Archean Geodynamics: Similar to or Different From Modern Geodynamics?

Kent C. Condie

Department of Earth & Environmental Science, New Mexico Institute of Mining & Technology, Socorro, New Mexico

Keith Benn

Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, University of Ottawa, Ottawa, Ontario, Canada

There is a wealth of geologic, geochemical, structural, volcanologic, and sedimentologic data that are consistent with Archean plate tectonics, especially after 3.0 Ga. Neither the eruption of submarine basalts onto thinned continental crust nor the existence of ductile or viscous diapirism precludes the existence of plate tectonics during the Archean. Some "missing indicators" of plate tectonics are found in Archean terranes (probable oceanic crust, melange, possible passive margin sequences, boninite), whereas the absence of others (such as blueschists) can be explained by a higher Archean mantle geotherm. Bimodal magmatism is not limited to the Archean but occurs in several modern tectonic settings. The relative abundance of komatiites in the Archean reflects hotter Archean mantle and possibly widespread mantle plume activity. Any viable model for Archean geodynamics must accommodate the following 10 constraints: During the Archean, the mantle was hotter than it is today; there are two styles of crustal deformation in the Archean; komatiite is proportionally more abundant in Archean greenstones than in younger greenstones; tonalite–trondhjemite–granodiorite depleted in heavy rare earth elements is more widespread in the Archean than afterwards; thick lithosphere underlies many Archean cratons; portions of the mantle were strongly depleted in large ion lithophile elements during the Archean; many Archean greenstones comprise arc-like rock assemblages; a significant proportion of Archean greenstones contain volcanic rocks with geochemical characteristics similar to modern plume-derived basalts; paleomagnetic data indicate that apparent polar wandering occurred during the Archean; and a large volume of continental crust was produced about 2.7 Ga.

INTRODUCTION

Were Archean tectonic regimes similar to or different from present tectonic regimes? This question has been with us for many years, and despite the large amount of high-precision data that has become available from Archean rocks, the question still lingers. From the very onset of modern studies of Archean greenstone belts [*Langford and Morin*, 1976; *Blackburn*, 1980], plate tectonics has been the favored paradigm. And from that time onwards, few seemed to have looked back: Plate tectonics carried the Archean banner [*Smithes and Champion*, 2000; *Chen et al.*, 2003; *Percival et al.*, 2004].

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At the same time, not all investigators have accepted that modern plate tectonics operated in the Archean. For instance, *Goodwin* [1977] suggested that granite-greenstone belts formed by "sagduction" (sagging of volcanic–sedimentary basins and remelting of the lower crust in response to plume-induced rifting; *Goodwin and Smith* [1980]). More recently, other investigators have challenged the plate tectonic paradigm, in whole or in part, as applied to the Archean [*Davies*, 1992; *Hamilton*, 1998; *Bleeker*, 2002; *Trendall*, 2002], with some suggesting that modern-style plate tectonics did not appear until the Late Archean [*Davies*, 1995; *Smithes et al.*, 2003; *Peschler et al.*, 2004].

In fact, a proper understanding of Archean geodynamics should not necessitate a choice between two end-member models (e.g., vertical or horizontal deformation). It is more likely that there was an evolution of geodynamic settings as Earth cooled during the Archean [*Vlaar et al.*, 1994]. In this short contribution, we address some of the questions that have been raised about plate tectonics in the Archean, chiefly from a geological and geochemical point of view. Geophysical considerations, such modes of continental accretion and rheological behavior of the the lithosphere, are more fully discussed in other papers in this volume. We present a list of 10 constraints that any model for Archean geodynamics must accommodate. This is not to say these are the only 10 constraints, but in our opinion, they are 10 of the most robust constraints.

PROBLEMS WITH ARCHEAN PLATE TECTONICS

Problems presented for the existence of Archean plate tectonics generally fall into one of three categories: eruption of greenstones onto felsic crust; the existence of vertical crustal tectonics in the Archean; and the absence, or apparent absence, of key plate tectonic indicators from the Archean geological record.

Early Felsic Crust

Archean greenstones that appear to have been erupted onto or through felsic crust have now been described from many cratons [*Martin et al.*, 1993; *Swager*, 1997; *Bleeker et al.*, 1999]. In some cases actual contacts are exposed such as at the classic site in Zimbabwe [*Bickle et al.*, 1994]. In other cases, Nd isotopic data or inherited components in igneous zircons indicate contamination of mafic and komatiitic magmas with felsic crust [*Stevenson*, 1995; *Lesher and Arndt*, 1995; *Tomlinson et al.*, 2004]. Although it is not yet clear what proportion of Archean greenstones are crustally contaminated, it is probably less than 50%. In cases where komatiitic and mafic lavas were erupted onto felsic Archean crust, the felsic component must have been relatively thin so as not to isostatically rise above sea level, or sea level must have been high to flood all or most of the continents. We can consider three possibilities to explain low-standing continental crust: (1) the production rate of felsic crust was very low prior the Late Archean; (2) Archean submarine volcanics were erupted on thin felsic crust around the margins of microcontinents, which were flooded in part or entirely with seawater; and (3) Archean felsic crust was thinned due to rifting or lateral flow of weak lower crust during or prior to submarine volcanism. Because Earth was hotter in the Archean [*Bickle*, 1978], it is unlikely that the production rate of continental crust was low—in fact, it should have been high. Perhaps the continental crust production rate was high, but the recycling rate into the mantle was even higher, such that only a small amount of this early crust survived. If so, we are faced with the question of why such high recycling rates?

