[American Journal of Science, Vol. 310, December, 2010, P. 1187–1209, DOI 10.2475/10.2010.01]

American Journal of Science

DECEMBER 2010

TWO TYPES OF ARCHEAN CONTINENTAL CRUST: PLUME AND PLATE TECTONICS ON EARLY EARTH

MARTIN J. VAN KRANENDONK*,**

ABSTRACT. Over 4.5 billion years, Earth has evolved from a molten ball to a cooler planet with large continental plates, but how and when continents grew and plate tectonics started remain poorly understood. In this paper, I review the evidence that 3.5 Ga continental nuclei in Australia formed as thick volcanic plateaux over hot, upwelling mantle and survived due to contemporaneous development of a thick, buoyant, unsubductable mantle root. This type of crust is distinct from, but complimentary to, high-grade gneiss terranes that formed through arc-accretion tectonics on what is envisaged as a vigorously convecting early Earth with small plates. Thus, it is proposed that two types of crust formed on early Earth, in much the same way as in modern Earth, but with distinct differences resulting from a hotter Archean mantle. A remaining question of how plate tectonics was initiated on Earth is investigated, using an analogy with Artemis Corona on Venus.

Key words: Archean, tectonics, continental crust, plumes, plates, subduction

INTRODUCTION

It has long been recognized that high-grade gneiss terranes (HGTs) and low-grade granite-greenstone terranes (GGTs) represent distinct types of Archean crust, identified on the basis of distinct rock types, structural styles, and metamorphic grade (Windley and Bridgwater, 1971). Whereas HGTs contained evidence of a horizontal tectonic regime (Bridgwater and others, 1974), GGTs were interpreted to be dominated by evidence for vertical tectonics (Macgregor, 1951; Anhaeusser, 1984; Hickman, 1984). Windley and Bridgwater (1971) suggested that the two types of crust represented different structural levels of the same crust, although alternative possible relationships include: 1) large greenstone basins formed on gneissic basement; 2) a continental margin model, whereby greenstone terrains developed adjacent to pre-existing protocontinental crust; or 3) collision, involving two unrelated segments of crust (Archibald and others, 1978; Gee and others, 1986; Campbell and Hill, 1988; Myers, 1995; Condie, 1997). More recent studies have shown that the relationship between high-grade and low-grade terrains is non-unique and may involve some, or all, of the above processes (Moser and others, 1996; Percival and others, 1997).

Debate has also focussed on whether modern-style plate tectonic (uniformitarian) processes applied to the growth of Archean continental crust—specifically, through growth in island arcs over subduction zones—or whether the tectonic style was different, dominated by vigorous mantle convection on a hotter early Earth with more buoyant crust, resulting in a more primitive form of tectonics characterized by crustal stretching, rifting and limited ocean opening, with limited sag-subduction, partial melting, and crust-mantle mixing processes (Talbot and Walton, 1973; Burke and

* Geological Survey of Western Australia, 100 Plain Street, East Perth, Western Australia 6004, Australia: e-mail: martin.vankranendonk@dmp.wa.gov.au

** Also at: School of Earth and Environment, The University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009 Australia

others, 1976; Kröner, 1981; Bickle, 1986; Hamilton, 2003, 2007a; Stern, 2005). Still others have suggested that plumes may have been less frequent on early Earth and that plate velocities may have been less than today (Korenaga, 2006, 2008a, 2008b), although the only actualistic measurement of Archean plate motions suggests rates up to 5 times faster than modern day (Strik and others, 2003; Blake and others, 2004).

More recently, tectonic models for the growth of Archean GGTs have focused almost exclusively on arc-accretion processes, dominated by evidence from the Superior Province and from models developed for the Barberton Greenstone Belt of the Kaapvaal Craton, South Africa (Card, 1990; de Wit and others, 1992; Moyen and others, 2006; Percival, 2007). Such models have been widely applied to other cratons, with a few important exceptions (Wilson and others, 1995; Chardon and others, 1998; Bédard, 2006). In places where hotspot-related volcanic successions do occur, they are commonly interpreted as either the product of mantle plume-arc interaction within a subduction-accretion framework (Wyman and others, 2002), or allochthonous slices accreted onto the margins of continental crust (Hoffman and Ranalli, 1988; Condie, 1997).

However, a major problem with continental growth solely through arc-accretion is many subduction zones include significant erosion of the over-riding plate and that, in fact, the amount of subduction-erosion is roughly equivalent to the amount of crust added through arc magmatism (Scholl and von Heune, 2007). When combined with the fact that 30 percent of modern crustal growth is through eruption of large igneous provinces—as continental flood basalts and oceanic plateaux (Coffin and Eldholm, 1993)—this leaves open the question as to the relative importance of arc-accretion versus mantle plume-dominated crustal growth over time, particularly in the Archean, when the mantle was up to 250 °C hotter and upwelling mantle plumes would have been more common and produced more voluminous magmatism (Arndt, 2003; Herzberg and others, 2007, 2010).

In this paper, I review the evidence for crust formation processes in the East Pilbara Terrane of the Pilbara Craton, Australia and in the West Greenland part of the North Atlantic Craton, and contend that these represent two different types of crust, formed over upwelling mantle and a proto-subduction zone, respectively. This conclusion is used to suggest that the tectonic style of Paleoarchean Earth was similar to modern Earth, with growth of continental crust in two distinct environments relating to plate tectonics driven by convecting mantle. Differences between Archean and modern crust are considered to be the result of differences in mantle potential temperature, size of crustal plates, thickness of oceanic lithosphere, and crustal rheology as a function of higher geothermal gradients and radioactive heat in crustal granites.

East Pilbara Terrane of the Pilbara Craton: a Volcanic Plateau

The granite-greenstone crust of the Pilbara Craton in Western Australia has been divided into five distinct tectono-stratigraphic terranes, a number of syn- to late-tectonic clastic sedimentary basins, and widespread suites of pre-, syn-, and post-tectonic granitic rocks, as described in more detail elsewhere (fig. 1: Van Kranendonk and others, 2007a).

The 3.52 to 3.23 Ga East Pilbara Terrane (EPT) is the largest, oldest terrane, forming the nucleus of the craton (fig. 2). A key feature of the EPT is a thick (up to 17 km), upward-younging stratigraphy that was deposited in three autochthonous groups collectively referred to as the Pilbara Supergroup. The Pilbara Supergroup is dominated by mafic-ultramafic volcanic rocks that are interbedded with subordinate, but locally thick, accumulations of andesitic to rhyolitic volcanic rocks and thin interflow units of dominantly chemical sedimentary rocks (mostly silicified carbonates) (Van Kranendonk, 2006; Van Kranendonk and others, 2007b). The stratigraphic base of the

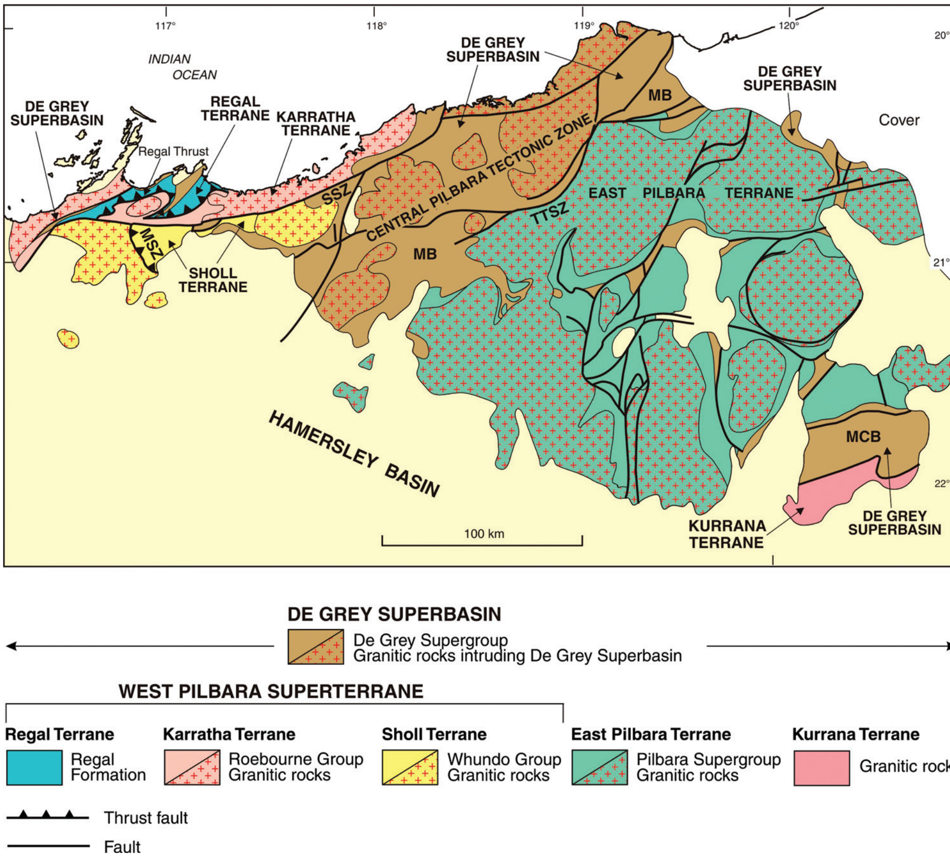

Fig. 1. Simplified geological map of the Pilbara Craton, showing terranes and major structures (from Van Kranendonk and others, 2007a). MB = Mallina basin; MCB = Mosquito Creek basin; MSZ = Maitland Shear Zone; SSZ = Sholl Shear Zone; TTSZ = Tabba Tabba Shear Zone.

two younger groups of the supergroup is marked by thick successions of mature to supermature clastic sedimentary rocks, including up to 1 km of cross-bedded quartz-rich sandstone that was derived, at least in part, through weathering and erosion of older continental basement up to 3602 Ma (Nelson, 1998; Van Kranendonk and others, 2007a). The base of the oldest group is everywhere an intrusive contact with younger granitic rocks, but data from inherited zircon, Nd-isotopic studies, and geochemical studies of granitic rocks indicate the involvement of older, at least in part, sialic, crust in the generation of even the oldest volcanic and granitic rocks (Van Kranendonk and others, 2007a; Smithies and others, 2009; Tessalina and others, 2010).

Rocks of the Pilbara Supergroup are preserved in (generally) steeply-dipping, synclinal greenstone belts that wrap around broad (average 60 km diameter), ovoid granitic domes (fig. 2: Van Kranendonk and others, 2002, 2004). The domes are composed of a variety of granitic rocks of different age and composition, ranging from 3.46 Ga tonalite-trondhjemite-granodiorite (TTG) to 2.85 Ga Sn-Ta-Li-bearing syenogranite (Van Kranendonk and others, 2007a, 2007b). Each of the domes contains a different proportion of the different age granitic suites, but all domes preserve the older components along their outer rind and successively younger components

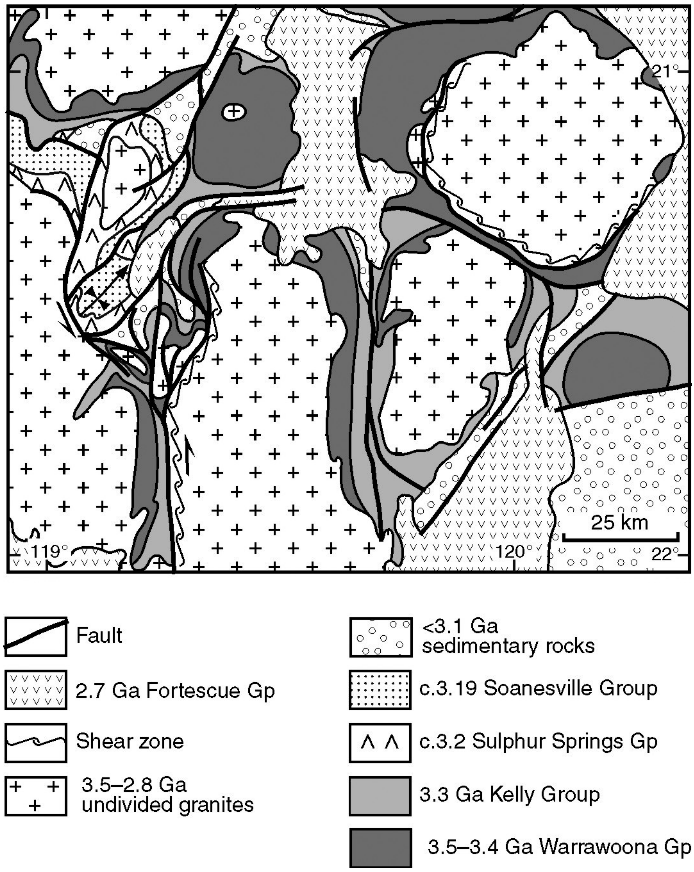

Fig. 2. Simplified geological map of the East Pilbara Terrane of the Pilbara Craton, showing the broad granite dome-and-greenstone keel architecture and distribution of the main volcano-sedimentary units.

progressively nearer to their core (Hickman, 1984; Van Kranendonk and others, 2002, 2004). An exception is the North Pole Dome, where a syn-volcanic laccolith occupies the core of moderately- to steeply-dipping greenstones (Blewett and others, 2004; Van Kranendonk and others, 2004, 2008).

