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## Fact-Fiction-Fantasy

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Article abstract

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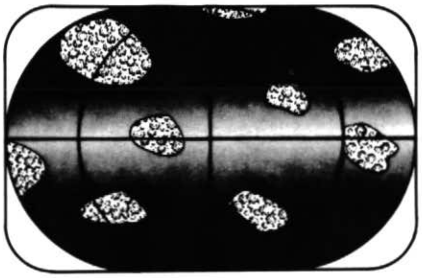
# Articles



## The Pre-3 b.y. Crust: Fact-Fiction-Fantasy

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### Summary

At this time the oldest rocks on Earth occur in W. Greenland. Radioactive dating methods give ages of about 3.8 billion years. The rock types involved are a complex mixture of metasediments, metavolcanic and intrusive rocks. The rock types appear to be rather normal in terms of modern analogues. But the structural geology of this, and similar ancient regions, indicates that ancient tectonic patterns may be unique. It is suggested that differentiation of the Earth was advanced 4 billion years ago and that there was an extensive acid crust.

Before attempting to explain the nature of the crust and tectonic processes in Archean times in terms of analogues among present day crustal processes and models, we feel that it is essential to examine some of the limited data available from better preserved and exposed ancient regions. To these writers, two regions which provide essential data are parts of the old cratons of Greenland and Southern Africa. Some of the old granulite terrains, although less well dated (e.g., Madagascar) must be considered.

Certain critical facts include:

1. Inspection of geologic maps of Archean terrains shows that 80 to 90 per cent are mapped as rocks of the granite clan (granites to tonalites) or gneisses derived from them (Bridgwater *et al.*, 1973). In high grade metamorphic terrains distinction between gneiss derived from acid volcanics and gneisses derived from intensely deformed and recrystallised granite plutons (McGregor, 1973) may be difficult or impossible.

The granitic rocks intrude or are tectonically mixed with supracrustal sequences comprised of extrusives ranging from ultrabasic to acidic composition together with smaller volumes of sediments. These are highly varied and include pelites, carbonate rocks, banded ironstones, cherts, graywackes, coarse clastics and a variety of aluminous and magnesium-rich quartzites of uncertain origin. Locally (for example in the Godthabsfjord region of W. Greenland) it has been possible to subdivide both the granitic and the supracrustal rocks into major groups ranging in age between 2.6 and 3.75 b.y. (Moorbath *et al.*, 1972, 1973; Pankhurst *et al.*, 1973) which are interlayered on a scale varying from a few metres to a few kilometres (McGregor, 1973; Bridgwater *et al.*, 1974). Elsewhere, as in the southern African shield, while dating is still perhaps inadequate, the work of Stowe (1968), Hunter (1970) and Wilson (1973) strongly suggests that some of the granites pre-date the major greenstone belts in the area. A similar time span of development to that found in Greenland is probable. In the greenstone-belt – granite type of terrain there is evidence that some of the greenstones pinch out completely between the granitic domes of the gregarious batholiths (McGregor, 1951).

2. In general, the rock types of the pre-3 b.y. crust have modern counterparts. The earliest igneous rocks known to us are amphibolites, dunites and acid volcanic boulders in a conglomerate from the 3750 m.y. Isua supracrustal sequence in W. Greenland (Bridgwater and McGregor, 1974). The earliest sediments known are the pelite, calc-silicate horizons, carbonate-bearing clastic sediments, and hematite-magnetite banded ironstones of the Isua formation, and the higher grade but similar sequences described by Stowe and Hunter from Rhodesia and Swaziland. More unusual rock types like the peridotite lavas (Anhaeusser *et al.*, 1969) and very anorthite-rich plagioclase anorthosites (An 80-99, Windley *et al.*, 1973) which are considerably more abundant in the Archean than later are readily explained on "Elder type" convective models (see later) in which basic magmas were derived from a "noiser"

