletion of the source of greenstone volcanics was ubiquitous (Chauvel *et al.* 1985; Jahn *et al.* 1987; Shirey & Hanson 1986). Isotopic analyses of Archaean cherts and banded iron formations have been interpreted to indicate that contempo-

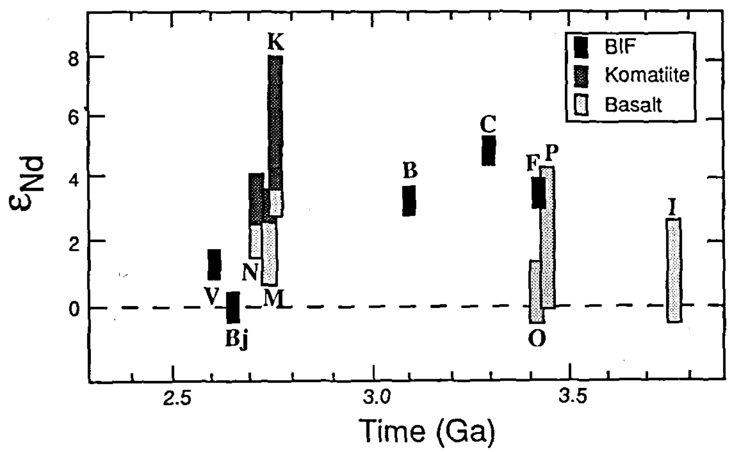


Fig. 2. $\varepsilon_{Nd}$ values of Archaean volcanic rocks and banded iron formations, plotted against their ages. The data have been compiled from Hamilton *et al.* (1979), Cattell *et al.* (1984), Chauvel *et al.* (1985), C. Chauvel (unpublished data), Gruau *et al.* (1987, 1990), Jacobsen & Pimentel-Klose (1988) and have been strongly filtered to eliminate samples believed to contain an older crustal component. For more complete compilations see e.g. Shirey & Hanson (1986), Jahn *et al.* (1987) and Chase & Patchett (1988).

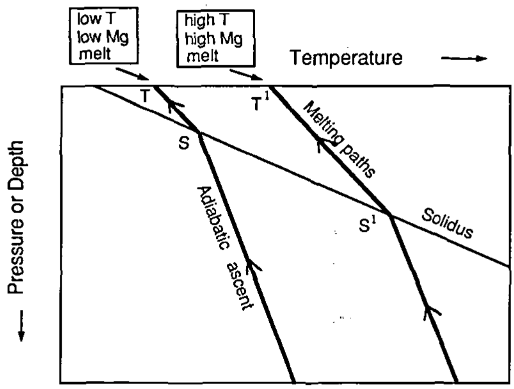


Fig. 3. Schematic representation of melting in the mantle. A hotter Archaean mantle results in a greater volume of melt and a thicker crust.

raneous volcanic rocks in ocean basins came from mantle as, or more, depleted than that beneath greenstone belts (Jacobsen & Dymek 1988). Widespread depletion of the mantle requires the existence of a complementary enriched reservoir. Although some authors propose that this reservoir consisted of enriched basalt, which either formed a thick, globe-enveloping crust (Galer & Goldstein 1991) or was subducted and stored somewhere in the mantle (Chase & Patchett 1988), early continental crust remains an alternative.

To summarize: widespread depletion of early mantle and locally abundant 4.2–4.3 Ga old zircons are consistent with the existence of widespread continental crust during part of the first 600 Ma of Earth history, but the outcrop record and the virtual absence of appropriate isotopic signatures in early granitoids argue against such an interpretation. An answer to this conundrum may lie in the ubiquitous presence of thick basaltic crust during the first 600 Ma of Earth history, and the role played by major impacting during this period.