The EPT has been interpreted to represent a long-lived volcanic plateau, built on a substrate of at least partly sialic older crust, analogous to the Kerguelen plateau (Van Kranendonk and Pirajno, 2004; Champion and Smithies, 2007; Van Kranendonk and others, 2007b). In these models, crust formation is interpreted to have involved melting of (dis?)continuously upwelling, hot mantle in the absence of arc-accretion tectonics to form a thick basaltic crust. Cyclical eruption, burial and partial melting of basaltic crust led to the formation of multiple generations of granitic rocks from 3.53 to 3.24 Ga and the development of thick continental lithosphere underlain by a melt-depleted, buoyant residual mantle keel (fig. 3: Champion and Smithies, 2007; Van Kranendonk and others, 2007a; Smithies and others, 2009). It was only after this crust had formed that the craton was affected by modern-style plate tectonics, including rifting at 3.2 Ga, and the subsequent generation of an intra-oceanic arc (3.12 Ga) and collisional orogeny (3.07 Ga: Smith and others, 1998; Smithies and others, 2005b; Van Kranendonk and others, 2007a, 2010).

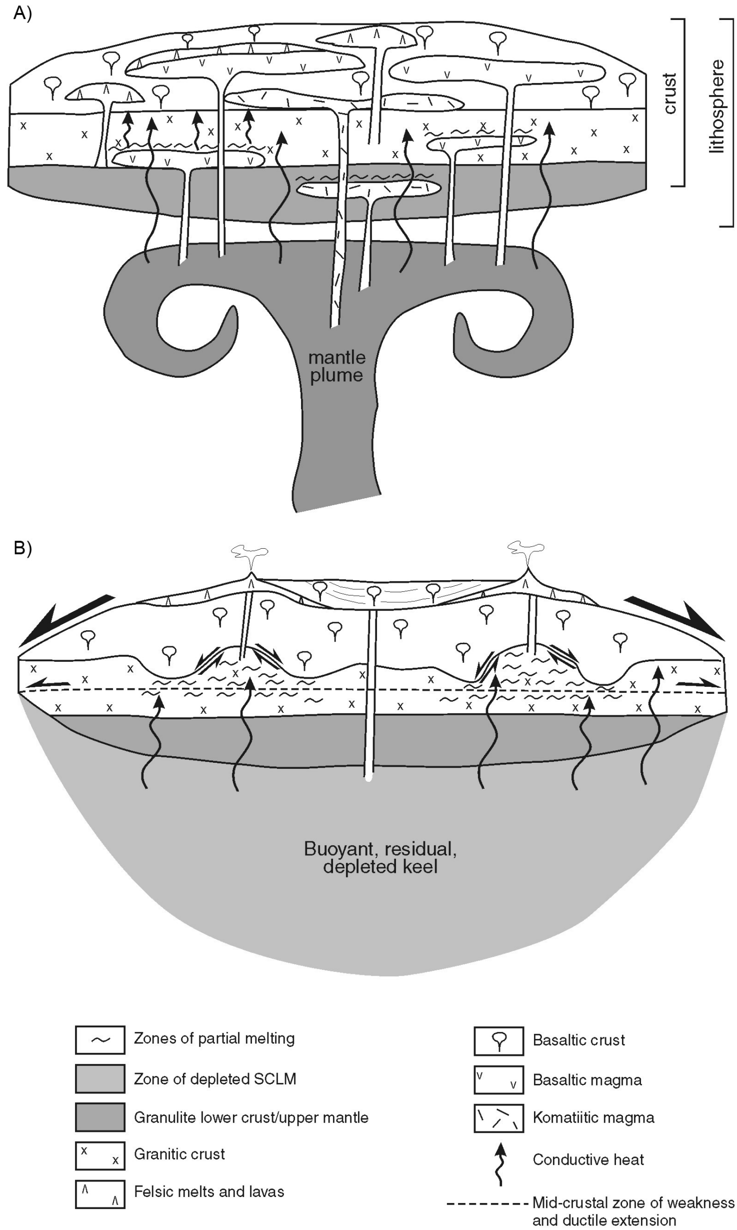

Fig. 3. Schematic model of formation of the East Pilbara Terrane as a thick oceanic plateau, resulting from multiple episodes of mantle melting, riding on a keel of highly depleted subcontinental mantle lithosphere (from Van Kranendonk and others, 2007b): (A) formation of a thick crustal plateau resulting from upwelling mantle melts, built on a substrate of older crust (x = older mafic and TTG crust; ~ = granitic partial melts; pillows = basaltic lavas; v = mafic sills; ^ = felsic magmas; fleck = ultramafic magmas); (B) magmatic overthickening results in internal melting and differentiation of the crust, extensional collapse across a mid-crustal detachment (dashed line with arrows), and the formation of dome-and-keel geometry: a buoyant, but depleted, subcontinental lithospheric keel arises from extensive mantle melting and stabilizes the craton.

Fig. 4. View of a kilometre-scale recumbent isoclinal fold from the Fiskenaesset region of West Greenland. Photograph courtesy of John Myers.

NORTH ATLANTIC CRATON: SUBDUCTION-ACCRETION TYPE CRUST

The West Greenland part of the North Atlantic Craton (NAC) consists of a "sea" of tonalitic gneisses with sparsely distributed and generally highly dismembered slivers of greenstones and layered anorthosite-gabbro intrusions (Bridgwater and others, 1974; Myers, 1984; Windley and Garde, 2009). Early researchers observed that the TTG had been emplaced as sheets into supracrustal rocks during periods of thrusting and large-scale recumbent isoclinal folding that predated, and accompanied, crustal thickening (fig. 4: Myers, 1976, 1984).

Detailed mapping and geochronology has shown that the apparently monotonous high-grade gneisses are derived from several distinct tectono-stratigraphic terranes, ranging from Eo- to Neoarchean in age and assembled during at least two main tectonic episodes in the Paleoarchean and Neoarchean (Nutman and others, 1989, 2002, 2007, 2009; Crowley and others, 2002; Hanmer and Greene, 2002). Each of the lithotectonic terranes has unique crustal histories, distinct supracrustal assemblages, and different metamorphic grade (fig. 5A: Friend and others, 1988; Nutman and others, 1989). Terranes are separated by thin mylonite zones that, together with the terranes themselves, have been affected by recumbent isoclinal folds and later upright folds associated with Neoarchean orogeny (fig. 5B). More recently, it has been discovered that even the best preserved and largest remnant of supracrustal rocks at Isua consists of two lithologically and geochronologically distinct packages, each of which is intruded by TTG of different age and separated by a thin zone of mylonitic metasedimentary rocks (Nutman and others, 2002, 2009).

TESTS OF THE MODEL

If the two types of crust described above actually derive from distinct tectonic processes, as suggested, then they should contain unique features that match a set of predictive criteria derived from the tectonic models. Specifically, each type of crust should have distinctive types, compositions, and isotopic characteristics of supracrustal rocks, geochemical signatures of granitic rocks, structural styles, metamorphism, and composition of the sub-continental mantle lithosphere. Each of these criteria is assessed individually below.

Supracrustal Sequences

Supracrustal successions in plateau-type crust are predicted to consist predominantly of mantle-derived melts, which may show evidence of crustal contamination but

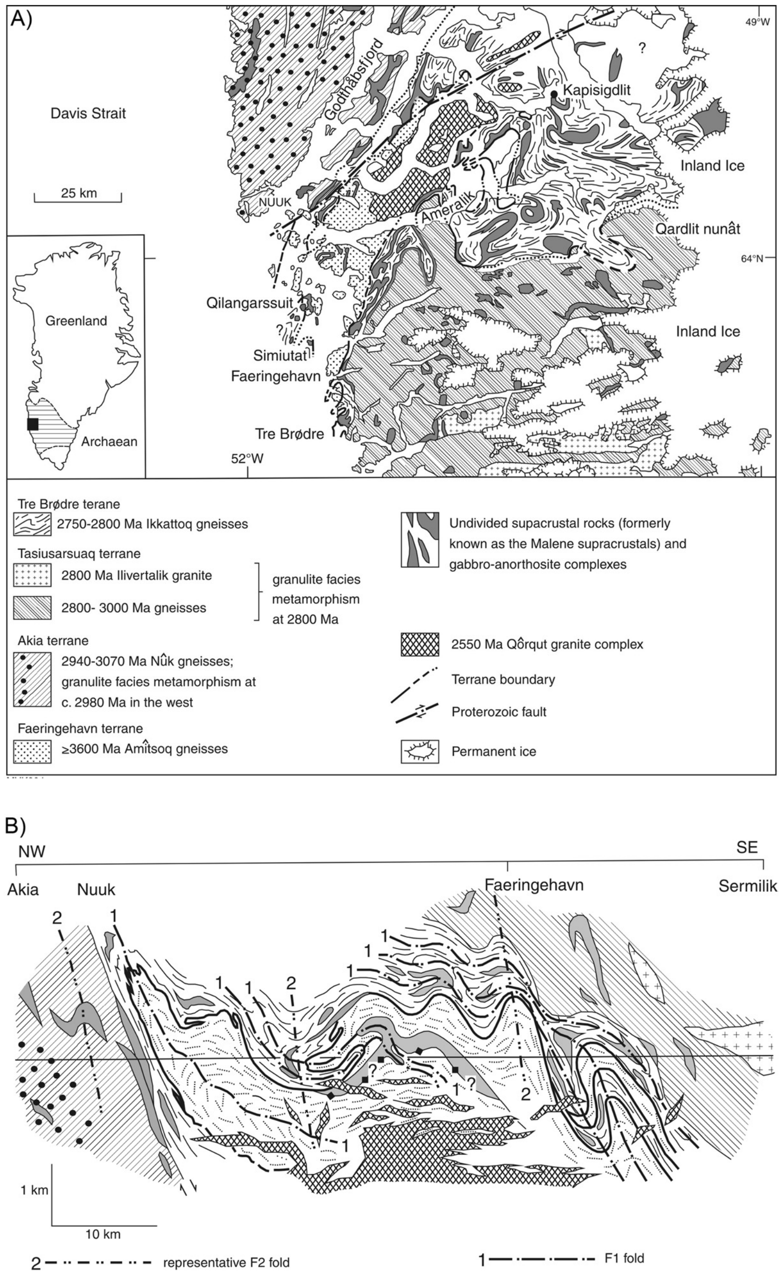

Fig. 5. (A) Geological map of part of the North Atlantic Craton in West Greenland, showing the division of high-grade gneisses into distinct litho-tectonic terranes. (B) Cross-section through the West Greenland terranes, showing large-scale thrusting and recumbent isoclinal folding formed during late Archean terrane amalgamation (Reproduced from Fig. 1 of Nutman and others (1989) with permission of American Geophysical Union).

contain no evidence of a subduction-modified mantle source. These rocks are also predicted to show autochthonous relationships, and they may contain stable platform successions. Crust formed through subduction-accretion processes, on the other hand, is predicted to contain supracrustal rocks that show evidence for allochthonous relationships between packages with different ages, contain deep marine sedimentary rocks, and have geochemical evidence for derivation of volcanic rocks from a variety of sources, including slices of MORB and basaltic and/or andesitic to rhyolitic volcanics derived from a subduction-modified source (for example, arc and/or suprasubduction zone sequences). Upper crustal sections may also contain ophiolites and syn-orogenic clastic successions, such as turbiditic accretionary complexes, foreland basins, *et cetera.*

Analysis of EPT supracrustal rocks shows that they are demonstrably autochthonous and consist of predominantly mantle-derived volcanic rocks interbedded with deep-marine chemical sedimentary rocks. The succession also includes thick (up to 1 km) units of mature and supermature clastic sedimentary rocks that locally form part of a subaerial to submarine platform succession (Van Kranendonk, 2007b). Geochemical analysis shows that the bulk of the volcanic rocks are typical Archean tholeiitic to komatiitic basalts, with lesser amounts of komatiite (Smithies and others, 2007). The bulk of these rocks, regardless of stratigraphic position, are similar to plateau-like basalts and are distinct from MORB in having slightly elevated light rare earth element profiles and evidence for crustal contamination, but they contain no evidence of derivation from a subduction-modified source (Green and others, 2000; Arndt and others, 2001; Van Kranendonk and Pirajno, 2004; Smithies and others, 2005a). Data from inherited zircon and Nd-isotopic studies indicate the involvement of older, at least in part sialic, crust in the generation of even the oldest volcanics (Van Kranendonk and others, 2007a; Tessalina and others, 2010). Basaltic rocks from throughout the supergroup, interbedded at a scale of meters to 100s of meters, show geochemical evidence of derivation from two distinct sources including continually replenished, fertile mantle, and a mantle source region that became progressively more depleted over time (Smithies and others, 2005a). Calc-alkaline andesitic to rhyolitic volcanic sequences in the lower part of the succession were derived from fractionation of tholeiitic magma affected by contamination by older felsic crust, as well as by coeval TTG magmas derived from melting of older, enriched basalts at a range of depths within the crust (Champion and Smithies, 2007; Smithies and others, 2009). Felsic volcanic units higher up in the succession were derived from partial melting of older felsic crust and/or basalt (Jahn and others, 1981; Smithies and others, 2007).