Eruption of greenstone volcanics on thin felsic crust around the margin of flooded microcontinents is feasible as pointed out by *Arndt* [1999]. Perhaps high sea level in the Archean was caused by high-standing ocean ridges or by numerous oceanic plateaus. Still another possibility is that Archean continental crust was subjected to intense rifting, possibly caused by mantle plumes. In the Slave and Superior provinces, there is evidence for rifting of the felsic basement upon which greenstone volcanics were erupted [*Percival*, 2001; *Bleeker*, 2002]. If mantle plumes were more widespread in the Archean, both possibilities two and three may have been responsible for eruption of thick submarine basalt successions onto thinned continental crust. Continental crust produced in the Early Archean by subduction-related processes may have been thinned by later rifting processes, such that it did not emerge above sea level. Magmas derived from mantle plumes, ocean ridges, or subduction zones could have been erupted on to such crust. As a Phanerozoic example, for instance, during early stages of the opening of the Red Sea and the Gulf of California in the Tertiary, pillow basalts may have erupted on extended continental crust. During the opening of back arc basins, such as the Rocas Verdes ophiolites in the southern Andes during the Cretaceous [*Stern and de Wit*, 2003], submarine basalts can be erupted onto extended continental crust. The Kerguelen oceanic plateau may have been erupted, at least in part, onto thin continental crust around the margin of Antarctica.

So what is the bottom line? Eruption of submarine basalts onto submerged continental crust, whether thinned by rifting or not, does NOT preclude the existence of plate tectonics in the Archean.

Vertical Tectonics in the Archean

Although structural, geochemical, and reflection seismology studies of Archean cratons have shown that horizontal tectonic regimes, much like modern plate tectonic regimes at convergent margins, dominated in the Late Archean [*Ludden et al.*, 1993; *Polat and Kerrich*, 2001; *Percival et al.*, 2004], there is evidence to support vertical tectonics, i.e., crustal diapirism in some Archean cratons [*Chardon et al.*, 1996; *Van Kranendonk et al.*, 2004; *Bedard et al.*, 2004]. The best documented case for vertical tectonics is in the Eastern Pilbara craton during the Mid-Archean [*Collins et al.*, 1998; *Hickman*, 2004; *Van Kranendonk et al.*, 2004]. The dome and keel pattern of the Eastern Pilbara has long been recognized as its salient feature. A similar pattern has been described in the Archean Slave province [*Bleeker*, 2002]. The greenstone successions in the Eastern Pilbara (3.7–3.5 Ga) contain no low-angle thrusts, and stratigraphic units can be correlated between greenstone belts. Intrusion of syntectonic tonalite–trondhjemite–granodiorite (TTG) sheets and laccoliths initiated doming (3.49–3.43 Ga) followed by gravity-driven diapiric doming and sinking of denser greenstones into adjacent synclines [*Hickman*, 2004]. Unlike the Eastern Pilbara, the Western Pilbara comprises a collage of three separate, fault-bounded terranes, each of which has a unique stratigraphic section and structural history. No diapiric domes are present in the Western Pilbara, where all deformation appears to result from episodes of compressive deformation, consistent with a plate tectonic regime [*Hickman*, 2004].

Should we abandon plate tectonics in the Archean because some examples of regions with crustal diapirism have been found? Is it not possible that crustal diapirism can operate on a plate tectonic Earth? The main question concerning crustal diapirism is that of the rheological behavior of continental crust and its response to body forces, tectonic stresses, and different geothermal gradients. Ductile or viscous diapirism in the Archean need not be inconsistent with global plate tectonics, as discussed below.

Apparent Absence of Key Plate Tectonic Indicators

One has to be very careful in using "apparent absence" of specific plate tectonic indicators in ancient rocks as evidence for the absence of plate tectonics. Some components, especially those that are subject to being subducted, such as melange, are not universally preserved even in the Phanerozoic record, yet we don't question the applicability of plate tectonics in arc successions where melange is missing. Ophiolites are commonly cited as examples of missing plate tectonic indicators in the Archean (a possible 2.5-Ga ophiolite has recently been described in China [*Kusky et al.*, 2001], but also see *Zhai et al.* [2002]; *Kusky and Li* [2002]). There are several problems with the recognition and preservation of complete ophiolite successions in the Archean. For instance, if Archean oceanic crust was significantly thicker than modern oceanic crust [*Sleep and Windley*, 1982; *Foley et al.*, 2003], deep portions of oceanic crust that contain sheeted dykes, layered gabbros, and ultramafic cumulate rocks may not be accreted to the continents in subduction zones but instead recycled into the mantle. The rheological profiles of thick oceanic crust could have resulted in tectonic delamination of the middle to lower crustal sections and mantle lithosphere during collisional tectonics, and the emplacement of only the upper, volcanic crust within Archean orogens ("oceanic flake tectonics" [*Hoffman and Ranalli*, 1988]). One of the great challenges of the future is that of recognizing Archean oceanic crust when and if it is preserved in greenstones. Perhaps many of the mafic plain greenstones are remnants of oceanic crust rather than of oceanic plateaus [*Condie*, 1994; *Tomlinson and Condie*, 2001].