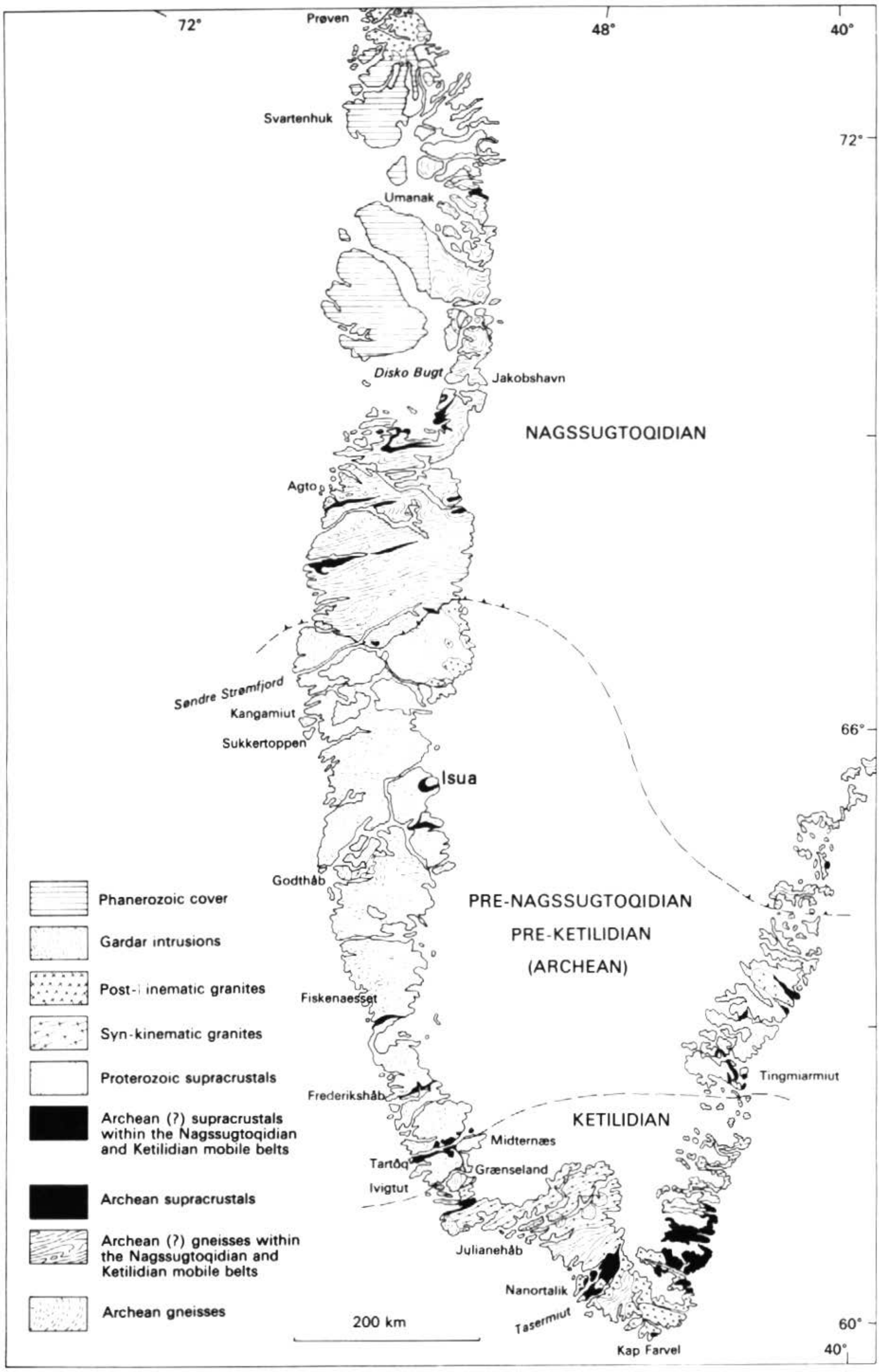

**Figure 1**
*Geologic map of West Greenland showing the situation of the Isua complex.*

**Figure 2**
*A conglomerate from the upper part of the Isua complex. The boulders and pebbles appear to be fine to medium grained acid volcanic fragments with a relatively high potassium content. The matrix contains quartz, microcline, plagioclase, carbonate and biotite.*

and higher level low-velocity zone than is present today.

The apparent normal nature of the early granitic rocks suggests that extensive differentiation of the Earth had been completed by 3.75 b.y. ago, the age of the earliest major units of granitic rock dated from Greenland. It seems highly improbable to us that fragments of relatively easily reworked material such as granite would survive from the earliest part of Earth history unless they had been very extensive and that a major part of the sialic material now found in the continental crust differentiated in the first 500 to 800 m.y. of Earth history. The universal field observation that the major Archean granites intrude the margins of the greenstone belts says nothing about the relative age of derivation of the basaltic and granitic rocks from the early mantle. Natural relaxation phenomena which would follow loading and burial of a granitic crust by extrusive basalt would produce an acid igneous event of the type seen in both the earliest rocks of the Greenland Archean and in Rhodesia.

3. All regions show that the hydrosphere was extensive. Weathering and sedimentary processes are a result of reactions of rocks with the atmosphere-hydrosphere-biosphere system. Modern sediments show that unless the interplay of this complex of variables in the low temperature environment is understood in detail, one cannot use sediments to indicate environment with any degree of significance. For example, amorphous silica in a modern marine sediment does not prove the oceans are saturated with amorphous silica; organisms in the open oceans precipitate both ferrous and ferric minerals which indicates nothing about atmospheric $P_{O_2}$; pyrite in sediments suggests certain types of bacterial sulphate reduction processes. Low temperature rock reactions need not reflect equilibrium with the inorganic physico-chemical environment even if we ignore the biospheric influences.