Supracrustal rocks in the subduction-accretion type crust of the North Atlantic Craton include deep-marine banded iron-formation and basaltic rocks with MORB-like compositions, as well as boninitic geochemical signatures, the latter of which has been used to suggest formation in an intra-oceanic arc setting (Polat and others, 2002; Jenner and others, 2009). Furnes and others (2007a, 2007b) have suggested that the Isua supracrustal rocks include components of an ophiolite, although this is controversial (Nutman and Friend, 2007; Hamilton, 2007b). Nevertheless, an oceanic setting for at least some of the basaltic rocks is strongly supported by the widespread distribution of dismembered, layered calcic anorthositic complexes, which are considered to be part of oceanic crust (Weaver and others, 1981). In addition to the evidence for oceanic-type crust, Nutman and others (2009) have recognized juvenile arc-type volcanic rocks. In summary, the presence of MORB-like and boninitic mafic volcanic rocks, combined with juvenile arc-type volcanic rocks, is fully consistent with an arc-accretion setting for the formation of the North Atlantic Craton.

Granitic Rocks

Grantic rocks in subduction-accretion type crust are predicted to consist largely of subduction-derived TTG, derived from high-pressure melting of basalt and emplaced

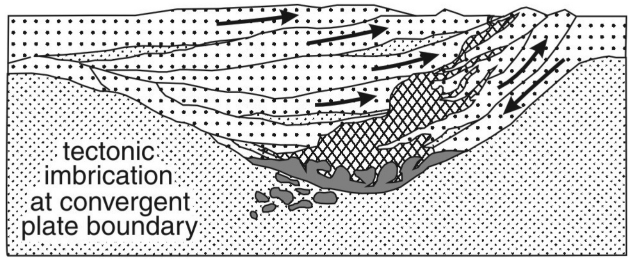

Fig. 6. Schematic model of shallow subduction/crustal imbrication in the formation of the West Greenland crust. Heavy stipple = undivided mafic crust; medium stipple = mantle and peridotite entrained in the crust; hachured pattern = TTG; grey shade = melted zone rich in residual garnet and clinopyroxene; arrows denote direction of tectonic transport. (Modified slightly from Fig. 3.3-13 of Nutman and others (2007) with permission of Elsevier).

prior to, and synchronous with, collision. A more limited amount of syn- to late-orogenic, potassic granites are also expected as a result of TTG melting during crustal thickening, which may be emplaced across terrane boundaries. Plateau-type crust, on the other hand, is predicted to consist of granitic rocks derived from infracrustal melting processes, first of basaltic crust, and subsequently of basalt and granitic rocks, and then granitic rocks only, as the crust progressively differentiates through multiple melting episodes. This process should result in progressively more highly fractionated granites through time.

Detailed investigations of granitic rocks from the NAC have shown them to be predominantly TTG in composition and derived from melting of basalt at subcrustal depths, most likely within some form of subduction zone (Drummond and Defant, 1990; Rapp and others, 1991). Geochronological evidence shows that whereas some TTG components were emplaced prior to terrane amalgamation, the bulk of TTG were emplaced during thrusting and recumbent isoclinal folding (fig. 6: Myers, 1976, 1984; Nutman and others, 1989, 1999, 2002). Limited volumes of more potassic granitic rocks accompanied episodes of crustal reworking and crosscut terrane boundaries (fig. 5B: Baadsgaard and others, 1986; Nutman and others, 1989).

In the EPT, granitic rocks accompanied periods of mafic-ultramafic through felsic volcanism and show a demonstrable, progressive change in composition through time, from TTG to more potassic compositions (Hickman, 1984; Bickle and others, 1989, 1993). Detailed geochemical studies show that the earliest syn-volcanic TTG (3.49-3.42 Ga) derive from infracrustal partial melting of LREE-enriched basalt + older TTG, rather than high-pressure melting of basalt (Bickle and others, 1993; Smithies and others, 2009), and that both these older, as well as younger TTG (3.32-3.22 Ga), derive from melting across a range of depths *within* the crust (Champion and Smithies, 2007). Younger granites evolve to progressively more fractionated compositions through time (including A-type granites with rapakivi textures at 3.24 Ga: Brauhart, ms, 1999; Van Kranendonk, 2000) as a result of repeated partial melting of older granitic crust (Smithies and others, 2003). The different age granitic suites of the EPT are similar across the different domes, even though the proportions of the suites differ between the domes (Van Kranendonk and others, 2002). Combined, these observations show that granite genesis in the EPT resulted from infracrustal processes, derived ultimately from heat emanating from the mantle, without the influence of subduction-accretion processes.

Structural Geology

Perhaps the most distinctive difference between the two types of crust should be manifest in their structural style, with subduction-accretion type crust dominated by evidence for strong horizontal shortening, and plateau-type crust affected by—if anything—evidence for extension *during* crust formation and compressional deformation *after* crust formation.

The North Atlantic Craton contains widespread evidence for very large-scale horizontal translation of crust, exemplified by the presence of kilometer-scale recumbent isoclinal folds (fig. 4: Myers, 1984). Whereas some have postulated that flat-lying structures such as these may arise from the vertical collapse of weak crust (for example, Sandiford, 1989; Harris and others, 2002; Bédard, 2006), this process does not account for the presence of litho-tectonic terranes, nor the widespread and voluminous presence of syn-tectonic, juvenile TTG: rather, any syn-tectonic granitic rocks that arise as a result of collapse of weak crust should be more potassic in composition and derive from remelting of the weakened, older continental crust.

In the EPT, the structural style is dominated by the large-scale granite dome-and-greenstone keel geometry, which has been well documented as having arisen through punctuated intervals of partial convective overturn (PCO) between a newly erupted, thick, dense greenstone cover sequence and partially molten, more buoyant, granitic middle crust, driven by a combination of conductive heat from mantle plumes, radiogenic heat from early TTG, and the thermal insulating effects of the newly erupted greenstones (fig. 7: Hickman, 1984; Collins, 1989; Collins and others, 1998; Rey and others, 2003; Sandiford and others, 2004; Van Kranendonk and others, 2004; Bodorkos and Sandiford, 2006). Whereas previous studies suggested an earlier episode of Alpine-style crustal thickening (Bickle and others, 1985) followed by dome formation as extensional core complexes (Zegers and others, 1996, 2001), more detailed mapping has shown that the former resulted from *local* compression within the restraining bend of a late (c. 2.94 Ga) transpressional shear zone and the latter to be a false construct resulting from incomplete mapping (Hickman and Van Kranendonk, 2004; Van Kranendonk and others, 2004). Rather, geochronological and stratigraphic studies have shown that the greenstones are everywhere the right way up, upward-younging, and at low metamorphic grade, thereby precluding tectonic stacking through horizontal tectonics (Van Kranendonk and others, 2007a, 2007b). Indeed, studies have now shown that deposition of the volcano-sedimentary succession was accommodated by extension in developing basins with lateral accumulation of the supracrustal succession as a series of off-lapping units (Nijman and others, 1998; Nijman and deVries, 2004; Van Kranendonk and others, 2004, 2008). It is only well after the crust of the EPT had formed (3.52-3.22 Ga) that it then experienced plate tectonics, including rifting at 3.2 Ga and much younger compressional deformation resulting from terrane accretion and far-field stresses at 3.07 to 2.93 Ga (Van Kranendonk and others, 2007a, 2010).

Metamorphism

Acrreting margins and collisional orogens are marked by high-pressure (P), low- to moderate-temperature (T), clockwise P-T paths and may contain terranes with different P-T conditions and histories, whereas terranes undergoing extension are characterized by low-P, high-T, anticlockwise P-T paths (England and Thompson, 1984; Thompson, 1989).

The characteristic hallmarks of subduction-accretion are found in the metamorphic history of the NAC, including rock with granulite-facies assemblages and clockwise P-T paths (Wells, 1979; Griffin and others, 1980; Riciputi and others, 1990), as well as tectonically juxtaposed litho-tectonic terranes that have different metamorphic assemblages and histories (Nutman and others, 1989). Estimated P-T conditions from granulite terranes indicate that the crust had been buried to 30 km depth during what has been widely interpreted as a period of crustal doubling through orogeny (Myers, 1976, 1984; Windley and Garde, 2009).

In contrast, the EPT is characterised by low-P, contact-style metamorphism, with isograds distributed concentrically around the large granite domes and varying from high-temperature (amphibolite facies) adjacent to the domes to low grade away from the domes (to prehnite-pumpellyite facies: Hickman, 1984). Ar-Ar dating of the contact metamorphic aureole around the Shaw Granitic Complex shows that the assemblages formed throughout the entire history of the terrane, over hundreds of millions of years (3.49-2.72 Ga: Zegers and others, 1999). When combined with the stratigraphic evidence of offlapping supracrustal successions, the contact-style distribution of assemblages, regional low pressure metamorphic conditions, and long duration of mineral assemblage formation, they indicate that metamorphism resulted from heat emanating from granite domes during episodes of PCO (fig. 7: Warren and Ellis, 1996; Collins and Van Kranendonk, 1999; Van Kranendonk and others, 2002, 2004). Local conditions of moderate-P metamorphism (4-6 kbars; Bickle and others, 1985; Delor and others, 1991) are restricted to the uplifted, strongly sheared margins of granite domes and are consistent with models of PCO (Mareschal and West, 1980; Collins and Van Kranendonk, 1999; Van Kranendonk and others, 2004).

SCLM

Another testable prediction is that the proposed different types of Archean crust should contain recognizable differences in their respective pieces of attached subcontinental mantle lithosphere (SCLM). For terranes formed through subduction-accretion, it is predicted that the crust should be underlain by imbricated oceanic lithosphere, metamorphosed to high metamorphic grade (eclogite), and potentially depleted in melt components (for example, Helmstaedt and Gurney, 1995). In contrast, Pilbara plateau-like crust should be underlain by extremely depleted subcontinental mantle lithosphere, with evidence for depletion through episodes of relatively deep mantle melting (for example, Griffin and O'Reilly, 2007a).

Indeed, there is some evidence to support such differences in the SCLM beneath these two types of crust, although more research into these differences is required. On the one hand, Pilbara plateau-like crust is principally underlain by depleted harzburgite, widely regarded as the product of melt depletion of normal mantle, down to considerable depths (Griffin and O'Reilly, 2007a, 2007b). Geochemical data from Pilbara Supergroup basaltic rocks suggest that this buoyant, highly depleted harzburgite keel developed contemporaneously with crust formation, progressively over time, as a result of multiple episodes of plume-derived mafic-ultramafic magmatism (Smithies and others, 2005a; Van Kranendonk and others, 2007b).

On the other hand, mantle samples from kimberlitic rocks cutting through the undisturbed portion of the North Atlantic Craton indicate a less orthopyroxene-rich composition with a mix of peridotitic and eclogitic garnets (Jensen and others, 2005; Wittig and others, 2008a). Significantly, the bulk of SCLM in the North Atlantic Craton was derived through shallow melting events, through processes similar to present-day mechanisms that form young lithosphere in oceanic settings (Wittig and others, 2008b) and distinct from the deep mantle melting events identified in plateau-like crust.