The apparent absence of high-pressure, low-temperature metamorphic rocks in the Archean has also been used to argue against plate tectonics [*Hamilton*, 1998; *Bleeker*, 2002]. Yet the absence of these rocks in the Archean is predicted from the probable higher temperature regimes in Archean subduction zones as convincingly shown by *Komiya et al.* [2002]. In fact, it would be a difficult problem if we found blueschists in the Archean!

Some have cited the apparent absence of passive margin successions in the Archean as evidence against plate tectonics [*Hamilton*, 1998; *Bleeker*, 2002]. To identify a passive margin sequence in the geologic record requires excellent preservation of rocks recording the opening of an ocean basin, something we do not have in the Archean (or at least have not yet recognized). There are, however, Archean sedimentary successions composed of shales and quartz arenites resting uncomfortably on older basement that could be remnants of passive margin successions, such as the Moodies Supergroup in South Africa [*Eriksson*, 1978; *Lowe*, 1994], remnants in the Narryer Complex in Western Australia [*Maas and McCulloch*, 1991], the Mount Bruce Supergroup in Western Australia [*Barley et al.*, 1992], the Bababudan Group in southern India [*Srinivasan and Ojakangas*, 1986], and sites in the Canadian shield [*Donaldson and de Kemp*, 1998] and in southern Zimbabwe [*Fedo and Eriksson*, 1996]. Certainly, lithologic packages characteristic of passive margins occur in the Archean.

The absence of melange and accretionary prisms in the Archean also has been used to question the existence of plate tectonics [*Hamilton*, 1998]. But are they really absent? First of all, melange is a rock type easily subducted into the mantle, and even pre-Mesozoic melanges are not universally preserved. *McCall* [2003] discussed the strong contrasts between the accretionary complexes of the convergent Makran margin, Iran, and Archean greenstone and metasedimentary belts, and concluded that zones of Archean plate convergence must have differed significantly from what we know to exist at present. However, a tectonic melange resembling a classic Mesozoic-style accretionary melange has been described from the Schreiber greenstone belt in the Superior Province of Canada [*Polat and Kerrich*, 1999]. Like Phanerozoic counterparts, this Archean melange is characterized by varying degrees of fragmentation and mixing, ranging from intact sedimentary layers and volcanic flows to intensely sheared, transposed, and mixed tectonic melange. It differs from Phanerozoic examples in the composition of the blocks that are included within the melange, and also in metamorphic facies. The total package of rocks in the Schreiber greenstone, however, is comparable to those found in young arc successions that evolved through compressional to transpressional deformation. In addition, there are several Archean greenstones that have been described that contain large blocks ranging from dismembered to intact, which are similar to blocks in young accretionary prisms [*Thurston*, 1994; *Mueller et al.*, 1996; *Stott*, 1997; *de Wit and Ashwal*, 1997; *de Wit*, 1998; *Kusky*, 1998]. The work of *Polat and Kerrich* [1999] underscores one major challenge in applying the plate tectonic model to the Archean: how to recognize Archean subduction–accretion complexes that may differ significantly from modern analogs.

TEN CONSTRAINTS FOR ARCHEAN TECTONIC REGIMES

A step in the right direction for a better understanding of the Archean is to come up with a list of robust constraints that must be accommodated into any viable tectonic scenario for the Archean. As a beginning to such a list, below we present 10 constraints, which seem to be well established from published data.

1. During the Archean, the mantle was hotter than it is today.

Several lines of evidence indicate that Earth's mantle was hotter in the Archean than afterwards [*Bickle*, 1978; *Hoffman and Ranalli*, 1988; *Davies*, 1992]. The higher concentrations of radiogenic isotopes (principally U, Th, and K) in the mantle prior to 2.5 Ga strongly suggest that radioactive heat production in the mantle was two to three times that of today [*Pollack*, 1997], although the ratio of heat loss to heat production in the early Earth is not well constrained.

2. There are two contrasting styles of Archean crustal deformation.

Structural signature may provide insights to geodynamic settings and rheological state of the lithosphere during the Archean. Two end-member structural types are documented by mapping in Archean terranes: dome and keel style and linear, upright fold belts. The latter are most common, but not restricted to the Late Archean (≤2.7 Ga).

The Eastern Pilbara province in Western Australia is the best documented example of a pre-2.9-Ga province with dome and keel structural architecture. Extensive structural, metamorphic, and geophysical modeling have provided abundant and compelling evidence for crustal diapirism in the Eastern Pilbara during the Mid-Archean [*Collins et al.*, 1998; *Van Kranendonk et al.*, 2004; *Peschler et al.*, 2004], resulting in the classical pattern of granite-gneiss domes that is strikingly displayed on satellite images of the region (Figure 1 in *Van Kranendonk et al.* [2004]). Diapirism occurred in response to the accumulation of thick mafic and komatiitic volcanic packages that sank into the felsic middle crust, resulting in "partial convective overturn" [*Collins et al.*, 1998]. The implication is that the middle crust was softened by thermal blanketing, conductive incubation [*Sandiford et al.*, 2004], and/or heating by a mantle plume, allowing the crust to flow under the weight of a 10–18-km-thick volcanic pile.

