Geologie en Mijnbouw **76:** 369–373, 1998.

Early Archean processes: evidence from the South African Kaapvaal craton and its greenstone belts (extended abstract)

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Received June 1997; accepted in revised form September 1997

Rocks of Early Archean age (3.0–4.0 Ga) have an exposed areal extent of less than 0.8 million km^2 worldwide (ca. 0.5% of the present-day exposed continental surface area), but only two sizable fragments of relatively pristine Early Archean continental lithosphere are preserved. They are found in Australia (Pilbara craton, ca. 60 000 km^2) and South Africa (eastern sector of Kaapvaal craton, ca. 80 000 km^2). These two cratons have similar ages, between 3.0 and 3.7 Ga, of tectonic events and litho-stratigraphic sequences. The eastern sector of the Kaapvaal craton is overlain by remnants of Late Archean basins of regional extent and was, therefore, a stable continental area by 3.0 Ga (De Wit et al. 1992; Figure 1). This sector of the Kaapvaal craton comprises a number of small cratonic fragments, which amalgamated between 3.2 and 3.3 Ga to form a complex craton with a mantle 350 to 400 km in depth. Its present-day effective elastic thickness is about 72 km with a basal lithospheric temperature of about 600 °C (Figure 2). Four distinct greenstone-belt sequences are exposed at the surface of this section of the craton (Figure 1), from north to south: the Pietersburg-Giyani, the Murchison, the Barberton, and the Natal-Nondwene greenstone belts, with respectively 2, 2, 8 and 15% of komatiites preserved throughout their complex tectonostratigraphic sequences (Brandl & De Wit 1997). In the most southerly belt, these komatiites are predominantly pyroxenites associated with Mg-andesites and boninite-like rocks (Wilson & Versfeld 1994), representing immature arc material of 3.2 to 3.3 Ga. The Murchison belt developed into a mature arc system by 3.2 Ga (Vearncombe 1991). The Pietersburg and Barberton belts contain vestiges of 3.4 to 3.5 Ga ophiolite-like sequences (De Wit et al. 1987; Brandl & De Wit 1997). Many of the komatiites of the Barberton belt are hypabyssal intrusions as part of a sheeted-sill complex within the ophiolite-like sequence (De Wit et al. 1987; Parman et al. 1997; Grove et al. 1997). This ophiolite-like sequence has been disrupted and overprinted by later (ca. 3.4 and 3.2 Ga) tectonomagmatic processes related to polyphase arc-tectonism (De Ronde & De Wit 1994). Each of the belts has distinct characteristics. Together with their surrounding variable granitoids, they collectively allow reconstruction of an early Earth dominated by plate-tectonic boundary processes (De Wit 1998).

New experimental work on komatiites from Barberton indicates that their magmas were hydrous (4–6% H_2O), and that their liquidus temperatures (1270–1350°C) are similar to those of magmas observed at modern plate boundaries (Parman et al. 1997). This suggests that the upper mantle in the Archean may not have been excessively hotter than today. The presence of significant dissolved water in komatiite magmas raises the possibility that the Earth lost more heat effectively through dehydration from a cool, wet and less viscous mantle.

Archean mantle dynamics may have been significantly different than the present ‘dry’ one. Since hotspot volcanism is not as efficient a way of loosing heat as spreading at mid-ocean ridges, it is unlikely that Archean plates were swamped by plumes, or plate tectonics replaced by plume tectonics. Rather, accretion and hydrothermal cooling processes at seafloor-spreading plate boundaries were possibly more efficient; and deep mantle-plume materials may have been deflected via the asthenosphere into these boundaries more effectively than observed today.

Modern plate tectonics probably has its roots in the Hadean-Archean transition between 4.0 and 4.2 Ga. Following gradual dehydration of the mantle from about 4.5 Ga onward, circa 70% of this mantle water accumulated in the hydrosphere by about 4.0 Ga (De Wit & Hynes 1995). At this time Earth’s accretion boundaries first came to operate below sea level, causing rapid onset of extensive hydrothermal