## Thick basaltic crust

Various authors (e.g. Sleep & Windley 1982; Nisbet 1984; Vlaar 1986) have pointed out that the oceanic crust of the Archaean Earth probably was far thicker that present-day oceanic crust. The reasoning can be explained with reference to Fig. 3. Temperatures in the modern mantle are such that a rising diapir intersects the solidus at relatively shallow levels and produces magma of essentially basaltic composition. According to Klein & Langmuir (1987) and McKenzie & Bickle (1988), the magmas that erupt are mixtures of low- and high-degree melts, with the most magnesian component having a picritic composition. Beneath ocean ridges, the rising mantle intersects the solidus at a pressure around 10 kbar, melt is produced over a relatively short interval between 30 and 5 km, the volume of melt is small and erupts to form a relatively thin, ~ 6 km, crust. Beneath regions like Iceland, hotter mantle intersects the solidus at greater depths, more voluminous and more magnesian magma results, and the crust is significantly thicker. Klein & Langmuir (1987) have demonstrated a correlation between depth to the oceanic ridge and the composition of the basalt at the ridge, which they interpret in terms of the depth at which melting starts and the thickness of oceanic crust. The relationship is shown in Fig. 4 (data taken from Klein & Langmuir (1987) but similar results are given by Sleep & Windley (1982) and McKenzie & Bickle (1988)).

In the Archaean, we expect to see a continuation of this trend: the mantle was significantly hotter, the solidus was intersected deeper, a larger volume of more magnesian melt formed, and a thicker basaltic crust was produced. If Archaean mantle temperatures were 200–400°C higher than present mantle temperatures (e.g. Richter 1985), it can be predicted that melting beneath greenstone belts started at pressures around 50 kbar and depths greater than 150 km.

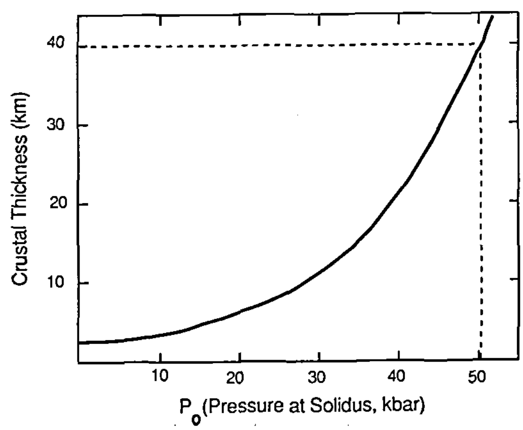


Fig. 4. Plot of depth at which mantle melting commences, vs thickness of basaltic crust (curve extrapolated from that of Klein & Langmuir (1987)).

If the relationship in Fig. 4 holds, the basaltic crust was at least 40 km thick. Such a thickness of basaltic crust would have had a great influence on Archaean tectonics, as described below.

## Impacting

The lunar cratering record provides evidence that the Moon was bombarded by large planetesimals from the time of its formation until ~ 3.9 Ga ago (Grieve & Parmentier 1984; Hartmann 1987). Mare Imbrium, for example, formed 3.9 Ga ago as the result of the impact of a ~ 100 km diameter object that excavated a crater ~ 500 km in diameter and 50 km or more deep. The Imbrium impact was merely one of the youngest of the type of event normal and common in the early history of the Moon, and presumably of the Earth as well. Hartmann (1987), for example, estimates that 10 km planetesimals impacted on the Earth at a rate of 1 per year 4.5 Ga ago, and 1 per Ma 4.0 Ga ago; for 100 km planetesimals, the values are 1 per 100 years and 1 per 100 Ma, respectively. The age of the oldest extant rocks on Earth coincides with the cessation of major impacting.

## Archaean tectonics

The first 600 Ma of Earth history was a period of high mantle temperatures and a time when large volumes of magnesian basalt erupted on the surface of the Earth to form a crust at least 40 km thick. Temperatures at the base of this crust were high enough to cause secondary melting that yielded felsic magmas – an analogy can be drawn with the rhyolites and granophyres that constitute a relatively large proportion of the ~ 30 km thick basaltic crust on Iceland. Intrusions of this type probably were the sources of zircons found in the Western Australian quarzites. The products of magmatic processes on the young Earth were large volumes of basaltic magma, a thick crust, and abundant secondary felsic melts.

The hot, thick crust resisted subduction because it was significantly less dense than mantle rock, and another process must have cycled basaltic crust back into the mantle. One possibility is the conversion of the lower part of the crust to eclogite, its delamination from the overlying, lower-density basaltic layer, and the subduction of the lower portion, as proposed by Hoffman & Ranalli (1988). Another possibility is that melting in regions of crumpling and thickening produced mafic residues with densities similar to or greater than those of typical mantle rocks, which foundered and returned to the mantle (Arndt & Goldstein 1989).