The Dharwar craton in southern India is another Archean province where studies have confirmed the role of crustal diapirism related to body forces. This interpretation is based on extensive mapping of structures and finite strain patterns in the Dharwar craton that appear to be related to diapirism that occurred ca. 3.0 Ga [*Bouhallier et al.*, 1993] or possibly later, between 2.8 and 2.6 Ga [*Chardon et al.*, 1998]. Diapiric tectonics between 2.9 and 2.7 Ga has also been proposed for the plutonic-gneissic Minto Block of northern Quebec [*Bédard et al.*, 2003], although a plate tectonic model has also been proposed for this region [*Percival et al.*, 1994].

The evidence provided by studies in the Pilbara and Dharwar cratons strongly supports the interpretation that crustal doming and diapiric deformation of continental crust occurred during the Archean, in particular in provinces older than 2.9 Ga. In contrast, post-2.8-Ga Archean provinces are generally elongate belts with strong linear structural trends parallel to the belts. For the most part, they are upright fold belts that may be bounded by subparallel fault lineaments and elongate intrusive complexes.

As examples, in both the southern Superior and Yilgarn provinces, upper, unreflective crust is deformed by upright folds with wavelengths on the order of tens of kilometers, and by fold-parallel fault zones continuous for hundreds of kilometers. The more reflective middle crust is also folded and cross-cut by ductile shear zones. In the Abitibi granite-greenstone belt, the amplitude of folds is sufficient to expose amphibolite-grade orthogneiss in anticlinal cores [*Benn*, 2004]. Upright folding of the middle crust is also interpreted from seismic profiles [*Wilde et al.*, 1996; *Benn*, this volume] and documented in the field in the amphibolite-grade Opatica and Pontiac belts that bound the Abitibi belt

[*Benn*, 1992, 1994]. Some shear zones are crustal-scale features interpreted as sutures, and elongate belts may be accreted tectono-stratigraphic terranes [*Calvert and Ludden*, 1999; *Wilde et al.*, 1996; *Goleby et al.*, 2004; *Benn*, this volume].

It is difficult to attribute the structural style of Late Archean crust, especially the upright regional-scale fold belts and locally transpressive shear zones, to geodynamic processes other than horizontal displacements and collisions of relatively rigid lithospheric plates [*Choukroune et al.*, 1997]. Disagreement may exist as to the identification of individual terrane sutures in Late Archean cratons, but a plate tectonic model is invoked by most workers to explain the first-order structures. Although elongate upright fold belts are less typical of pre-2.8-Ga crust, this does not preclude horizontal activity by tectonics before 2.8 Ga. As mentioned previously, in the Western Pilbara province, thrust stacking of identifiable lithotectonic terranes, the presence of elongate fold belts and plutonic complexes, and documented large-scale transcurrent shear zones provide compelling evidence for tectonic plate collisions prior to 2.9 Ga [*Hickman*, 2004]. The apparent plate collisions in the Western Pilbara would have occurred during a period between two crustal diapirism events in the Eastern Pilbara.

Thus, it appears that prior to 2.9 Ga, the rheology of continental crust was such that crustal diapirism was an efficient process for the redistribution of mass and heat. This imposes a constraint of relatively weak and hot middle and perhaps lower crust compared to the Phanerozoic, where such large-scale vertical tectonism is unknown. Several questions arise. Does crustal diapirism record transient thermal anomalies or a high steady-state geotherm in Early Archean continents? Was the "extra" heat in the pre-2.9-Ga continental crust internally generated [*Sandiford et al.*, 2004], in which case it might have been an intrinsic property of the early continental crust? Or was it derived from an external source, such as mantle plumes, which may have been more common in the Archean [*Stein and Hofmann*, 1994; *Choukroune et al.*, 1997; *Tomlinson and Condie*, 2001], or catastrophic mantle overturn events in a layered mantle [*Davies*, 1995]?

Our existing database confirms that tectonic terrane accretion occurred in the western Pilbara at least as early as 2.9 Ga [*Hickman*, 2004] and in the Barberton granite-greenstone belt as early as 3.2 Ga [*Diener et al.*, this volume]. Therefore, horizontal displacements of relatively rigid lithospheric plates (i.e., plate tectonics) must have occurred at that time, and we expect that constructive, destructive, and transcurrent terrane boundaries existed as well. This leads to two important questions: (1) How did tectonic forces generated by plate convergence and collision interact with body forces in weak crust, inboard from plate boundaries where crustal diapirism occurred, and (2) what was the dynamic and thermal nature of early Archean subduction zones?