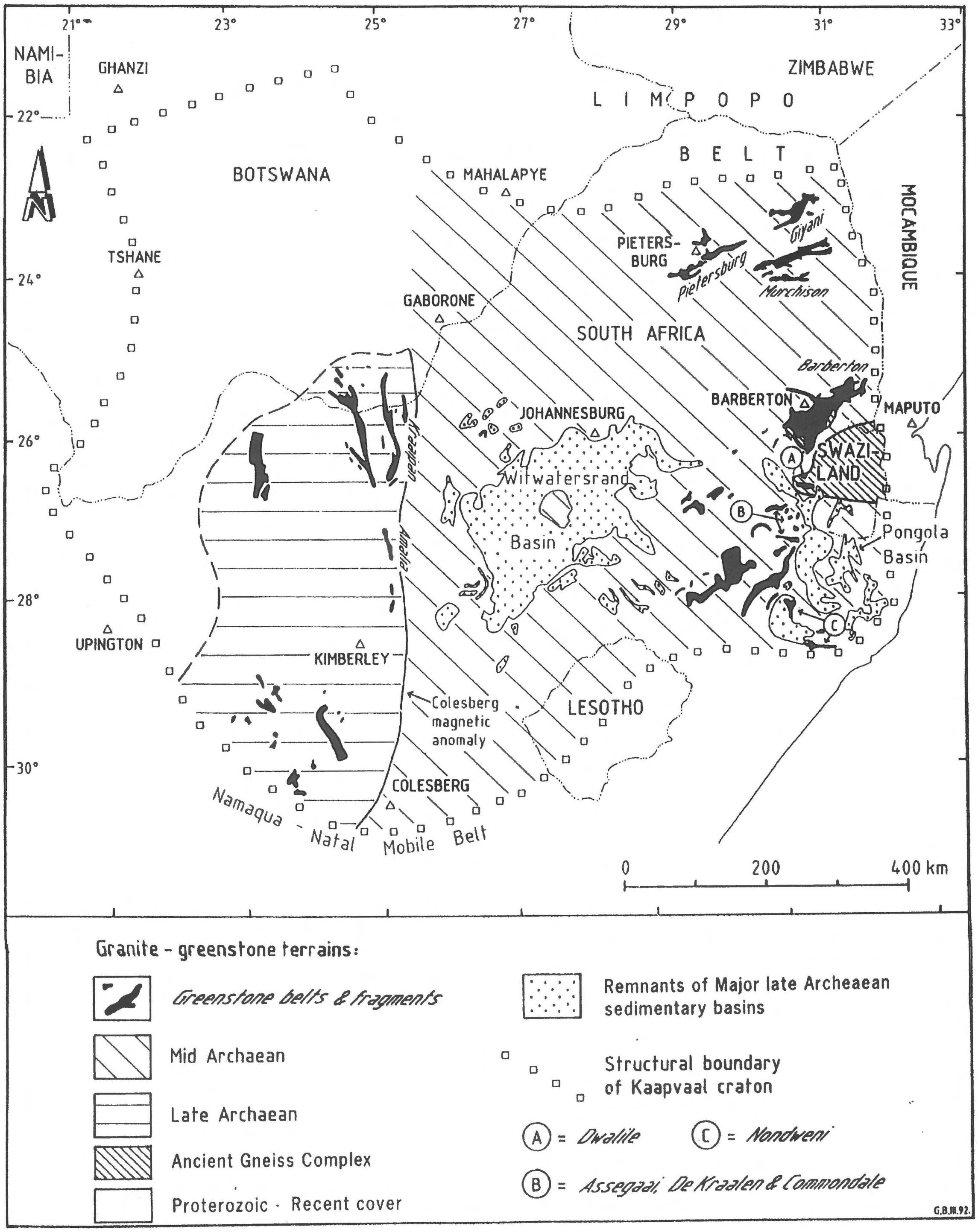

Figure 1. Schematic map of the Kaapvaal craton showing the location of its major greenstone belts and the overlying remnants of Late Archean sedimentary basins (from Brandl & De Wit 1997).