DISCUSSION

Earth was a molten ball at 4.5 Ga, after the giant Moon-forming impact event, and was covered by an initial crust within a few tens to a couple of hundred million years thereafter (for example, Blichert-Toft and Arndt, 1999; Kamber, 2007; Kramers, 2007). Oceans were formed by at least 4.3 Ga (Cavosie and others, 2005) and the early crust was recycled back into the mantle, and continuously resurfaced throughout the period of late heavy meteorite bombardment to ~3.85 Ga, after which time the first large areas of continental crust became preserved (Nutman and others, 1999; Van Kranen-

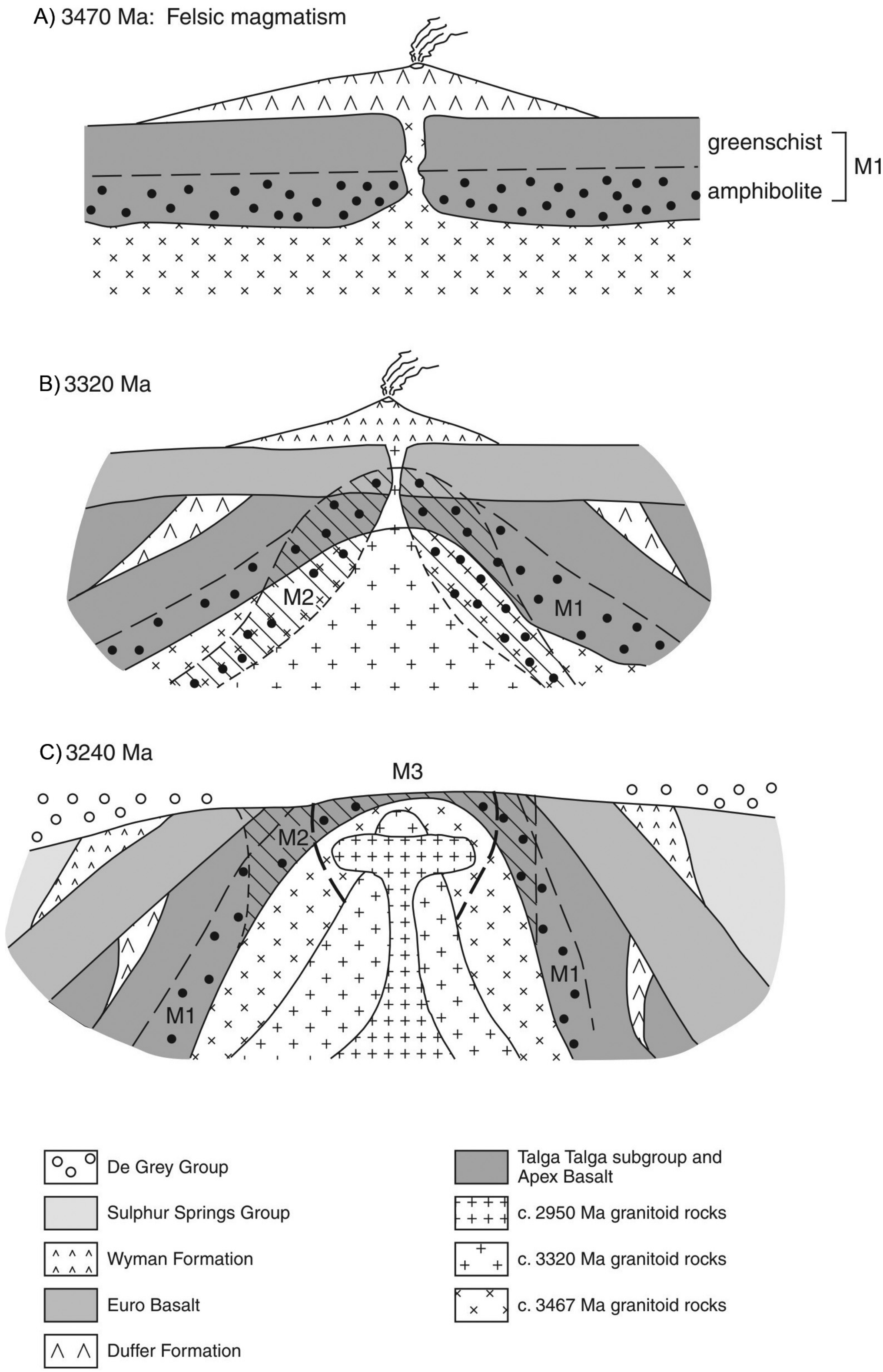
A) 3470 Ma: Felsic magmatism
greenschist
amphibolite
M1
B) 3320 Ma
M2
M1
C) 3240 Ma
M3
M2
M1
M1
De Grey Group
Sulphur Springs Group
Wyman Formation
Euro Basalt
Duffer Formation
Talga Talga subgroup and Apex Basalt
c. 2950 Ma granitoid rocks
c. 3320 Ma granitoid rocks
c. 3467 Ma granitoid rocks

Fig. 7.

donk, 2007). From 3.85 Ga to present day, Earth has undergone a dramatic secular change in mantle heat (for example, Labrosse and Jaupart, 2007; Herzberg and others, 2010) and was accompanied by resultant changes in the tectonic style and composition of continental lithosphere (for example, Rey and others, 2003; Griffin and O'Reilly, 2007a; Chardon and others, 2009), although exactly what types of change this involved in terms of plate tectonics is still uncertain (for example, de Wit and Hart, 1993; Korenaga, 2006, 2008a, 2008b).

The model presented here suggests that, as with modern Earth, continental crust was formed on early Earth through two distinct, but complementary processes:

1. As thick plateaux over upwelling mantle;
2. At subduction zones, through arc magmatism and terrane accretion.

These two end-member processes support the operation of plate tectonics on an early Earth with a vigorously convecting mantle (for example, Park, 1997). If correct, and plate tectonics operated throughout most of Earth history, then a predictive consequence of the model is that these two types of crust should be present throughout the geological record. And indeed, a number of published examples support the formation of plateau- and subduction-accretion-type crust throughout the geological record. For example, in addition to the Paleoarchean Pilbara Craton cited above, examples of plume-generated, plateau-like crust include Mesoarchean crust in the Baltic Shield and Superior Craton (Puchtel and others, 1998; Bédard, 2006), Neoarchean crust in several greenstone belts (for example, Tomlinson and Condie, 2001), Paleoproterozoic crust in the Man Craton, West Africa (Abouchami and others, 1990), and the Phanerozoic Kerguelen and Ontong-Java plateaux (Grégoire and others, 1998; Wallace and others, 2002; Taylor, 2006). Amongst the multitude of Precambrian examples of crust formed through subduction-accretion processes are the Neoarchean development of the Superior Craton (for example Card, 1990; Calvert and others, 1995) and the Paleoproterozoic Trans-Hudson Orogen (for example, Stern and others, 1999) and Fenno-Scandian Shield (Peltonen and Kontinen, 2004). In addition, a plate tectonic/convecting mantle model of early Earth also predicts that there will be hybrid examples of these two end-member crust-forming processes, with plumes erupted onto older continental crust (for example, Bleeker and others, 1999; Polat and others, 2006; Maurice and others, 2009) and accretion of plateau-like crust within subduction-accretion complexes (for example, Polat and others, 1998; Percival, 2007). These examples of diverse and interactive ways of forming Archean continental crust show that each terrane (regardless of age) must be analyzed purely on the basis of its unique geological record and that it is time to abandon the simplistic and polarising debate on whether or not plate tectonics existed on Archean Earth (for example, Stern, 2005; Hamilton, 2007a) and focus instead on the rate of crustal growth (see Hawkesworth and others, 2010), the *relative contribution* of plume *versus* plate tectonics to crust formation, and how these different, but related, processes may influence the prospectivity of Archean continental crust.

How Did Subduction Start?

Two remaining questions in regard to early Earth tectonics are; When and how did plate tectonics start? The answer to the first question may remain unknown due to the paucity of the very early geological record, and the answer to the second question

Fig. 7. Schematic model showing stages in the development of partial convective overturn of the upper and middle crust in the East Pilbara Terrane. Note the internal unconformities between groups, associated with progressive doming and extensional basin formation, and the contact metamorphic aureole around granite domes, arising from multiple, overprinting heating events (M1, M2, M3) associated with episodes of granite emplacement. (Modified from Van Kranendonk and others, 2002).

will rely heavily on the results of increasingly more sophisticated modeling, but this will only succeed to the degree that we understand the physical properties of early Earth (mantle temperature, crustal composition and thickness) and the 4-dimensional geometry-through-time of interacting components of a convecting planetary system.

Previous workers have proposed a number of scenarios for how plate tectonics may have been initiated on early Earth:

1) Davies (1992) suggested that tectonics on early Earth was achieved through subcrustal delamination or dripping, whereby crust forms either by thrust accumulation of basalt slices over asymmetrically subducting oceanic mantle lithosphere, or by the same mechanism over symmetrically downgoing zones, or drips;
2) Hansen (2007a) postulated that subduction commenced as a result of bolide impact, resulting in mantle upwelling and generation of mafic crust, in turn leading to spreading and subduction;
3) Ueda and others (2008) used numerical models to show that subduction can be generated by mantle plumes if they cause critical weakening of the lithosphere;
4) Nair and Chacko (2008) suggested that the formation of thick, buoyant oceanic plateaux in the Archean helped to initiate subduction of normal oceanic lithosphere around the margins of the plateaux, which generated voluminous TTG magmas through hydrous partial melting of the subducted slab.

None of these models are satisfactory on their own. Model 1 does not provide mechanisms for the initiation of subduction and it is difficult to imagine how bolide impacts in model 2 could initiate a planet-wide, self-organized system of subduction. Models 3 and 4 contain aspects of interest, although the latter does not accord with the Pilbara and Kaapvaal record of TTG magmatism *accompanying* plateau formation and deriving from a range of depths *within* the crust (Champion and Smithies, 2007).

Previous authors have commented on the difficulty (but not impossibility) of subduction on early Earth, due to the effects of a hotter Archean mantle producing young, thick, and thermally buoyant oceanic lithosphere (Bickle, 1978; Sleep and Windley, 1982; Park, 1997; Davaille and others, 2003; Korenaga, 2006, 2008a, 2008b). Hot upwelling mantle, regardless of the temperature, speed of convection, or size of convection cells, results in either thickening of the crust on a dry planet incapable of plate tectonics, and/or spreading of oceanic lithosphere on a planet lubricated by water (for example, Abbott and Hoffman, 1984). In the latter case, newly formed oceanic crust would necessarily be recycled at zones of intra-oceanic imbrication and subduction, but it may be that a thick, thermally buoyant oceanic lithosphere was able to return to the mantle only in a shallow manner, more akin to underthrusting than modern, steep subduction, with resultant changes in magma composition relative to modern subduction zones (Davies, 1992; Smithies and others, 2003; Martin and others, 2005).

Perhaps the way to overcome the problem of subduction initiation on a planet with a thick, buoyant, oceanic crust is through the influence of large plumes, which perturb the situation and impose a distinctive 3-dimensional geometry to the surface. Studies of our neighboring planets show the dramatic influence that plumes can have on a stationary crust. For example, on Mars, stationary, long-lived mantle melting has produced an enormously thick, elevated crustal welt—the Tharsis Rise—on which Olympus Mons, the largest volcano in the solar system (8 km high) is perched (Smith and others, 1999). The weight of this crustal welt has resulted in a >5000 km diameter set of radiating dikes and the 8 km deep Valles Marineris rift valley (Mège, 2001). On Venus, plume magmatism has also resulted in the creation of thick crust at a range of

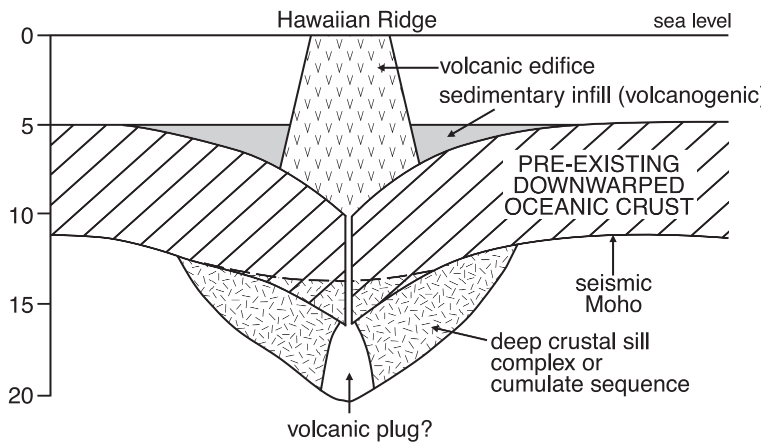

Fig. 8. Schematic model of the crustal structure of the Hawaiian-Emperor chain near the island of Oahu (from Wilson, 1989, after Fig. 6 of Watts and others, 1985).

scales, from tens of kilometers in diameter to elevated crustal welts comprising several merged coronae, 1000s of kilometres long (Squyres and others, 1992).

On Earth, the products of such long-lived plume events have generally been dispersed as a result of its moving plates, but plume-derived crustal welts such as Hawaii and Iceland still influence the lithosphere on which they are constructed, deflecting them downwards (fig. 8: Watts and others, 1985). With less mobile crust in the early Archean, and with increased degrees of partial melting from hotter mantle plumes, plume-derived magmatic welts may have been much larger, similar to Artemis Corona on Venus (fig. 9A: Hansen, 2002, 2007b; Bannister, ms, 2006).