3. Komatiite is proportionally more abundant in Archean greenstones than in younger greenstones.

As more quantitative data have become available from greenstones, it is clear that relative to basalt, komatiite is more abundant in Archean greenstones than it is in either Proterozoic or Phanerozoic greenstones [*de Wit and Ashwal*, 1995]. The significance of this observation, however, remains elusive [*Arndt et al.*, 1998; *Grove and Parman*, 2004]. Most Archean komatiites occur in "mafic plain" type greenstones, which appear to represent remnants of oceanic plateaus or oceanic crust [*Condie*, 1994, 2003a]. If this is the case, the relative abundance of Archean komatiite may indicate that mantle plumes were more abundant before 2.5 Ga [*Xie and Kerrich*, 1994; *Kerrich et al.*, 1999; *Galer and Mezger*, 1998; *Campbell*, 1998; *Tomlinson and Condie*, 2001]. If so, this is important because it may mean that plume cooling of the mantle was more important in the Archean than afterwards. However, evidence from experimental petrology, geochemistry, and field studies suggest that at least some komatiites crystallized from water-rich magmas, perhaps associated with subduction [*Grove and Parman*, 2004]. Although both dry and hydrous komatiite magmas demand high temperatures in their mantle sources, mantle plume sources suggest temperatures of 300–500°C higher than at present, whereas subduction sources require temperatures only about 100°C higher than at present. Perhaps komatiite magma is produced in more than one mantle source; one of our future challenges is to come up with criteria to distinguish komatiites from different sources, if they exist.

So at present all we can conclude is that the relative abundance of Archean komatiites reflects higher mantle temperatures in the Archean, but it may not mean that any one tectonic setting, such as mantle plumes, was more widespread in the Archean.

4. TTG depleted in heavy rare earth elements (REE) is more widespread in the Archean than at later times.

Because TTGs are the most voluminous rock type in the preserved Archean crust, it is critical to understand their source and origin to better understand the origin and early evolution of continents. Even in the Tertiary, TTGs are an important juvenile component added to the continental crust in the Andes and other continental-margin arcs. Because of geochemical similarities of TTGs to modern high-silica adakites, they are commonly assumed to have similar origins [*Drummond and Defant*, 1990; *Martin*, 1999; *Martin et al.*, 2005], and in some cases, the two terms are used interchangeably. Both rock types exhibit strong enrichment in the most incompatible elements, with notable negative anomalies at Nb-Ta and Ti and strong depletion in heavy REE and Y [*Martin*, 1993]. Hence, as with high-silica adakites, TTGs are commonly assumed to represent melts of descending slabs, a conclusion with important implications for tectonic settings in the Archean [*Martin et al.*, 2005]. However, some investigators have pointed to dissimilarities between high-silica adakites and TTGs, and hence to different tectonic settings [*Smithes*, 2000; *Kamber et al.*, 2002; *Condie*, 2004a]. It is important to emphasize that geochemical data can be used to help constrain tectonic setting, but it cannot be used alone to reconstruct ancient tectonic settings.

Although high-Al TTG and high-silica adakite show strongly fractionated REE and incompatible element patterns, many TTGs have lower Sr, Mg, Ni, Cr, and Nb/Ta than many high-silica adakites [*Condie*, 2004a]. These compositional differences cannot be easily related by shallow fractional crystallization. While high-silica adakites are probably slab melts that have reacted with ultramafic rocks in the mantle wedge during ascent, many TTGs may be produced by partial melting of hydrous mafic rocks in the lower crust in arc systems, or in the Archean, perhaps in the root zones of oceanic plateaus [*White et al.*, 1999; *Smithes*, 2000; *Whalen et al.*, 2002; *Condie*, 2004a]. Depletion in heavy REE and low Nb/Ta ratios in Archean TTGs require both garnet and low-Mg amphibole in the restite, whereas moderate to high Sr values allow little if any plagioclase in the restite [*Foley et al.*, 2003]. To meet these requirements requires melting in the hornblende eclogite stability field between 40 and 80 km deep and between 700°C and 800°C. The thick mafic root and the descending slab models have in common the requirement of garnet and hornblende in the source restite.

If many Archean TTGs are not adakites, as appears to be the case, how do we produce a thick mafic crust during the Archean in which TTG magmas are generated? At present, two models are in the running: (1) beneath oceanic plateaus, and (2) underplated mafic crust from subduction zone magmas. Our challenge in the near future is to find geochemical and isotopic approaches to further evaluate these two models and see if either can withstand the test of time.