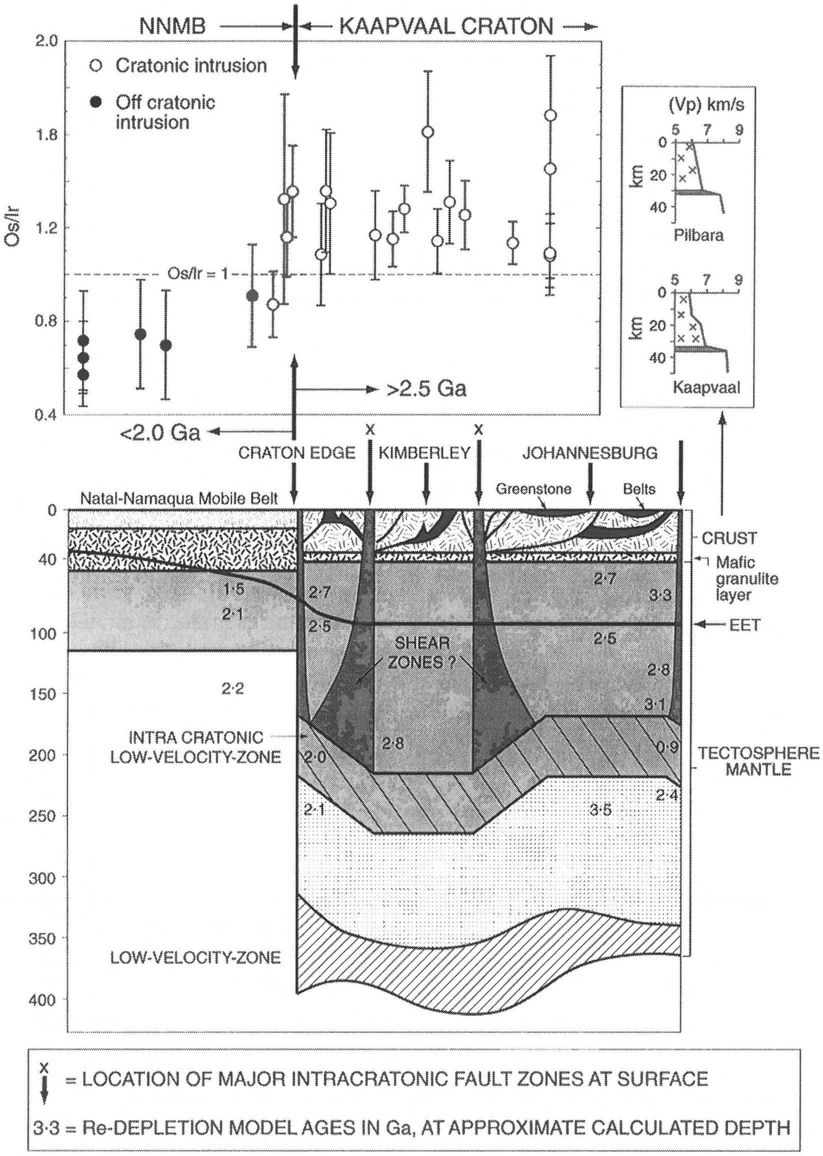

Figure 2. Schematic NE-SW section through the Kaapvaal craton based on seismic, gravimetric, geological and geochemical studies (from De Wit 1997). Note the distinctly different structure and thickness of the cratonic crust compared to that of the adjacent Proterozoic crust. Inset shows crustal seismic sections of the Pilbara and Kaapvaal cratons (from Durrheim & Mooney 1994). Significant local crustal thickness variations of up to 8–10 km are known (Muller 1991). The depth to the bottom of the cratonic keel is taken from Vinnik et al. (1996), the intracratonic low-velocity zone from E. Pederby (unpublished; see De Wit et al. 1992), and the Effective Elastic Thickness (EET) from Doucoure et al. (1996). A distinct seismic anisotropy in the upper lithospheric mantle may be due to old inherited shear zones (this is not proven; other interpretations suggest that the anisotropy may be due to more recent deformation; Vinnik et al. 1995). The deep shear zones and major flexures to the depth of the low-velocity zone may link up with major crustal domain boundaries mapped at the surface (De Wit et al. 1992). The inferred increase in width of the shear zones with depth as shown on this figure, is based on field and experimental work on Phanerozoic mantle shear zones and wet olivine rocks, respectively (Drury et al. 1991; Vissers et al. 1995). Note that the thickness of the lithosphere sensu stricto (cf. Anderson 1995), as defined by the EET, is relatively shallow (ca. 72 km) compared to ancient cratons worldwide (Doucoure et al. 1996); this Kaapvaal structure has a basal temperature of ca. 600 °C. A similar interpretation explains both seismic and deep electrical anisotropies within the old, deep lithospheric mantle of the North American Superior Province (Mareshal et al. 1995; Silver & Kanashima 1993). The geochemistry of the cratonic mantle is distinct, both in its major and trace elements as well as in minerals and elements of economic significance (diamonds, platinum-group elements, gold). The upper diagram clearly displays this geochemical characteristic in terms of Os/Ir ratios (McDonald et al. 1995). The cratonic (tectosphere) mantle also has distinctly heterogeneous domains of Re/Os model ages (selected data, from Pearson et al. 1995), which illustrate that at least some of the lower parts of the keel are of Early Archean age. Such a structure would rule out major episodes of delamination of this cratonic keel.