We find that the evidence for a significantly different atmosphere or water chemistry is not convincing. Isua sediments for example, appear to be very normal. No evidence has been found to suggest that they differ significantly from rocks from 1000 m.y. younger greenstone belts. If the atmosphere had less oxygen, as seems reasonable from the Berkner and Marshall (1965) analysis, and if ultaviolet levels partly controlled both the type of life, and environments where life was prolific, it would be no surprise if anaerobic bacteria in sediments left a greater mark than today. This again would not directly reflect the nature of the atmosphere. Tectonic environments such as the size of ocean basins and continents must play a major role in controlling types of sedimentation and volcanism in the Archean and the tectonic environments themselves are a function of thermal activity. Features such as the commonly cited lack of red-beds in the Archean could be as much a function of continent size and the persistence of intermontane basins as one of lack of oxygen in the atmosphere. The superficial chemical resemblance of some Archean volcanic rocks to modern ocean floor lavas reflects the ease of access of mantle material and need not indicate the presence of ocean floor of the type and extent found at present. Most Archean volcanic sequences are either dominated by rocks showing chemical characteristics resembling present day island arc suites or show a fairly rapid transition between rocks akin to modern ocean floor volcanics to rocks resembling those found in modern island arc environments (see for example Gélinas and Brooks, 1974). Transitions of this type might reflect either an incomplete separation of continental and ocean floor crust at the time or perhaps more probably smaller continents and oceans with a correspondingly large ocean-continent interface.

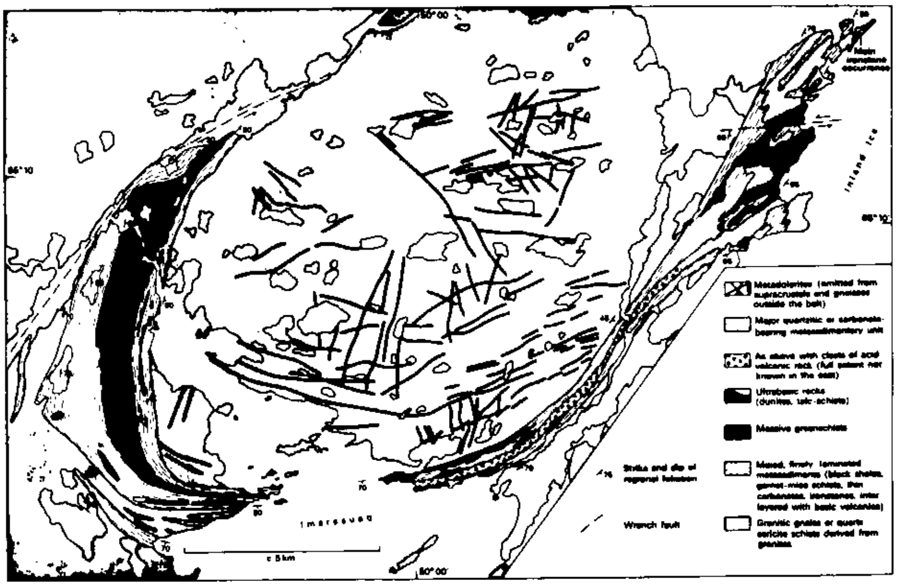

**Figure 3**
*Sketch map of the Isua spracrustal belt, West Greenland. From Bridgewater* et al., *"The Archean gneiss complex", in A. Escher and W. S. Watt, eds., "Geology of Greenland": Geol. Survey Greenland, in press.*

4. The main difference between Archean supracrustal successions and those formed at later times is one of scale. Few units in very old rocks can be followed for distances exceeding tens of kilometres. The size of Archean greenstone belts varies inversely with age from the major successions of the Canadian shield formed approximately 2.8 b.y. ago to the much smaller belt preserved at Isua. Part of this difference in size may be explained as a secondary effect of granite intrusion and break up of the original successions. However in a relatively well preserved terrain such as Rhodesia each greenstone belt is stratigraphically unique and appears to be a separate entity and not necessarily part of an original single sequence. The Isua belt or those of Rhodesia appear as mini-versions of say the modern circum-Pacific belt. Large coherant regions of extrusive basic rocks do not seem to have been present. The rapid changes within Archean volcanic successions (basalt to rhyolite) suggest a close association in space and time of mantle eruptive sites and mobilized acid crust.