5. A large volume of continental crust was produced about 2.7 Ga.

Nd isotopes and detrital zircon age distributions strongly suggest a peak in production of continental crust at 2.7 Ga [*Condie*, 1998, 2000; *Bennett*, 2003; *Rino et al.*, 2004]. This peak has been related to a catastrophic mantle overturn event, which gave rise to a large number of mantle plumes [*Condie*, 1998]. Supporting a global mantle plume event at 2.7 Ga is a large peak in the frequency of plume proxies, such as komatiites, oceanic plateau basalts, flood basalts, giant dyke swarms, and large layered intrusions [*Ernst and Buchan*, 2003; *Condie*, 2003b]. In addition, flood basalt eruptions occur at this time on both the Kaapvaal (Ventersdorp, 2725–2710 Ga) and Pilbara cratons (Fortescue, 2764–2756 Ga). The formation of perhaps the first supercontinent or supercratons [*Aspler and Chiarenzelli*, 1998; *Bleeker*, 2003] followed peak crustal production by 10 to 50 My as indicated by U/Pb zircon chronology of Archean TTG-greenstones [*Condie*, 2000]. A peak in gold production between 2700 and 2650 Ma also correlates with supercontinent formation. Also consistent with a worldwide mantle plume event at 2.7 Ga is a peak in La/Yb ratios of TTGs, reflecting perhaps an increased production rate of garnet-rich, mafic crust that served as TTG magma sources. In addition, a possible sudden increase in Nb/Th ratio of plume-related basalts after 2.7 Ga may reflect rapid extraction of juvenile crust from deep mantle sources via plumes during the 2.7-Ga event [*Condie*, 2003a, b].

A catastrophic mantle plume event at 2.7 Ga also should affect the ocean/atmosphere/biosphere systems and may leave a permanent imprint in the geologic record. Possible examples include the following [*Condie et al.*, 2001; *Condie*, 2003b]: (1) Evidence for low sea level 2.7 Ga may reflect direct hits of mantle plumes beneath the only two large cratons, Kaapvaal and Pilbara; (2) relatively high Chemical Index of Alterations values in shales of this age may record global warming caused by increased input of CH_4 and/or CO_2 into the atmosphere; (3) a corresponding peak in black shale deposition may reflect increased input of nutrients into the oceans and increased anoxia related to CH_4 input; (4) a small peak in deposition of banded iron formation at 2.7 Ga may be related to enhanced hydrothermal spring activity pumping more Fe into the oceans; and (5) a well-defined decrease in $\delta^{13}C$ of kerogens at 2.7 Ga could reflect enhanced activity of methanogenic bacteria due to greater input of CH_4 into the oceans.

6. Thick lithosphere underlies many Archean cratons.

Seismic velocity distribution beneath Archean cratons suggests that the lithosphere is often unusually thick, as great s 300 km or more in some cratons [*James et al.*, 2001; *Gung et al.*, 2003]. In addition, surface heat flow is typically low within these cratons, averaging about 40 mW m^{-2} [*Nyblade* and *Pollack*, 1993]. Mantle xenoliths from beneath Archean cratons are chiefly lherzolites that are highly refractory, having undergone significant degrees of melt extraction [*Boyd*, 1989]. Most have been partially refertilized by one or more stages of penetration with metasomatic fluids [*Griffin et al.*, 1999, 2003]. Furthermore, Re/Os model ages indicate that the deep depleted keels of Archean cratons formed at or before the overlying crust, perhaps as part of the same event or events that formed the crust [*Pearson et al.*, 1995; *Chesley et al.*, 1999; *Irvine et al.*, 2001].

The origin and survival of these deep depleted roots of some Archean cratons has attracted much attention in recent years. They appear to have survived because they are cool and refractory, and thus less dense than surrounding asthenosphere. Just how they formed, however, remains controversial. Two models have been suggested. In the first, the thick keels are formed from the collection of buoyant oceanic plates beneath continental lithosphere of normal thickness. Because Earth was hotter in the Archean, oceanic plates were warmer at the time of subduction and should undergo flat subduction and perhaps accumulate as thick keels beneath the continents. One of the problems with this model is that large volumes of oceanic crust should have been plastered beneath Archean continents, and yet deep-seated mafic xenoliths (eclogite, garnet, granulite) are not common in Archean xenolith suites.

In contrast, if the depleted lherzolites carried to the surface in kimberlite pipes are representative of the deep Archean roots, and if they formed as restites from one or more dry-melting events in mantle plumes, up to 40% komatiite melt must have been extracted [*Walter*, 1999]. For a keel 200 km thick, the resulting succession of komatiites would exceed 70 km in thickness [*Rudnick*, 2004]. Because such thicknesses are not found in Archean greenstones, if this mechanism of keel formation is viable, large quantities of komatiite melt must never have reached the surface, and/or must have rapidly been recycled back into the mantle, while the restite accumulated beneath the continents. One possibility is that the melts were more dense than the restite and thus never made it to the surface [*Boyd*, 1989]. Another is that the melts somehow traveled laterally and were erupted in ocean basins to become part of the oceanic crust, which was rapidly recycled into the mantle. And still another, favored by the Fe/Mg ratio of mantle xenoliths, is that the keels represent the restite remaining after extraction of plume-type basaltic magma rather than komatiitic magma [*Herzberg*, 2004].

7. Portions of the mantle were strongly depleted in large ion lithophile elements during the Archean.

Large positive E_{Nd} values in Early Archean igneous rocks require depletion of large ion lithophile elements in at least one mantle reservoir, probably caused by extraction of continental crust [*Bennett*, 2003]. Although E_{Nd} values $\geq+3$ may reflect post-crystallization disturbance in the Sm/Nd system, values up to +2 were prevalent in the Early Archean upper mantle. If E_{Nd} values $\geq+3$ at 3.8 Ga are real, however, this is very important in that it requires extreme fractionation in the mantle within the first 400 My of Earth history.