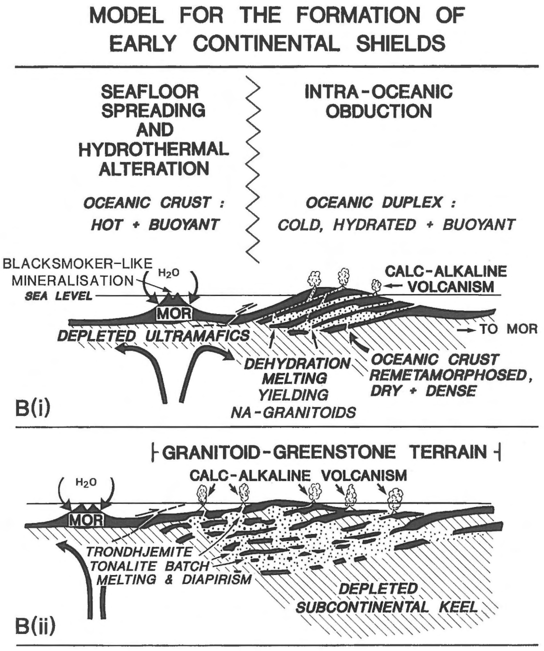

Figure 3. Cartoon showing the preferred model for the formation of Early Archean cratons as discussed in the text. The earliest fragments of oceanic lithosphere, formed at mid-ocean-like ridges (MOR), are thought to have been intensely hydrated and less dense than modern oceanic lithosphere. Such buoyant Archean oceanic lithosphere resisted subduction and delaminated to form stacks of allochthonous sheets (flakes) which upon continuous tectonic burial underwent dehydration melting to yield tonalitic melts at depths between 20 to 100 km. Such melts rose to form overlying and amalgamated crustal sheets. Continued subsidence in turn caused melting of the sheets to yield granites at depths of 30 to 35 km, leaving a residue of mafic-intermediate granulites. Partially dehydrated meta-basalts and peridotites were further 'buried' into the K-richterite and phlogopite fields.

cooling and alteration of upper oceanic lithosphere as observed today. Only then did 'modern' production of granitoids become possible during the recycling of Earth's lithosphere. Processes at convergent plate boundaies, however, evolved more slowly into modern subduction-dehydration style over the course of the Archean. In the earliest Archean, recycling of oceanic materials into the mantle may not have been efficient, and back-arc spreading processes may have been absent. Instead, hydrated oceanic lithosphere 'piled-up' to form intraoceanic tectonic thrust-stacks, which in turn evolved into the first continental fragments through internal differentiation during tectonic thickening and construction of deep lithospheric keels (Figure 3). These fragments amalgamated into larger cratonic fragments throughout Archean times. Minimum continental crustal growth-rates of the Kaapvaal and other cratons (De Wit 1997) illustrate that Early Archean continental crustal growth must have been 'explosive', and that only a small fraction of this crust has been preserved (Bowring & Housch 1995). Since recycling at subduction zones does not appear to have been efficient during the Early Archean, I speculate that many Early Archean continental fragments, possibly those lacking a thick buoyant mantle keel, were episodically 'flushed' whole-scale, back into the convecting mantle. Those cratons that survived, built up and/or retained thick Early Archean mantle keels. Delamination of these keels cannot, therefore, be invoked to explain subsequent Archean (and) tectonic events recorded at the surface of the cratons. The style of modern subduction-related recycling emerged during the Late Archean following gradual change to slab-pull-dominated processes at convergent margins.

Inferred secular changes in Earth's tectonic processes, are mostly based on qualitative statements concerning the relative abundance of rock associations preserved through time. There is no quantitative data that indicates an unequivocal decline in the volume of preserved komatiites, or in the maximum MgO content of ultramafic magma, from the Early Archean greenstone belts globally (De Wit & Ashwal 1997). Similarly, there may have been abundant kimberlites in the Early Archean, as indicated by detrital diamonds in the Archean basins of the Kaapvaal craton. These examples illustrate a need for greater quantitative rigour in Archean studies.

The accelerating pace of accurate geochronology can now sustain more reliable paleomagnetic studies to resolve Archean tectonic displacements, and also geochemical flux studies to track Archean reservoir systems. Together with new mapping and experimental work, particularly on mafic-ultramafic sequences, these will shed new light on Archean geodynamics.

Acknowledgements

I would like to thank Stan White and Cor Langereis for their hospitality at the Faculty of Earth Sciences of Utrecht University during my recent sabbatical leave. Spending the year amongst Utrecht University's Pilbara researchers has been stimulating. With their generosity and that of the Schürmann Foundation, as well as that of the Netherlands Organisation for Scientific Research (NWO), I was able to visit the Pilbara, and complete paleomagnetic measurements on the Barberton rocks (for which Ton van Hoof did most of the laboratory work). This note is an extract from a review paper (De Wit 1998), which I completed during my stay in Utrecht. I am thankful in particular to H. de Boorder, M. Drury, A. Kloppenburg, W. Nijman, M. van Bergen, T. van Hoof, S. van der Laan, N. Vlaar, S. White, J. Wijbrans and T. Zegers for sharing thoughts and 'borrels'; to M. Martens and M. van der Tol for Dutch survival skills; and to members of the technical staff for their help with graphics. Finally, I would like to thank H.N.A. Priem and other members of the Schürmann Foundation for inviting me to participate in the conference and a memorable dinner.

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