In fact, the geometry of Artemis Corona provides a potentially important analogue to how more modern subduction may have commenced on Earth. Artemis Corona is a 1500 km diameter, nearly circular topographic high, formed by melting of deep upwelling mantle and voluminous basaltic eruption (Smrekar and Stofan, 1999). It is encircled by a deep trough and outer rise, and transected by a central rift valley, complete with transform faults (figs. 9B and 9C). Although several different processes have been suggested for the formation of Artemis Corona (Spencer, 2001; Bannister, ms, 2006; Hansen, 2007a), its geometry suggests that it most likely resulted from emplacement, inflation, overflow and extensional collapse of a thick magmatic welt derived from melting of an upwelling mantle plume; such features are common to large plume-derived upwellings (for example, Bailey, 1999; Mège and Ernst, 2001). In this model, continued magmatism led to over-inflation of the corona, and this, combined with conductive heat from the plume, led to gravitational collapse and spreading of its central part (Mège and Ernst, 2001; Rey and others, 2001). The weight of the erupting plume-derived magmatic welt deflected the surrounding crust (lower plate) downward, which is partly compensated for by an outer forebulge (fig. 9C). The geometry displayed by Artemis Corona is nearly identical to that of tectonic plates, spreading centers and subduction zones on Earth, but because the lack of water on Venus severely restricts the degree to which rocks can slide past one another, full-scale plate tectonics never really got going on our sister planet, despite its local inception (Schubert and Sandwell, 1995). On early Earth, however, where it is clear from oxygen isotope studies that water was present since 4.3 Ga (Mojzsis and others, 2001; Peck and others, 2001; Valley and others, 2002; Cavosie and others, 2005), the hydrous alteration and concomitant decrease in rheology of erupted basaltic and ultramafic oceanic crust

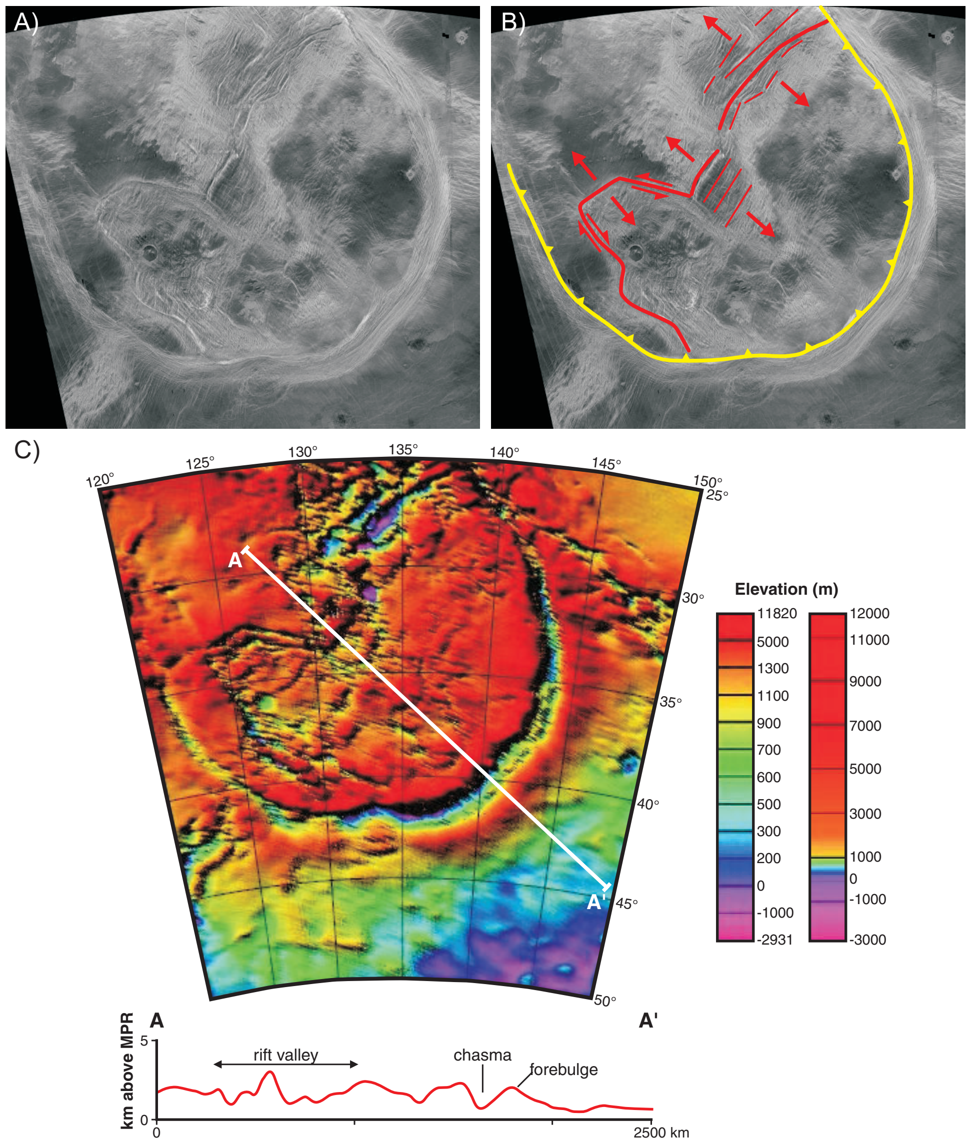

Fig. 9. (A) Synthetic aperture radar (SAR) image of Artemis corona on Venus, diameter 1500 km. (B) Annotated SAR image of Artemis Corona, showing central rift valley (heavy red lines, with symmetrical arrows) and linking transform faults (asymmetric red arrows), possible subduction zone on the inner ring of annular trough (yellow line with teeth on upper plate side). (C) Topographic map and cross-section A-A′ of Artemis Corona, showing central rift valley, annular trough (chasma) and outer forebulge. MPR = mean planetary radius. (Modified from Bannister, ms, 2006).

means that under similar conditions as on Venus, the formation of large coronae on Earth may have led to the onset of plate tectonics through the generation of subduction zones along the margins of coronae, lubricated by surface water oceans. The onset of steep subduction would then have generated superposed, arc-like crust along the margins of the plateaux (Smithies and others, 2005b; Nair and Chacko, 2008).

Conclusions

Evidence is presented in support of the contention that Paleoarchean continental crust consists of two distinct types; high-grade gneiss terranes that formed within primitive subduction-accretion zones, and volcanic plateau-type crust that formed over upwelling mantle. Support for two distinct types of crust comes from analysis of supracrustal assemblages, the geochemistry of igneous rock associations, structural geology, metamorphism, and composition of the subcontinental mantle lithosphere. Examples of both types of crust are found throughout the geological record, and the predicted hybrid types of crust resulting from the interaction of these two processes are referred to. The results are used to infer the operation of subduction and plate tectonics on Earth since at least 3.6 Ga and to develop a model for how plate tectonics may have been initiated on early Earth.

Acknowledgments

It is with great pleasure that I acknowledge the great influence that Alfred Kröner has had on my career, through his stimulating books on Precambrian tectonics and papers on South African geology. His global interests and unrivalled enthusiasm continue to inspire. Special thanks to Vicki Hansen for an illuminating introduction to Venus and to John Myers for providing me with the photograph for figure 4 and for much stimulus over the years. Reviews by Jean Bédard, Kent Condie, and an anonymous reviewer helped significantly improve the manuscript. Susanne Dowsett and Dellys Sutton drafted the figures. This paper is published with permission of the Executive Director, Geological Survey of Western Australia.

References

Abbott, D. H., and Hoffman, S. E., 1984, Archaean plate tectonics revisited 1. Heat flow, spreading rate, and the age of subducting oceanic lithosphere and their effects on the origin and evolution of continents: Tectonics, v. 3, p. 429–448, doi:10.1029/TC003i004p00429.

Abouchami, W., Boher, M., Michard, A., and Albarede, F., 1990, A major 2.1 Ga event of mafic magmatism in West Africa: An early stage of crustal accretion: Journal of Geophysical Research, v. 95, B11, p. 17,605–17,629, doi:10.1029/JB095iB11p17605.

Anhaeusser, C. R., 1984, Structural elements of Archaean granite-greenstone terranes as exemplified by the Barberton Mountain Land, southern Africa, *in* Kröner, A., and Greiling, R., editors, Precambrian Tectonics Illustrated: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, p. 57–78.

Archibald, N. J., Bettenay, L. F., Binns, R. A., Groves, D. I., and Gunthorpe, R. J., 1978, The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia: Precambrian Research, v. 6, p. 103–131, doi:10.1016/0301-9268(78)90008-6.

Arndt, N., 2003, Komatiites, kimberlites, and boninites: Journal of Geophysical Research, v. 108 (B6), 2293, p. ECV 5-1–5-11, doi:10.1029/2002JB002157.

Arndt, N., Bruzak, G., and Reischmann, T., 2001, The oldest continental and oceanic plateaus: Geochemistry of basalts and komatiites of the Pilbara Craton, Australia, *in* Ernst, R. E. and Buchan, K. L., editors, Mantle Plumes: Their identification through time: Geological Society of America, Special Paper 352, p. 359–387, doi:10.1130/0-8137-2352-3.359.

Baadsgaard, H., Nutman, A. P., and Bridgwater, D., 1986, Geochronology and isotopic variation of the early Archaean Amitsoq gneisses of the Isukasia area, southern West Greenland: Geochimica et Cosmochimica Acta, v. 50, p. 2173–2183, doi:10.1016/0016-7037(86)90072-4.

Bailey, R. C., 1999, Gravity-driven continental overflow and Archaean tectonics: Nature, v. 398, p. 413–415, doi:10.1038/18866.

Bannister, R., ms, 2006, Geologic analysis of deformation in the interior of Artemis (Venus, 34°S, 132°E): Duluth, Minnesota, M.Sc. Thesis, University of Minnesota, M.Sc. Thesis, 83 p.

Bédard, J., 2006, A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle: Geochimica and Cosmochimica Acta, v. 70, p. 1188–1214, doi: 10.1016/j.gca.2005.11.008.

Bickle, M. J., 1978, Heat loss from the Earth: A constrain on Archaean tectonics from the relation between geothermal gradients and the rate of plate production: Earth and Planetary Science Letters, v. 40, p. 301–315, doi:10.1016/0012-821X(78)90155-3.

——— 1986, Implications of melting for stabilisation of the lithosphere and heat loss in the Archaean: Earth and Planetary Science Letters, v. 8, p. 314–324, doi:10.1016/0012-821X(86)90113-5.

Bickle, M. J., Morant, P., Bettenay, L. F., Boulter, C. A., Blake, T. S., and Groves, D. I., 1985, Archaean tectonics of the Shaw Batholith, Pilbara Block, Western Australia: structural and metamorphic tests of the batholith concept, *in* Ayers, L. D., Thurston, P. C., Card, K. D., and Weber, W., editors, Evolution of Archean Supracrustal Sequences: Geological Association of Canada, Special Paper 28, p. 325–341.

Bickle, M. J., Bettenay, L. F., Chapman, H. J, Groves, D. I., McNaughton, N. J., Campbell, I. H., and de Laeter, J. R., 1989, The age and origin of younger granitic plutons in the Archean of the Pilbara Block, Western Australia: Contributions to Mineralogy and Petrology, v. 101, p. 361–376, doi: 10.1007/BF00375320.

——— 1993, Origin of the 3500–3300 Ma calc-alkaline rocks in the Pilbara Archaean: isotopic and geochemical constraints from the Shaw Batholith: Precambrian Research, v. 60, p. 117–149, doi:10.1016/0301-9268(93)90047-6.

Blake, T. S., Buick, R., Brown, S. J. A., and Barley, M. E., 2004, Geochronology of a Late Archaean flood basalt province in the Pilbara Craton, Australia: constraints on basin evolution, volcanic and sedimentary accumulation, and continental drift rates: Precambrian Research, v. 133, p. 143–173, doi:10.1016/j.precamres.2004.03.012.

Bleeker, W., Ketchum, J. W. F., Jackson, V. A., and Villeneuve, M. E., 1999, The Central Slave Basement Complex; Part I: Its structural topology and autochthonous cover: Canadian Journal of Earth Sciences, v. 36, p. 1083–1109, doi:10.1139/cjes-36-7-1083.

Blewett, R. S., Shevchenko, S., and Bell, B., 2004, The North Pole Dome: a non-diapiric dome in the Archaean Pilbara Craton, Western Australia: Precambrian Research, v. 133, p. 105–120, doi:10.1016/j.precamres.2004.04.002.

Blichert-Toft, J., and Arndt, N. T., 1999, Hf isotope compositions of komatiites: Earth and Planetary Science Letters, v. 171, p. 439–451, doi:10.1016/S0012-821X(99)00151-X.

Bodorkos, S., and Sandiford, M., 2006, Thermal and mechanical controls on the evolution of Archean crustal deformation: Examples from Western Australia, *in* Benn, K., Mareschal, J.-M., and Condie, K., editors, Archean Geodynamics and Environments: American Geophysical Union, Geophysical Monograph Series, v. 164, p. 131–147.

Brauhart, C., ms, 1999, Regional alteration systems associated with Archean volcanogenic massive sulphide deposits at Panorama, Pilbara, Western Australia: Perth, University of Western Australia, Unpublished Ph. D. Thesis, 194 p.