The question of where this depleted mantle resides and how large a volume it represents is still one of disagreement. In terms of high field strength element (HFSE) ratios Nb/Th, Zr/Nb, Nb/Y, and Zr/Y, most basalts from mafic plain type Archean greenstones are similar to oceanic plateau basalts derived from mantle plume sources [*Condie*, 2003a, 2004b). The near absence of Archean greenstone basalts with HFSE ratios similar to NMORB is puzzling, and may mean that a "shallow" depleted mantle source was absent or volumetrically small in the Archean. In that case, the Archean depleted mantle source may have resided in the deep mantle, thus contributing to mantle plumes. Such a source has been documented today for at least some mantle plumes, such as Iceland [*Fitton et al.*, 1997; *Kempton et al.*, 2000]. If this is the case, we are immediately faced with the question of how this deep depleted reservoir formed. Perhaps it formed at shallow depths from extraction of early crust, and then it was recycled into the deep mantle by some catastrophic event in the first few hundred million years of Earth history?

High field strength element ratios in Archean basalts also indicate the existence of recycled components HIMU, EM1, and EM2 in the mantle by the Late Archean [*Condie*, 2003a]. This suggests that oceanic lithosphere as well as perhaps continental lithosphere were recycled into the deep mantle and became incorporated in some mantle plumes by the Late Archean. High field strength element ratios also indicate an important contribution of continental crust and/or subcontinental lithosphere to some mafic plain type Archean greenstone basalts. This implies that at least thin continental lithosphere was relatively widespread in the Archean. Such a conclusion is also supported by widespread isotopic evidence of contamination of Archean greenstone basalts by continental crust [*Tomlinson et al.*, 2004].

8. Many Archean greenstones comprise arc-like rock assemblages.

Archean greenstones can roughly be divided into two major types: those that comprise chiefly basalt and komatiite, the "mafic plain type", and those that contain calc-alkaline volcanics and related sediments, the "arc type". The arc-type greenstones are widespread in the Archean Superior province in Canada and also occur in the Yilgarn province in western Australia [*Condie and Harrison*, 1976; *Davis and Condie*, 1976; *Hallberg et al.*, 1976; *Giles and Hallberg*, 1982; *Cousens*, 2000; *Polat and Kerrich*, 2001; *Percival et al.*, 2004]. They appear to be the most important type of greenstone in the Late Archean terranes of Zimbabwe and Kenya [*Condie and Harrison*, 1976]. Although composed dominantly of pillow basalts, arc-type greenstones include up to 50% calc-alkaline volcanics, dominantly andesites and dacites [*Boily and Dion*, 2002]. In addition, these greenstones contain appreciable amounts of graywacke and felsic tuff. The Raquette Lake Formation in the Archean Slave

Province is a superb example of a volcanic–sedimentary succession that appears to represent a fragment of a continental margin arc system [*Mueller and Corcoran*, 2001]. Detailed mapping and sedimentologic studies show facies of high-energy clastic sedimentation contemporary with explosive volcanism, much like that found along modern continental margin arcs like Japan and the Andes. In recent years, the occurrence of boninite has been documented in several Archean greenstones, some as old as 3 Ga [*Boily and Dion*, 2002; *Smithes et al.*, 2004].

Most Archean terranes are bimodal in composition, as pointed out long ago by *Barker and Arth* [1976]. Some recent investigators have cited this bimodality as another argument against plate tectonics in the Archean [*Hamilton*, 1998]. However, bimodal magmatism is widespread in the Phanerozoic record, found in both continental rift systems and in many island arcs [*Yoder*, 1973; *Feiss*, 1982; *Nakajima and Arima*, 1998; *Smith et al.*, 2003; *Leat et al.*, 2003). Thus, bimodal magmatism is clearly not an Archean phenomenon and it occurs in at least two major plate tectonic settings.

To summarize: The striking similarity of lithologic associations in arc-type Archean greenstones, including boninite in some, argues strongly for a subduction-related origin for these greenstones.

9. A significant proportion of Archean greenstones contain volcanic rocks with geochemical characteristics similar to modern plume-derived basalts.

In terms of the worldwide database for greenstone belts, it would appear that about 35% of Late Archean (3.0–2.5 Ga) greenstone belts have plume affinities [*Condie*, 1994; *Tomlinson and Condie*, 2001]. Possibly as much as 80% of Early Archean greenstone belts may have plume affinities, although there are relatively few examples to base this on. These proportions of Archean plume-related greenstones are greater than those found in most post-Archean greenstones [*Condie*, 1994].

The observation that plume-related basalts and komatiites are more frequent in the Archean than subsequently rests in part on two major assumptions: (1) These volcanics are truly part of oceanic plateaus and not crust generated at ocean ridges, and (2) the relative abundance of greenstone belts with plume affinities is not a relict of preservational bias in the Archean.