5. Metamorphic environments are those of steep thermal gradients (e.g., Fyfe and Leonardos, 1973). Low pressure amphibolite-granulite series; sillimanite, andalusite, cordierite rocks are common. Kyanite is sometimes present but is usually partly replaced by sillimanite. Eclogite, blueschist rocks have not yet been found. Rapid changes in metamorphic grade are frequent. Such observations are fitting to a thinner, more radioactive acid crust but we would stress that if basic rocks of low radioactivity predominate, the crust need not be thin.

6. Archean granite suites frequently show a sequence from early syntectonic tonalites through potash metasomatised migmatites to post tectonic potash granite plutons (Viljoen and Viljoen, 1969). This succession is generally ascribed to changes in primary magmas released from the mantle. We consider it more likely to represent the result of the melting from the base upwards of an earlier sialic crust the lower parts of which have been depleted in Rb, U, K and other mobile elements under the prevalent high gradients.

7. The significance of some geochemical and isotopic parametres (e.g., the low U/Th ratios of Greenland gneisses, Kalsbeek, 1974), the low U/Th and K/Rb ratios of Lewisian gneisses (Bridgwater *et al.*, 1973) and similar features of some Archean granites, must be approached with caution. If the acid crust was thinner and more mobile on account of fast igneous turnover the activity of hydrothermal leaching systems may have been vastly more

extensive than today. Moreover, if in general geothermal gradients were steeper, drier acid magmas would result which in turn could rise to higher levels and drive Wairakei type systems (Elder, 1968). The shallow intrusive-extrusive sub-aqueous environment is the optimum for metasomatic events and it seems logical that such environments could have been more extensive (and hence the common occurrence of ore deposits in older rocks). This process may be the explanation for the widespread occurrence in the Greenland Archean of "skarn-rocks" which now consist dominantly of diopside, epidote, scapolite, sphene but many of which appear to be derived from basic pillow lavas (T. C. R. Pulvertaft and L. S. Andersen, pers. comm., 1973). Depletion of Rb and U from sialic crustal rocks at a shallower depth than later in the Earth's history under the influence of higher thermal gradients would mean that Archean granites would all show isotopic ratios close to the theoretical mantle curves (Faure and Powell, 1972) whether they were derived from earlier sial, from Archean ocean crust, or from the mantle.

## Conclusion

There is considerable evidence for a pre-3 b.y. earth consisting of extensive acid crust with a close spacing of mantle eruption centres (and of necessity, equally closely spaced subduction zones). A model of convection cells on something like a 100 km wavelength pattern could be appropriate.

If granitic rocks had much higher radioactivity than at present, perhaps five times (Birch, 1965), the granitic crust could not exceed about 10 km in thickness without melting at the base and would therefore spread over a larger area than the equivalent volume of sial at present.

With a hotter Earth, it seems logical following Elder (1968) to suppose that the zones of melting in the upper mantle were at higher levels and thermally much more erratic (i.e., the amplitude of T fluctuations could be larger, see Elder, Fig. 23). If this suggestion is coupled to Ramberg's analysis of plume spacing (Ramberg, 1967) it is also logical that basalt penetration would be on a smaller wave length scale than at present. Thus more primative magma types or less modified magma types might erupt and the turnover time or crust mantle recycling time would be much shorter (cf. Armstrong, 1968).

If major amounts of granite had already differentiated by the time the earliest rocks still preserved on the Earth's crust were formed, and the evidence from geological maps is compelling, and if these formed a thin extensive crust as dictated by the high radioactivity of the early sial, and if convection cells were small and closely spaced, global tectonics in the pre-3 b.y. period would not be like the modern situation. We do not yet know how the ancient Earth worked. But one might suggest that basalt underplating mechanisms and sub-crust basalt flow could have been extensive. The calcic anorthosites could result from such mechanisms. Extensive flow at the base of the crust would cause instability in the overlying sial with the formation of closely spaced rifts (Illies, 1970) and extrusion of mantle derived basic magma to form impersistent ocean basins floored by sial. The depressed sial would remelt intruding the basic rocks and the cycle begin again. Modern subduction mechanisms would have to be modified in a hotter Earth by cut off in a thicker, higher level, low-velocity zone. The frequent presence of horizontal thrust structures might indicate that the acid crust thickening process which dominated was overthrusting of mini-continental blocks (followed by repeated igneous relaxation resulting in re-spreading) and that random fluctuations in smaller convection could drive such thrust motions.

The continent-ocean basin geometry of the past may have been drastically different from the present. If this is considered possible, differences in the sedimentary and volcanic deposits may reflect such differences as much as those of other surface environmental factors.

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