Bridgwater, D., McGregor, V. R., and Myers, J. S., 1974, A horizontal tectonic regime in the Archaean of Greenland and its implications for early crustal thickening: Precambrian Research, v. 1, p. 179–197, doi:10.1016/0301-9268(74)90009-6.

Burke, K., Dewey, J. F., and Kidd, W. S. F., 1976, Dominance of Horizontal Movements, Arc and Microcontinental Collision During the Later Permobile Regime, *in* Windley, B. F., editor, The early history of the Earth: London, Wiley, p. 113–129.

Calvert, A. J., Sawyer, E. W., Davis, W. J., and Ludden, J. N., 1995, Archaean subduction inferred from seismic images of a mantle suture in the Superior Province: Nature, v. 375, p. 670–674, doi:10.1038/375670a0.

Campbell, I. H., and Hill, R. I., 1988, A two-stage model for the formation of the granite-greenstone terrains of the Kalgoorlie-Norseman area, Western Australia: Earth and Planetary Science Letters, v. 90, p. 11–25, doi:10.1016/0012-821X(88)90107-0.

Card, K. D., 1990, A review of the Superior Province of the Canadian Shield, a product of Archean accretion: Precambrian Research, v. 48, p. 99–156, doi:10.1016/0301-9268(90)90059-Y.

Cavosie, A. J., Valley, J. W., Wilde, S. A., and E. I. M. F., 2005, Magmatic $\delta^{18}O$ in 4400–3900 Ma detrital zircons: A record of the alteration and recycling of crust in the Early Archean: Earth and Planetary Science Letters, v. 235, p. 663–681, doi:10.1016/j.epsl.2005.04.028.

Champion, D. C., and Smithies, R. H., 2007, Geochemistry of Paleoarchean granites of the East Pilbara Terrane. Pilbara Craton, Western Australia: Implications for early Archean crustal growth, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennet, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 369–409, doi:10.1016/S0166-2635(07)15043-X.

Chardon, D. H., Choukroune, P., and Jayananda, M., 1998, Sinking of the Dharwar Basin (South India); implications for Archaean tectonics: Precambrian Research, v. 91, p. 15–39, doi:10.1016/S0301-9268(98)00037-0.

Chardon, D., Gapais, D., and Cagnard, F., 2009, Flow of ultra-hot orogens: A review from the Precambrian, clues for the Phanerozoic: Tectonophysics, v. 477, p. 105–118, doi:10.1016/j.tecto.2009.03.008.

Coffin, M. F., and Eldholm, O., 1993, Large Igneous Provinces: Scientific American, v. 269, p. 26–33, doi:10.1038/scientificamerican1093-42.

Collins, W. J., 1989, Polydiapirism of the Archaean Mount Edgar batholith, Pilbara Block, Western Australia: Precambrian Research, v. 43, p. 41–62, doi:10.1016/0301-9268(89)90004-1.

Collins, W. J., and Van Kranendonk, M. J., 1999, Model for the development of kyanite during partial convective overturn of Archaean granite-greenstone terranes: the Pilbara Craton, Australia: Journal of Metamorphic Geology, v. 17, p. 145–156, doi:10.1046/j.1525-1314.1999.00187.x.

Collins, W. J., Van Kranendonk, M. J., and Teyssier, C., 1998, Partial convective overturn of Archaean crust in the east Pilbara Craton, Western Australia: Driving mechanisms and tectonic implications: Journal of Structural Geology, v. 20, p. 1405–1424, doi:10.1016/S0191-8141(98)00073-X.

Condie, K. C., 1997, Contrasting sources of upper and lower continental crust: the greenstone connection: The Journal of Geology, v. 105, p. 729–736, doi:10.1086/515980.

Crowley, J. L., Myers, J. S., and Dunning, G. R., 2002, Timing and nature of multiple 3700–3600 Ma tectonic events in intrusive rocks north of the Isua greenstone belt, southern West Greenland: Geological Society of America Bulletin, v. 114, p. 1311–1325, doi:10.1130/0016-7606(2002)114⟨1311:TANOMM⟩2.0.CO;2.

Davaille, A., Le Bars, M., and Carbonne, C., 2003, Thermal convection in a heterogeneous mantle: Comptes Rendu Geoscience, v. 335, p. 141–156, doi:10.1016/S1631-0713(03)00003-8.

Davies, G. F., 1992, On the emergence of plate tectonics: Geology, v. 20, p. 963–966.

Delor, C., Burg, J.-P., and Clarke, G., 1991, Relations diapirisme-metamorphisme dans la Province du Pilbara (Australie-occidentale): implications pour les régimes thermiques et tectoniques à la Archéen: Comptes Rendus de l'Academie des Sciences Paris, v. 312, p. 257–263.

de Wit, M. J., and Hart, R. A., 1993, Earth's earliest continental lithosphere, hydrothermal flux and crustal recycling: Lithos v. 30, p. 309–335, doi:10.1016/0024-4937(93)90043-C.

de Wit, M. J., de Ronde, C. E. J., Tredoux, M., Roering, C., Hart, R. J., Armstrong, R. A., de Ronde, C. E. J., Green, R. W. E., Peberdy, E., and Hart, R. A., 1992, Formation of an Archaean continent: Nature, v. 357, p. 553–562, doi:10.1038/357553a0.

Drummond, M. S., and Defant, M. J., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons: Journal of Geophysical Research, v. 95, No. B13, p. 21503–21521, doi:10.1029/JB095iB13p21503.

England, P. C., and Thompson, A. B., 1984, Pressure-temperature-time paths of regional metamorphism, I. Heat transfer during the evolution of regions of thickened continental crust: Journal of Petrology, v. 25, p. 894–928, doi:10.1093/petrology/25.4.894.

Friend, C. R. L., Nutman, A. P., and McGregor, V. R., 1988, Late Archean terrane accretion in the Godthab region, southern West Greenland: Nature, v. 335, p. 535–538, doi:10.1038/335535a0.

Furnes, H., de Wit, M., Staudigel, H., Rosing, M., and Muehlenbachs, K., 2007a, A vestige of Earth's oldest ophiolite: Science, v. 315, p. 1704–1707, doi:10.1126/science.1139170.

——— 2007b, Response to comments on "A vestige of Earth's oldest ophiolite": Science, v. 318, p. 746e, doi:10.1126/science.1144231.

Gee, R. D., Myers, J. S., and Trendall, A. F., 1986, Relation between Archaean high-grade gneiss and granite-greenstone terrain in Western Australia: Precambrian Research, v. 33, p. 87–102, doi:10.1016/0301-9268(86)90016-1.

Green, M. G., Sylvester, P. J., and Buick, R., 2000, Growth and recycling of early Archaean continental crust: geochemical evidence from the Coonterunah and Warrawoona Groups, Pilbara Craton, Australia: Tectonophysics, v. 322, p. 69–88, doi:10.1016/S0040-1951(00)00058-5.

Grégoire, M., Cottin, J. Y., Giret, A., Mattielli, N., and Weis, D., 1998, The meta-igneous granulite xenoliths from Kerguelen Archipelago: evidence of a continent nucleation in an oceanic setting: Contributions to Mineralogy and Petrology, v. 133, p. 259–283, doi:10.1007/s004100050451.

Griffin, W. L., and O'Reilly, S. Y., 2007a, The earliest subcontinental lithospheric mantle, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 1013–1036, doi:10.1016/S0166-2635(07)15082-9.

——— 2007b, Cratonic lithospheric mantle: is anything subducted?: Episodes, v. 30, p. 43–53.

Griffin, W. L., McGregor, V. R., Nutman, A., Taylor, P. N., and Bridgwater, D., 1980, Early Archaean granulite-facies metamorphism south of Ameralik, West Greenland: Earth and Planetary Science Letters, v. 50, p. 59–74, doi:10.1016/0012-821X(80)90119-3.

Hamilton, W. B., 2003, An alternative Earth: GSA Today, v. 13, p. 4–12, doi:10.1130/1052-5173(2003)013⟨0004:AAE⟩2.0.CO;2.

——— 2007a, Earth's first two billion years—The era of internally mobile crust, *in* Hatcher, R. D., Jr., Carlson, M. P., McBride, J. H., and Martínez Catalán, J. R., editors, 4-D Framework of Continental Crust: Geological Society of America, Memoir 200, p. 233–296, doi:10.1130/2007.1200(13).

——— 2007b, Comment on "A vestige of Earth's oldest ophiolite": Science, v. 318, p. 746d, doi:10.1126/science.1144931.

Hanmer, S. and Greene, D. C., 2002, A modern structural regime in the Paleoarchean (~3.64 Ga); Isua Greenstone Belt, southern West Greenland: Tectonophysics, v. 346, p. 201–222, doi:10.1016/S0040-1951(02)00029-X.

Hansen, V. L., 2002, Artemis: Surface expression of a deep mantle plume on Venus: Geological Society of America Bulletin, v. 114, p. 839–848, doi:10.1130/0016-7606(2002)114⟨0839:ASEOAD⟩2.0.CO;2.

——— 2007a, Subduction origin on early Earth: A hypothesis: Geology, v. 35, p. 1059–1062, doi:10.1130/G24202A.1.

——— 2007b, Venus: A thin-lithosphere analogue for early Earth?, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 987–1012, doi:10.1016/S0166-2635(07)15081-7.

Harris, L. B., Koyi, H. A., and Fossen, H., 2002, Mechanisms for folding of high-grade rocks in extensional tectonic settings: Earth-Science Reviews, v. 59, p. 163–210, doi:10.1016/S0012-8252(02)00074-0.

Hawkesworth, C. J., Dhuime, B., Pietranik, A. B., Cawood, P. A., Kemp, A. I. S., and Storey, C. D., 2010, The generation and evolution of continental crust: Journal of the Geological Society, London, v. 167, p. 229–248, doi:10.1144/0016-76492009-072.

Helmstaedt, H. H., and Gurney, J. J., 1995, Geotectonic controls of primary diamond deposits: implications for area selection: Journal of Geochemical Exploration, v. 53, p. 125–144, doi:10.1016/0375-6742(94)00018-7.

Herzberg, C., Asimow, P. D., Arndt, N., Niu, Y., Lesher, C. M., Fitton, J. G., Cheadle, M. J., and Saunders, A. D., 2007, Temperatures in ambient mantle and plumes: constraints from basalts, picrites, and komatiites: Geochemistry Geophysics Geosystems, v. 8, Q02006, p. 1–34, doi:10.1029/2006GC001390.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, doi:10.1016/j.epsl.2010.01.022.

Hickman, A. H., 1984, Archaean diapirism in the Pilbara Block, Western Australia, *in* Kröner, A., and Greiling, R., editors, Precambrian Tectonics Illustrated: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlund, p. 113–127.