Constant impacting of large planetesimals prevented the granitoid material from aggregating, maturing and forming continents. The effects of a major impact are two-fold: (a) it thoroughly mixes material within the crust; (b) it causes upwelling in the mantle beneath the excavated region, which leads to further melting and the eruption of voluminous basalts, and to the destruction of any nascent lithosphere that might have provided a platform for a continent. As a result of the impacting, the earliest crust of the Earth would have been a mixture of mafic and felsic materials – a breccia or regolith. This crust was heterogeneous on a small scale (m to km) but relatively homogeneous on a continent or worldwide scale. To speak of continents and oceanic crust in this context is unwarranted.

The crust was mainly basalt but also contained a significant felsic component. Basalt continually cycled between crust and mantle, entering via basaltic volcanism and returning by the foundering of eclogite or the mafic residues of partial melting. The felsic component, which formed by melting at the base of the crust, continually migrated towards the surface and little of it was recycled to the mantle. The felsic component thereby remained in the surficial layer, largely isolated from the mantle, and its residence there led to the isotopic depletion of the Archaean mantle, as well as providing a source of pre-4 Ga zircons. The basaltic crust was also moderately enriched in incompatible elements compared with its source, and its presence at the surface contributed to mantle depletion; however, because it cycled from and to the mantle, its isotopic composition traced that of the mantle. A consequence of impact mixing is the dilution of the felsic component of the crust by juvenile basalt, probably to the extent that the bulk isotopic composition of the crust would not have deviated greatly from mantle compositions.

The chemical and isotopic evolution of the crust and depleted portion of the mantle could

Table 1. Calculation of the Nd Isotopic Composition of Depleted Mantle, 3.9 Ga ago.

| | Felsic Component | Primitive Mantle | Depleted Mantle |
|---|---|---|---|
| Relative proportion | 2% of upper mantle, to 670 km depth | | |
| Nd (ppm) | 30[a] | 1.2[b] | 0.6[c] |
| Sm (ppm) | 6[d] | 0.39[d] | 0.27[c] |
| $^{147}Sm/^{144}Nd$ | 0.12 | 0.1967 | 0.2720[c] |
| εNd (T=3.9 Ga) | −4[e] | 0 | +1[e] |

[a] From Taylor & McLennan (1985)
[b] From Hofmann (1988)
[c] Calculated using a volume of felsic material equal to that of modern continental crust, or 2% of the upper mantle
[d] Calculated using the $^{147}Sm/^{144}Nd$ given in the Table
[e] Calculated using the $^{147}Sm/^{144}Nd$ from the Table and an average age of 4.2 Ga

have been modelled in a quantitative manner using an approach like that of Chase & Patchett (1988), but this was not attempted because the uncertainties surrounding assumptions of the sizes and the compositions of the various reservoirs are overwhelming and severely limit the usefulness of such an exercise. Instead we present a simple calculation which shows that: (a) the extent of mantle depletion inferred from the compositions of mantle-derived magmas ($\varepsilon_{Nd}$ ~ +1 at 3.9 Ga) can be attributed to the felsic component of the early crust, and (b) the existence of this component would not necessarily be manifested in the isotopic compositions of the earliest granitoids. For the calculation we assumed that the felsic component of the crust had the same volume as modern continental crust, as argued by Armstrong (1981). We look upon this as an extreme limit in view of the probability of crustal growth during the Archaean and Proterozoic. The felsic material was mixed with basalt in a global, 40 km thick crust. If the felsic component had an average age of 4.2 Ga and a Sm/Nd like those of normal granitoids ($^{147}Sm/^{144}Nd$ ~ 0.12), its $\varepsilon_{Nd}$ value 3.9 Ga ago would be ~ −4. Taking the estimates of the Nd and Sm contents of the granitoid material and mantle listed in Table 1, we calculated from mass balance that the isolation of this material at the surface produced an $\varepsilon_{Nd}$ value of ~ +1 in 3.9 Ga old depleted upper mantle. This value is similar to that estimated by Chase & Patchett (1988).

Granitoid material with the volume of present-day continental crust, if dispersed throughout a 40 km thick crust, would constitute about 25% of this crust. The basaltic component would have had an isotopic composition like that of the depleted mantle. Taking the parameters listed in Table 2 we calculate that the $\varepsilon_{Nd}$ of the mixture was −1.8, a value not very different from that of primitive mantle. The strontium isotopic composition of the mixture, calculated in the same way (Table 2), varies between 0.7009 and 0.7031.