Because lithologic assemblages formed at ocean ridges and mantle plumes may be similar (i.e., submarine basalts and intrusive equivalents together with minor chemical sediments), ocean ridge and oceanic plateau basalts may be difficult to distinguish from each other, especially in the Archean, when the production rate of oceanic crust was probably greater than today [*Abbott et al.*, 1994]. If Archean oceanic crust was the order of 20 km thick [*Sleep and Windley*, 1982; *Galer and Mezger*, 1998], the oceanic lithosphere would have been more buoyant and could have behaved much like an oceanic plateau. So where do we draw the line between oceanic plateau and ocean ridge basalt in greenstone successions? The following two observations favor, but do not prove, plume affinities for many Archean mafic plain greenstones [*Tomlinson and Condie*, 2001]. First of all, komatiites, which reflect higher mantle temperatures and greater melting depths than basalts [*Herzberg*, 1995] occur almost exclusively in mafic plain greenstone belts. If komatiites require a mantle plume source as previously mentioned, then komatiite-bearing greenstones should reflect mantle plume sources. The problem is that some komatiites may be formed in subduction zones, also as mentioned previously. Secondly, the Th/Ta, Zr/Nb, and Nb/Th ratios in Archean mafic plain basalts differ from these ratios in NMORB yet are similar to ratios in young oceanic plateau basalts [*Condie*, 2003a, 2004b].

If plume-related basalts are selectively preserved in the Archean, their higher frequency may reflect a preservational bias rather than a greater abundance of Archean mantle plumes. What may lead to increased preservation of plume-related greenstones in the Archean? If oceanic plateaus were more buoyant in the Archean, they would be less subductable, and during plate collisions they may have accreted to the growing continental crust [*Xie and Kerrich*, 1994; *Condie*, 1997; *Kerrich et al.*, 1999; *Polat and Kerrich*, 2001], thus selectively preserving volcanic rocks with plume sources compared to volcanic rocks with arc sources. After the Archean, when mantle temperatures fell, oceanic plateaus may have been more subductable and thus the frequency of preservation of oceanic plateau type greenstones decreased.

In any case, we are then faced with the difficult question of what proportion of the Archean ocean floor was plume-generated and what proportion was generated at ocean ridges.

10. Paleomagnetic data indicate that apparent polar wandering occurred during the Archean.

Paleomagnetic data from the Archean of the Kaapvaal craton in southern Africa indicate that there has been significant polar wandering during the Late Archean [*Layer et al.*, 1989; *Kroner and Layer*, 1992]. Results suggest that between 3450 and 2700 Ma the Kaapvaal craton moved from polar to equatorial latitudes at least twice for an average latitudinal plate velocity of 17 mm/y [*Kroner and Layer*, 1992]. Pole positions estimated from Late Archean flood basalts from the Pilbara craton in Western Australia also suggest plate movements, some at a considerably faster rate than present-day rates [*Strik et al.*, 2003; *Blake et al.*, 2004]. The minimum movement rate of plates deduced from flood basalts from Nullagine synclinorum is 10 cm/y. If such fast rates are verified by future studies, this implies that of the two mechanisms suggested for escape of the greater Archean heat flux—longer ocean ridges or faster plate motions—the latter may have been very important [*Blake et al.*, 2004].

However, perhaps the most important conclusion from the paleomagnetic data (assuming that true polar wander was minor) is that plates were moving about on Earth's surface by 3.5 Ga, and hence plate tectonics *in some form* must have been operative by this time.

WHAT'S ON THE ARCHEAN HORIZON?

With all the renewed interest in the Archean, we might ask where do we stand and where are we going? Plate tectonics, which is assumed by most investigators to have operated in the Archean, is now being challenged. And indeed, such a challenge should bring about renewed efforts to understand if and how the Archean differs from later times in Earth history. Despite the challenges, however, a wealth of geologic, geochemical, structural, volcanologic, and sedimentologic data are, at very least, consistent with plate tectonics, at least in the Late Archean. Yes, there are some differences, most of which, however, can be explained by a hotter mantle along with, at least periodically, more elevated crustal geothermal gradients, in the Archean. It would seem to us that rather than abandon plate tectonics, which so well explains so much observational data, it is better to look for differences in dynamic processes and tectonic regimes to explain the "unusual" tectonic signatures we see in the Archean geological record.

Clearly we need more precise information to answer some of the problems with Archean plate tectonics. Why is evidence not found for a shallow depleted mantle similar to that from which NMORB is derived? If the major depleted reservoirs in the Archean mantle were at great depth, how did they form? If diapirism tectonics is important on some Archean cratons but not on others, what does this mean for evolving plate tectonic regimes? If the Archean lower crust was hotter and less viscous in some cratons, so that it convected [*Collins et al.*, 1998], how did other (most?) Archean cratons escape such heating? Perhaps a thick depleted mantle keel is the answer. In that case, we must further ask why some cratons developed keels and others did not. And finally what really happened 2.7 Ga in Earth's mantle? If it was a mantle overturn event, what caused it and what effect did it have on evolving Archean tectonic regimes?

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K. Benn, Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, University of Ottawa, Ottawa, Ontario K1N 6N5, Canada. (kbenn@uottawa.ca)

K. C. Condie, Department of Earth & Environmental Science, New Mexico Institute of Mining & Technology, Socorro, New Mexico 87801, USA. (kcondie@nmt.edu)