Hickman, A. H., and Van Kranendonk, M. J., 2004, Diapiric processes in the formation of Archaean continental crust, East Pilbara Granite-Greenstone Terrane, Australia, *in* Eriksson, P. G., Altermann, W., Nelson, D. R., Mueller, W. U., and Catuneau, O., editors, The Precambrian Earth: Amsterdam, Elsevier, Tempos and Events: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 12, p. 118–138.
Hoffman, P. F., and Ranalli, G., 1988, Archean ocean flake tectonics: Geophysical Research Letters, v. 15, p. 1077–1080, doi:10.1029/GL015i010p01077.
Jahn, B.-M., Glikson, A. Y., Peucat, J. J., and Hickman, A. H., 1981, REE geochemistry and isotopic data of Archean silicic volcanics and granitoids from the Pilbara Block, Western Australia: implications for the early crustal evolution: Geochimica et Cosmochimica Acta, v. 45, p. 1633–1652, doi:10.1016/S0016-7037(81)80002-6.
Jenner, F. E., Bennett, V. C., Nutman, A. P., Friend, C. R. L., Norman, M. D., and Yaxley, G., 2009, Evidence for subduction at 3.8 Ga: Geochemistry of arc-like metabasalts from the southern edge of the Isua Supracrustal Belt: Chemical Geology, v. 261, p. 83–98, doi:10.1016/j.chemgeo.2008.09.016.
Jensen, S. M., Sand, K. K., and Steenfelt, A., 2005, Regional distribution and chemistry of indicator minerals from *in situ* rocks and surficial deposits in the Maniitsoq and Sarfartoq regions, *in* Secher, K., and Neilsen, M. N., editors, Workshop on Greenland's diamond potential: Danmarks og Gronlands Geologiske Undersogelse Rapport 2005/68, p. 43–51.
Kamber, B. S., 2007, The enigma of the terrestrial protocrust: Evidence for its former existence and the importance of its complete disappearance, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 75–89, doi:10.1016/S0166-2635(07)15024-6.
Korenaga, J., 2006, Archean geodynamics and the thermal evolution of Earth, *in* Benn, K., Mareschal, J.-C., and Condie, K., editors, Archean Geodynamics and Environments: Washington, D. C., American Geophysical Union Monograph 164, p. 7–32.
——— 2008a, Urey ratio and the structure and evolution of Earth's mantle: Reviews of Geophysics, v. 46, RG2007, doi:10.1029/2007RG000241.
——— 2008b, Plate tectonics, flood basalts and the evolution of Earth's oceans: Terra Nova, v. 20, p. 419–439, doi:10.1111/j.1365-3121.2008.00843.x.
Kramers, J. D., 2007, Hierarchical Earth accretion and the Hadean Eon: Journal of the Geological Society, London, v. 164, p. 3–17, doi:10.1144/0016-76492006-028.
Kröner, A., 1981, Precambrian plate tectonics, *in* Kröner, A., editor, Precambrian Plate Tectonics: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 4, p. 57–90, doi:10.1016/S0166-2635(08)70008-2.
Labrosse, S., and Jaupart, C., 2007, Thermal evolution of the earth: secular changes and fluctuations of plate characteristics: Earth and Planetary Science Letters, v. 260, p. 465–481, doi:10.1016/j.epsl.2007.05.046.
Macgregor, A. M., 1951, Some milestones in the Precambrian of Southern Rhodesia: Transactions of the Geological Society of South Africa, v. 54, p. xxvii–xxi.
Mareschal, J.-C., and West, G. F., 1980, A model for Archean tectonism. Part 2. Numerical models of vertical tectonism in greenstone belts: Canadian Journal of Earth Sciences, v. 17, p. 60–71, doi:10.1139/e80-006.
Martin, H., Smithies, R. H., Rapp, R., Moyen, J.-F., and Champion, D., 2005, An overview of adakite, tonalitie-trondhjemite-granodiorite (TTG) and sanukitoid: relationships and some implications for crustal evolution: Lithos, v. 79, p. 1–24, doi:10.1016/j.lithos.2004.04.048.
Maurice, C., David, J., Bédard, J. H., and Francis, D., 2009, Evidence for a widespread mafic cover sequence and its implications for continental growth in the northeastern Superior Province: Precambrian Research, v. 168, p. 45–65, doi:10.1016/j.precamres.2008.04.010.
Mège, D., 2001, Uniformitarian plume tectonics: The post-Archean Earth and Mars, *in* Ernst, R. E., and Buchan, K. L., editors, Mantle plumes: Their identification through time: Boulder, Geological Society of America, Special Paper 352, p. 141–164, doi:10.1130/0-8137-2352-3.141.
Mège, D., and Ernst, R. E., 2001,Contractional effects of mantle plumes on Earth, Mars, and Venus, *in* Ernst, R. E., and Buchan, K. L., editors, Mantle plumes: Their identification through time: Boulder, Geological Society of America, Special Paper 352, p. 103–140, doi:10.1130/0-8137-2352-3.103.
Mojzsis, S. J., Harrison, T. M., and Pidgeon, R. T., 2001, Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago: Nature, v. 409, p. 178–181, doi:10.1038/35051557.
Moser, D. E., Heaman, L. M., Krogh, T. E., and Hanes, J. A., 1996, Intracrustal extension of an Archean orogen revealed using single-grain U-Pb zircon geochronology: Tectonics, v. 15, p. 1093–1109, doi:10.1029/96TC00130.
Moyen, J.-F., Stevens, G., and Kisters, A. F. M., 2006, Record of mid-Archaean subduction from metamorphism in the Barberton terrain, South Africa: Nature, v. 442/3, p. 559–562, doi:10.1038/nature04972.
Myers, J. S., 1976, Granitoid sheets, thrusting, and Archean crustal thickening in West Greenland: Geology, v. 4, p. 265–268, doi:10.1130/0091-7613(1976)4⟨265:GSTAAC⟩2.0.CO;2.
——— 1984, Archean tectonics in the Fiskenaesset region of southwest Greenland, *in* Kröner, A., and Greiling, R., editors, Precambrian Tectonics Illustrated: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlund, p. 95–112.
——— 1995, The generation and assembly of an Archaean supercontinent: evidence from the Yilgarn Craton, Western Australia, *in* Coward, M. P., and Ries, A. C., editors, Early Precambrian processes: The Geological Society, London, Special Publication, v. 95, p. 143–154, doi:10.1144/GSL.SP.1995.095.01.09.
Nair, R., and Chacko, T., 2008, Role of oceanic plateaus in the initiation of subduction and origin of continental crust: Geology, v. 36, p. 583–586, doi:10.1130/G24773A.1.
Nijman, W., and de Vries, S. T., 2004, Early Archaean crustal collapse structures and sedimentary basin dynamics, *in* Eriksson, P. G., Altermann, W., Nelson, D. R., Mueller, W. U., and Catuneau, O., editors, The Precambrian Earth: Tempos and Events: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 12, p. 139–154.

Nijman, W., de Bruijne, K. C. H., and Valkering, M. E., 1998, Growth fault control of Early Archaean cherts, barite mounds and chert-barite veins, North Pole Dome, Eastern Pilbara, Western Australia: Precambrian Research, v. 88, p. 25–52, doi:10.1016/S0301-9268(97)00062-4.

Nelson, D. R., 1998, 142836: volcaniclastic sedimentary rock, Gorge Creek; Geochronology dataset 393, *in* Compilation of geochronology data, 2010 update: Geological Survey of Western Australia, on dvd.

Nutman, A. P. and Friend, C. R. L., 2007, Comment on "A vestige of Earth's oldest ophiolite": Science, v. 318, n. 5851, p. 746c, doi:10.1126/science.1144148.

Nutman, A. P., Friend, C. R. L., Baadsgaard, H., and McGregor, V. R., 1989, Evolution and assembly of Archean gneiss terranes in the Godthåbsfjord region, southern west Greenland: structural, metamorphic, and isotopic evidence: Tectonics, v. 8, p. 573–589, doi:10.1029/TC008i003p00573.

Nutman, A. P., Bennett, V. C., Friend, C. R. L., and Norman, M. D., 1999, Meta-igneous (non-gneissic) tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua supracrustal belt, southern West Greenland: constraints on early crust formation: Contributions to Mineralogy and Petrology, v. 137, p. 364–388, doi:10.1007/s004100050556.

Nutman, A. P., Friend, C. R. L., and Bennett, V. C., 2002, Evidence for 3650–3600 Ma assembly of the northern end of the Itsaq Gneiss Complex, Greenland: Implication for early Archaean tectonics: Tectonics, v. 21, doi:10.1029/2000TC001203.

Nutman, A. P., Friend, C. R. L., Horie, K., and Hidaka, H., 2007, The Itsaq gneiss complex of southern West Greenland and the construction of Eoarchean crust at convergent plate boundaries, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 187–218, doi:10.1016/S0166-2635(07)15033-7.

Nutman, A. P., Friend, C. R. L., and Paxton, S., 2009, Detrital zircon sedimentary provenance ages for the Eoarchean Isua Supracrustal Belt southern West Greenland: Juxtaposition of an imbricated ca. 3700 Ma juvenile arc against an older complex with 3920–3760 Ma components: Precambrian Research, v. 172, p. 212–233, doi:10.1016/j.precamres.2009.03.019.

Park, R. G., 1997, Early Precambrian plate tectonics: South African Journal of Geology, v. 100, p. 23–35.

Peck, W. H., Valley, J. W., Wilde, S. A. and Graham, C. M., 2001, Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: Ion microprobe evidence for high $\delta^{18}O$ continental crust and oceans in the Early Archean: Geochimica et Cosmochimica Acta, v. 65, p. 4215–4229, doi:10.1016/S0016-7037(01)00711-6.

Peltonen, P., and Kontinen, A., 2004, The Jormua Ophiolite: A mafic-ultramafic complex from an ancient ocean-continent transition zone, *in* Kusky, T. M., editor, Precambrian Ophiolites and Related Rocks: Developments in Precambrian Geology, v. 13, Amsterdam, Elsevier, p. 35–71, doi:10.1016/S0166-2635(04)13001-6.

Percival, J. A., 2007, Eo- to Mesoarchean terranes of the Superior Province and their tectonic context, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V. C., editors, Earth's Oldest Rocks: Developments in Precambrian Geology, v. 15, Amsterdam, Elsevier, p. 1065–1085, doi:10.1016/S0166-2635(07)15084-2.

Percival, J. A., Roering, C., Van Reenen, D. D., and Smit, C. A., 1997, Tectonic evolution of associated greenstone belts and high-grade terrains, *in* de Wit, M. J., and Ashwal, L. D., editors, Tectonic evolution of greenstone belts: Oxford, Oxford Monograph on Geology and Geophysics, p. 398–420.

Polat, A., Kerrich, R., and Wyman, D. A., 1998, The late Archean Schreiber-Hemlo and White River-Dayohessarah greenstone belts, Superior Province: collages of oceanic plateaus, oceanic arcs, and subduction-accretion complexes: Tectonophysics, v. 289, p. 295–326, doi:10.1016/S0040-1951(98)00002-X.

Polat, A., Hofmann, A. W., and Rosing, M. T., 2002, Boninite-like volcanic rocks in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: geochemical evidence for intra-oceanic subduction zone processes in the early Earth: Chemical Geology, v. 184, p. 231–254, doi:10.1016/S0009-2541(01)00363-1.

Polat, A., Li, J. H., Fryer, B., Kusky, T., Gagnon, J., and Zhang, S., 2006, Geochemical characteristics of the Neoarchean (2800-2700 Ma) Taishan greenstone belt, North China Craton: Evidence for plume-craton interaction: Chemical Geology, v. 230, p. 60–87, doi:10.1016/j.chemgeo.2005.11.012.

Puchtel, I. S., Hofmann, A. W., Mezger, K., Jochum, K. P., Shchipansky, A. A., and Samsonov, A. V., 1998, Oceanic plateau model for continental crustal growth in the Archaean: A case study from the Kostomuksha greenstone belt, NW Baltic Shield: Earth and Planetary Science Letters, v. 155, p. 57–74, doi:10.1016/S0012-821X(97)00202-1.

Rapp, R. P., Watson, E. B., and Miller, C. F., 1991, Partial melting of amphibolite/eclogite and the origin of Archean trondhjemites and tonalites: Precambrian Research, v. 51, p. 1–25, doi:10.1016/0301-9268(91)90092-O.

Rey, P. F., Vanderheaghe, O., and Teyssier, C., 2001, Gravitational collapse of continental crust: definition, regimes, and modes: Tectonophysics, v. 342, p. 435–449, doi:10.1016/S0040-1951(01)00174-3.

Rey, P. F., Philippot, P., and Thébaud, N., 2003, Contribution of mantle plumes, crustal thickening and greenstone blanketting to the 2.75–2.65 Ga global crisis: Precambrian Research, v. 127, p. 43–60, doi:10.1016/S0301-9268(03)00179-7.

Riciputi, L. R., Valley, J. W., and McGregor, V. R., 1990, Conditions of Archean granulite metamorphism in the Godthab-Fiskenaesset region, southern West Greenland: Journal of Metamorphic Geology, v. 8, p. 171–190, doi:10.1111/j.1525-1314.1990.tb00464.x.

Sandiford, M., 1989, Horizontal structures in granulite terrains: A record of mountain building or mountain collapse?: Geology, v. 17, p. 449–452, doi:10.1130/0091-7613(1989)017⟨0449:HSIGTA⟩2.3.CO;2.

Sandiford, M., Van Kranendonk, M. J., and Bodorkos, S., 2004, Conductive incubation and the origin of dome-and-keel structure in Archean granite-greenstone terrains: a model based on the eastern Pilbara Craton, Western Australia: Tectonics, v. 23, TC1009, doi:10.1029/2002TC001452.

Scholl, D. W., and von Heune, R., 2007, Crustal recycling at modern subduction zones applied to the past—Issues of crustal growth and preservation of continental basement crust, mantle geochemistry, and supercontinent reconstruction, *in* Hatcher, R. D., Jr., Carlson, M. P., McBride, J. H., and Martínez Catalán, J. R., editors, 4-D Framework of Continental Crust: Geological Society of America, Memoir 200, p. 9–32, doi:10.1130/2007.1200(02).

Schubert, G., and Sandwell, D. T., 1995, A global survey of possible subduction sites on Venus: Icarus, v. 117, p. 173–196, doi:10.1006/icar.1995.1150.

Sleep, N. H., and Windley, B. F., 1982, Archean plate tectonics: Constraints and inferences: The Journal of Geology, v. 90, p. 363–379, doi:10.1086/628691.

Smith, D. E., Zuber, M. T., Solomon, S. C., Phillips, R. J., Head, J. W., Garvin, J. B., Banerdt, W. B., Muhleman, D. O., Pettengill, G. H., Neumann, G. A., Lemoine, F. G., Abshire, J. B., Aharonson, O., Brown, C. D., Hauck, S. A. Ivanov, A. B., McGovern, P. J., Zwally, H. J., and Duxbury, T. C., 1999, The global topography of Mars and implications for surface evolution: Science, v. 284, p. 1495–1503, doi:10.1126/science.284.5419.1495.