Table 2. Calculation of Isotopic Compositions of Mixed Granitoid-Basalt Crust

| Proportion of basalt | Basalt | | Granitoid | | εNd Mixture[c] |
|---|---|---|---|---|---|
| | Nd content[a] | εNd[b] | Nd content[a] | εNd[b] | |
| 75% | 8 | +1 | 30 | −4 | −1.8 |

| Proportion of basalt | Basalt | | Granitoid | | $Sr_o$ Mixture[c] |
|---|---|---|---|---|---|
| | Sr content | $Sr_o$ | Sr content | $Sr_o$[d] | |
| 75% | 150 | 0.700 | 350 | 0.702 | 0.7009 |
| 75% | 150 | 0.700 | 350 | 0.707 | 0.7031 |

[a] Nd and Sr concentrations (in ppm) from average granitoid (Taylor & McLennan 1985) and average P-MORB (Sun & McDonough, 1989)
[b] Initial isotopic compositions, 3.9 Ga ago, from Table 1.
[c] Composition of mixture from mass balance:

$$^{IC}\text{mixture} = {}^{IC}B^* \frac{C_B}{(C_B+f^*C_G)} + IC_G^* \frac{f^*C_G}{(C_B+f^*C_G)}$$

where IC is the isotopic composition and C the elemental abundances in basalt (B) or granitoid (G), and f is G/B, the ratio of the two components in the mixture
[d] Strontium isotopic compositions resulting from evolution with low or high Rb/Sr.

These values are only moderately elevated compared with those estimated for the mantle, but are far lower than those of the pure granitoid component.

Numerous studies have shown that continental crust usually forms from a mixture of juvenile mantle-derived material and older crust. Such is the case during later Precambrian (e.g. DePaolo 1981; Chauvel *et al.* 1987; Abouchami *et al.* 1990) and modern orogenic events (e.g. Hildreth & Moorbath 1988). It is likely that juvenile material from the depleted mantle was an important constituent of the source of the oldest surviving granitoids, and that this material further diluted the older granitoid component. Under such circumstances the isotopic contribution from pre-4 Ga felsic material would be unrecognisable. On the basis of these arguments we maintain that mantle-like isotopic compositions of most of the oldest surviving granitoids cannot be used to deny the existence of still older felsic material.

On the cessation of major impacting around 3.9 Ga ago, the process that had prevented the formation of continents was eliminated. The oldest surviving regions in Greenland, Canada and Antarctica are relicts of the earliest true continents, which formed by reworking of mixtures of pre-existing felsic rock and juvenile material, perhaps through processes like those in modern convergent margins, perhaps by other processes. A significant proportion of the felsic material was dispersed throughout the basaltic layer and may have been cycled back into the mantle rather than being incorporated into the newly-forming continents. The volume of the continental relicts with ages greater than 3.5 Ga may not be an accurate reflection of the total volume of felsic material that existed at the time.

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## Dansk sammendrag

Høje temperaturer i den unge jordklodes indre førte til begyndende smeltning dybt i kappen (>150 km) og produktion af store magmamængder, som dannede en over 40 km tyk basaltisk jordskorpe. Tilstedeværelsen overalt af denne skorpe var en dominerence faktor ved Arkæiske tektoniske processer. Granitoide bjergarter, som var kilden til Vestaustralske zirkoner med aldre >4000 mill. år, dannedes ved partielt opsmeltning i den nedre del af skorpen i de første 600 mill. år af jordens historie, men vedblev at være mindre voluminøse end basalterne.

Vores kendskab til månen tyder på, at både den og jorden var udsat for omfattende meteoritnedslag i denne periode. Nedslagene blandede granitoider og basalter, der stammede fra kappen, til en to-komponent granitoid-basalt skorpe, der havde isotopsammensætninger tæt på gennemsnittet for hele jorden ('bulk Earth'). Der findes dog ikke nogen evidens for dette granitoid-basalt lag i de ældste bevarede kontinenter, som dannedes for omkring 3900 mill. år siden efter at meteoritnedslagene var ophørt.

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