Smith, J. B., Barley, M. E., Groves, D. I., Krapez, B., McNaughton, N. J., Bickle, M. J., and Chapman, H. J., 1998, The Sholl Shear Zone, West Pilbara: evidence for a domain boundary structure from integrated tectonostratigraphic analyses, SHRIMP U-Pb dating and isotopic and geochemical data of granitoids: Precambrian Research, v. 88, p. 143–171, doi:10.1016/S0301-9268(97)00067-3.

Smithies, R. H., Champion, D. C., and Cassidy, K. F., 2003, Formation of Earth's early Archaean continental crust: Precambrian Research, v. 127, p. 89–101, doi:10.1016/S0301-9268(03)00182-7.

Smithies, R. H., Van Kranendonk, M. J., and Champion, D. C., 2005a, It started with a plume—early Archaean basaltic proto-continental crust: Earth and Planetary Science Letters, v. 238, p. 284–297, doi:10.1016/j.epsl.2005.07.023.

Smithies, R. H., Champion, D. C., Van Kranendonk, M. J., Howard, H. M., and Hickman, A. H., 2005b, Modern-style subduction processes in the Mesoarchaean: Geochemical evidence from the 3.12 Ga Whundo intraoceanic arc: Earth and Planetary Science Letters, v. 231, p. 221–237, doi:10.1016/j.epsl.2004.12.026.

Smithies, R. H., Champion, D. C., and Van Kranendonk, M. J., 2007, The oldest well-preserved volcanic rocks on Earth: Geochemical clues to the early evolution of the Pilbara Supergroup and implications for the growth of a Paleoarchean continent, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 339–367, doi:10.1016/S0166-2635(07)15042-8.

——— 2009, Formation of Paleoarchean continental crust through infracrustal melting of enriched basalt: Earth and Planetary Science Letters, v. 281, p. 298–306, doi:10.1016/j.epsl.2009.03.003.

Smrekar, S. E., and Stofan, E. R., 1999, Origin of corona-dominated topographic rises on Venus: Icarus, v. 139, p. 100–115, doi:10.1006/icar.1999.6090.

Spencer, J. E., 2001, Possible giant metamorphic core complex at the center of Artemis Corona, Venus: The Geological Society of America Bulletin, v. 113, p. 333–345, doi:10.1130/0016-7606(2001)113⟨0333:PGMCCA⟩2.0.CO;2.

Squyres, S. W., Janes, D. M., Baer, G., Bindschadler, D. L., Schubert, G., Sharpton, V. L., and Stofan, E. R., 1992, The morphology and evolution of coronae on Venus: Journal of Geophysical Research, v. 97, No. E8, p. 13611–13634, doi:10.1029/92JE01213.

Stern, R. A., Machado, N., Syme, E. C., Lucas, S. B., and David, J., 1999, Chronology of crustal growth and recycling in the Paleoproterozoic Amisk collage (Flin Flon Belt), Trans-Hudson orogeny, Canada: Canadian Journal of Earth Sciences, v. 36, p. 1807–1827, doi:10.1139/cjes-36-11-1807.

Stern, R. J., 2005, Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time: Geology, v. 33, p. 557–560, doi:10.1130/G21365.1.

Strik, G. M. H. A., Blake, T. S., Zegers, T. E., White, S. H., and Langereis, C. G., 2003, Paleomagnetism of flood basalts in the Pilbara Craton, Western Australia: Late Archaean continental drift and the oldest known reversal of the geomagnetic field: Journal of Geophysical Research, v. 108, No. B12, 2551, doi:10.1029/2003JB002475.

Talbot, C. J., and Walton, B. J., 1973, A plate tectonic model for the Archaean crust: Philosophical Transactions of the Royal Society of London A, v. 273, p. 413–427, doi:10.1098/rsta.1973.0008.

Taylor, P., 2006, The single largest oceanic plateau: Ontong-Java-Manihiki-Hikurangi: Earth and Planetary Science Letters, v. 241, p. 372–397, doi:10.1016/j.epsl.2005.11.049.

Tessalina, S. G., Bourdon, B., Van Kranendonk, M., Birck, J.-L., and Philippot, P., 2010, Influence of Hadean crust evident in basalts and cherts from the Pilbara Craton: Nature Geoscience, v. 3, p. 214–217, doi:10.1038/ngeo772.

Thompson, P. H., 1989, Moderate overthickening of thinned sialic crust and the origin of granitic magmatism and regional metamorphism in low-*P*-high-*T* terranes: Geology, v. 17, p. 520–523, doi:10.1130/0091-7613(1989)017⟨0520:MOOTSC⟩2.3.CO;2.

Tomlinson, K. Y., and Condie, K. C., 2001, Archean mantle plumes: Evidence from greenstone belt geochemistry, *in* Ernst, R. E., and Buchan, K. L., editors, Mantle plumes: Their identification through time: Boulder, Geological Society of America, Special Paper 352, p. 341–357, doi:10.1130/0-8137-2352-3.341.

Ueda, K., Gerya, T., and Sobolev, S. V., 2008, Subduction initiation by thermal-chemical plumes: Numerical studies: Physics of the Earth and Planetary Interiors, v. 171, p. 296–312, doi:10.1016/j.pepi.2008.06.032.

Valley, J. W., Peck, W. H., King, E. M., and Wilde, S. A., 2002, A cool early Earth: Geology, v. 30, p. 351–354, doi:10.1130/0091-7613(2002)030⟨0351:ACEE⟩2.0.CO;2.

Van Kranendonk, M. J., 2000, Geology of the North Shaw 1:100 000 sheet: Geological Survey of Western Australia, 1:100 000 Geological Series Explanatory Notes, 86 p.

——— 2006, Volcanic degassing, hydrothermal circulation and the flourishing of early life on Earth: A review of the evidence from c. 3490–3240 Ma rocks of the Pilbara Supergroup, Pilbara Craton, Western Australia: Earth-Science Reviews, v. 74, p. 197–240, doi:10.1016/j.earscirev.2005.09.005.
——— 2007, Tectonics of early Earth, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 1105–1116, doi:10.1016/S0166-2635(07)15086-6.
Van Kranendonk, M. J., and Pirajno, F., 2004, Geochemistry of metabasalts and hydrothermal alteration zones associated with c. 3.45 Ga chert and barite deposits: implications for the geological setting of the Warrawoona Group, Pilbara Craton, Australia: Geochemistry: Exploration, Environment, Analysis, v. 4, p. 253–278, doi:10.1144/1467-7873/04-205.
Van Kranendonk, M. J., Hickman, A. H., Smithies, R. H., Nelson, D. N., and Pike, G., 2002, Geology and tectonic evolution of the Archaean North Pilbara terrain, Pilbara Craton, Western Australia: Economic Geology, v. 97, p. 695–732, doi:10.2113/gsecongeo.97.4.695.
Van Kranendonk, M. J., Collins, W. J., Hickman, A. H., and Pawley, M. J., 2004, Critical tests of vertical vs. horizontal tectonic models for the Archaean East Pilbara Granite-Greenstone Terrane, Pilbara Craton, Western Australia: Precambrian Research, v. 131, p. 173–211, doi:10.1016/j.precamres.2003.12.015.
Van Kranendonk, M. J., Smithies, R. H., Hickman, A. H., and Champion, D. C., 2007a, Secular tectonic evolution of Archaean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia: Terra Nova, v. 19, p. 1–38, doi:10.1111/j.1365-3121.2006.00723.x.
——— 2007b, The East Pilbara Terrane of the Pilbara Craton, Western Australia: Formation of a continental nucleus through repeated mantle plume magmatism, *in* Van Kranendonk, M. J., Smithies, R. H., and Bennett, V., editors, Earth's Oldest Rocks: Amsterdam, Elsevier, Developments in Precambrian Geology, v. 15, p. 307–337, doi:10.1016/S0166-2635(07)15041-6.
Van Kranendonk, M. J., Philippot, P., Lepot, K., Bodorkos, S., and Pirajno, F., 2008, Geological setting of Earth's oldest fossils in the c. 3.5 Ga Dresser Formation, Pilbara Craton, Western Australia: Precambrian Research, v. 167, p. 93–124, doi:10.1016/j.precamres.2008.07.003.
Van Kranendonk, M. J., Smithies, R. H., Hickman, A. H., Wingate, M. T. D., and Bodorkos, S., 2010, Evidence for Mesoarchean (~3.2 Ga) rifting of the Pilbara Craton: The missing link in an early Precambrian Wilson cycle: Precambrian Research, v. 177, p. 145–161, doi:10.1016/j.precamres.2009.11.007.
Wallace, P. J., Frey, F. A., Weis, D., and Coffin, M. F., 2002, Origin and evolution of the Kerguelen Plateau, Broken Ridge and Kerguelen archipelago: Editorial: Journal of Petrology, v. 43, p. 1105–1118, doi: 10.1093/petrology/43.7.1105.
Warren, R. G., and Ellis, D. J., 1996, Mantle underplating, granite tectonics, and metamorphic P-T-t paths: Geology, v. 24, p. 663–666, doi:10.1130/0091-7613(1996)024⟨0663:MUGTAM⟩2.3.CO;2.
Watts, A. B., ten Brink, U. S., Buhl, P., and Brocher, T. M., 1985, A multichannel seismic study of lithospheric flexure across the Hawaiian-Emperor seamount chain: Nature, v. 315, p. 105–111, doi:10.1038/315105a0.
Weaver, B. L., Tarney, J., and Windley, B., 1981, Geochemistry and petrogenesis of the Fiskenaesset anorthosite complex, southern West Greenland: nature of the parent magma: Geochimica et Cosmochimica Acta, v. 45, p. 711–725, doi:10.1016/0016-7037(81)90044-2.
Wells, P. R. A., 1979, Chemical and thermal evolution of Archaean sialic crust, southern West Greenland: Journal of Petrology, v. 20, p. 187–226, doi:10.1093/petrology/20.2.187.
Wilson, J. F., Nesbitt, R. W., and Fanning, C. M., 1995, Zircon geochronology of Archaean felsic sequences in the Zimbabwe craton: a revision of greenstone stratigraphy and a model for crustal growth, *in* Coward, M. E., and Reis, A. C., editors, Early Precambrian Processes: Geological Society of London, Special Publication, v. 95, p. 109–126, doi:10.1144/GSL.SP.1995.095.01.07.
Wilson, M., 1989, Igneous petrogenesis: London, HarperCollins Academic, 466 p.
Windley, B. F., and Bridgwater, D., 1971, The evolution of Archaean low- and high-grade terrains: Geological Society of Australia, Special Publication v. 3, p. 33–46.
Windley, B. F., and Garde, A., 2009, Arc-generated blocks with crustal sections in the North Atlantic Craton of West Greenland: Crustal growth in the Archean with modern analogues: Earth-Science Reviews, v. 93, p. 1–30, doi:10.1016/j.earscirev.2008.12.001.
Wittig, N., Pearson, D. G., Webb, M., Ottley, C. J., Sand, K. K., Jensen, S. M., and Nowell, G. M., 2008a, Evolution of the mantle root beneath the North Atlantic Craton: Frankfurt, Germany, 9th International kimberlite conference, Extended Abstracts No. 91KC-A-00267.
Wittig, N., Pearson, D. G., Webb, M., Ottley, C. J., Irvine, G. J., Kopylova, M., Jensen, S. M., and Nowell, G. M., 2008b, Origin of cratonic lithospheric mantle roots: A geochemical study of peridotites from the North Atlantic Craton, West Greenland: Earth and Planetary Science Letters, v. 274, p. 24–33, doi:10.1016/j.epsl.2008.06.034.
Wyman, D. A., Kerrich, R., and Polat, A., 2002, Assembly of Archean cratonic mantle lithosphere and crust: plume-arc interaction in the Abitibi-Wawa subduction-accretion complex: Precambrian Research, v. 115, p. 37–62, doi:10.1016/S0301-9268(02)00005-0.
Zegers, T. E., White, S. H., de Keijzer, M., and Dirks, P., 1996, Extensional structures during deposition of the 3460 Ma Warrawoona Group in the eastern Pilbara Craton, Western Australia: Precambrian Research, v. 80, p. 89–105, doi:10.1016/S0301-9268(96)00007-1.
Zegers, T. E., Wijbrans, J. R., and White, S. H., 1999, $^{40}Ar/^{39}Ar$ age constraints on tectonothermal events in the Shaw area of the eastern Pilbara granite-greenstone terrain (W Australia): 700 Ma of Archaean tectonic evolution: Tectonophysics, v. 311, p. 45–81, doi:10.1016/S0040-1951(99)00157-2.
Zegers, T. E., Nelson, D. R., Wijbrans, J. R., and White, S. H., 2001, SHRIMP U-Pb zircon dating of Archean core complex formation and pancratonic strike-slip deformation in the East Pilbara Granite-Greenstone Terrain: Tectonics, v. 20, p. 883–908, doi:10.1029/2000TC001210.