Short-term episodicity of Archaean plate tectonics

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ABSTRACT

By combining geochemical data and geodynamical models, evidence is provided to address the existence and style of Archaean plate tectonics, a topic of vigorous debate for decades. Using careful analyses of lithostratigraphic Archaean assemblages and numerical model results, we illustrate that a short-term episodic style of subduction was a viable style of tectonics in the early Earth. Modeling results show how, due to the low strength of slabs in a hotter Earth, frequent slab break-off events prevented a modern-style long-lived subduction system, and resulted in frequent cessation and re-initiation of the subduction process on a typical time scale of a few million years. Results fit with geochemical observations that suggest frequent alternation of arc-style and non-arc-style volcanism on a similarly short time scale. Such tectonics could provide the link between early pre-plate tectonic style of tectonics (or stagnant-lid convection) and modern-style plate tectonics, in which short-term episodes of proto-subduction evolved over time into a longer-term, more successful style of plate tectonics as mantle temperature decayed.

INTRODUCTION

A key issue to our understanding of Archaean tectonics is the apparent contradiction between the petrological and structural/geophysical observations. While the former show that many Archaean felsic igneous rocks do carry an "arc" geochemical signature, structural analysis, such as the lack of clear thrust and fold belts, tectonic mélanges, or undisputed ophiolites, seems at odds with subduction-related deformation in the Archaean (e.g., Stern, 2005). Geodynamical models for Archaean tectonics also illustrate the difficulties of having modern-style stable subduction in a hotter Archaean mantle (e.g., Davies, 1992; Sizova et al., 2010; van Hunen and van den Berg, 2008).

In this study, we demonstrate that the Archaean subduction record typically corresponds to short-lived events, much shorter than in the modern Earth, and show how this fits geodynamical modeling results for Archaean subduction.

SHORT-LIVED ARCHAEAN SUBDUCTION EPISODES: THE GEOLOGICAL RECORD

One of the main arguments for the existence of Archaean subduction is geochemical; i.e., the existence of an "arc" signature in some rocks (Polat and Kerrich, 2001; Wyman et al., 2002). The core feature of the arc signature is decoupling of large-ion lithophile elements (LILE) and high-field strength elements (HFSE) (Pearce and Peate, 1995). Two relevant petrogenetic scenarios can account for this signature. Firstly, fluid-fluxed melting of a (depleted) upper mantle, with LILE being preferentially carried over HFSE (Pearce and Peate, 1995) will form mafic to intermediate "arc" rocks. As this requires burying of hydrated surface matter down into the mantle, it is commonly taken as evidence for subduction. Secondly, Archaean granitoids forming the widely occurring TTG (tonalites, trondhjemites, and granodiorites) suite (Martin, 1994) also carry an arc signature, which reflects melting of mafic compositions (Moyen and Stevens, 2006), with stable rutile and/or amphibole in the residuum trapping HFSE (Foley et al., 2002). TTGs are actually rather ambiguous as a subduction marker; while the genesis of part of the TTG group (with very high La/Yb and low HFSE) does require high-pressure melting, at 20 kbar or more (Halla et al., 2009; Moyen, 2011), and can therefore be regarded as a subduction indicator, it is equally possible to form TTG(-like) rocks at much lower pressure (Willbold et al., 2009). TTGs are a composite group made of a range of distinct rock types, and some care must be exercised in using them as evidence for subduction.

In the Western Abitibi in the Superior Province, Canada, several lithostratigraphic "assemblages" and concomitant plutonic complexes have been recognized and analyzed, each representing a distinct age between 2750 and 2670 Ma (Ayer et al., 2004). Different assemblages clearly show distinct geochemical affinities (Fig. 1; see the review in Benn and Moyen, 2008): (1) an "arc" affinity (calc-alkaline associations), (2) a "plume" affinity (komatiites and tholeitic basalts), or (3) a bimodal affinity with both types of rocks present. TTGs from the nearby Kenogamissi complex (Benn and Moyen, 2008) show a similar pattern. An early group of ca. 2740 Ma "low-pressure TTGs" (Moyen, 2011) was interpreted by Benn and Moyen (2008) as melting at the base of an oceanic plateau, and are synchronous with the "plume" Pacaud assemblages. In contrast, the ca. 2710 Ma tonalitic plutons of the Kenogamissi complex (Kidd-Munro to Tisdale time) show a clear "deep" signature. The 2720–2740 Ma Gogama orthogneisses show a more heterogeneous signature, as can be expected from a complex of tectonically mixed rocks (Benn, 2004); at least part of the gneisses show a "deep" signature, and Benn and Moyen (2008) suggested that this would correspond to the "Deloro-age" portion of the orthogneisses. So, the "subduction" events in the Western Abitibi, as recorded by both plutonic and volcanic geochemical record, seem to occur in three to four discrete events, all of them short-lived (5–10 Ma) and superimposed on a "background" plume-like activity.

Although not always so well documented, a similar pattern can be observed throughout the Archaean (see the GSA Data Repository[1]). In the paleo-Archaean East Pilbara (Australia) (felsic interruptions in the Warrawoona groups; Smithies et al., 2007; Van Kranendonk et al., 2007), as well as in the Barberton Belt of South Africa) (H6 unit and concomittant Theespruit and Stolzburg TTG plutons; Lowe and Byerly, 2007) rare felsic layers that can be regarded as evidence for subduction correspond to ca. 10 Ma intervals, interlayered in a dominantly "plume" sequence. The well-characterized meso-Archaean assemblages of boninites, and light rare earth element (LREE)-enriched basalts in the Whim Creek Belt and the Mallina basin of the West Pilbara (Smithies et al., 2005; Smithies and Champion, 2000), are equally short-lived; the longest (in the Whundo group) not exceeding 20 m.y. A similar episodicity is observed in the Zimbabwe craton (Rollinson, 2011), with four short "arc" events between 2.74 and 2.62 Ga.

In contrast, Phanerozoic (and late-Proterozoic) subduction is much longer (see the Data Repository). The duration of a subduction in an accretionary orogen is commonly on the order of 100 m.y.; individual pulses of arc-related magmatism, such as calc-alkaline batholiths, are commonly in the region of 20–40 m.y., five times more than the Archaean subduction events identified here. This suggests that Archaean subduction events were

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[1]GSA Data Repository item 2012131, Figure DR1 (geochemical features of mafic rocks for the assemblages used in Figure 1), Figure DR2 (comparison of the duration of Archean "arc" events and recent subduction periods), and Movie DR1 (numerical modeling setup and animation), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

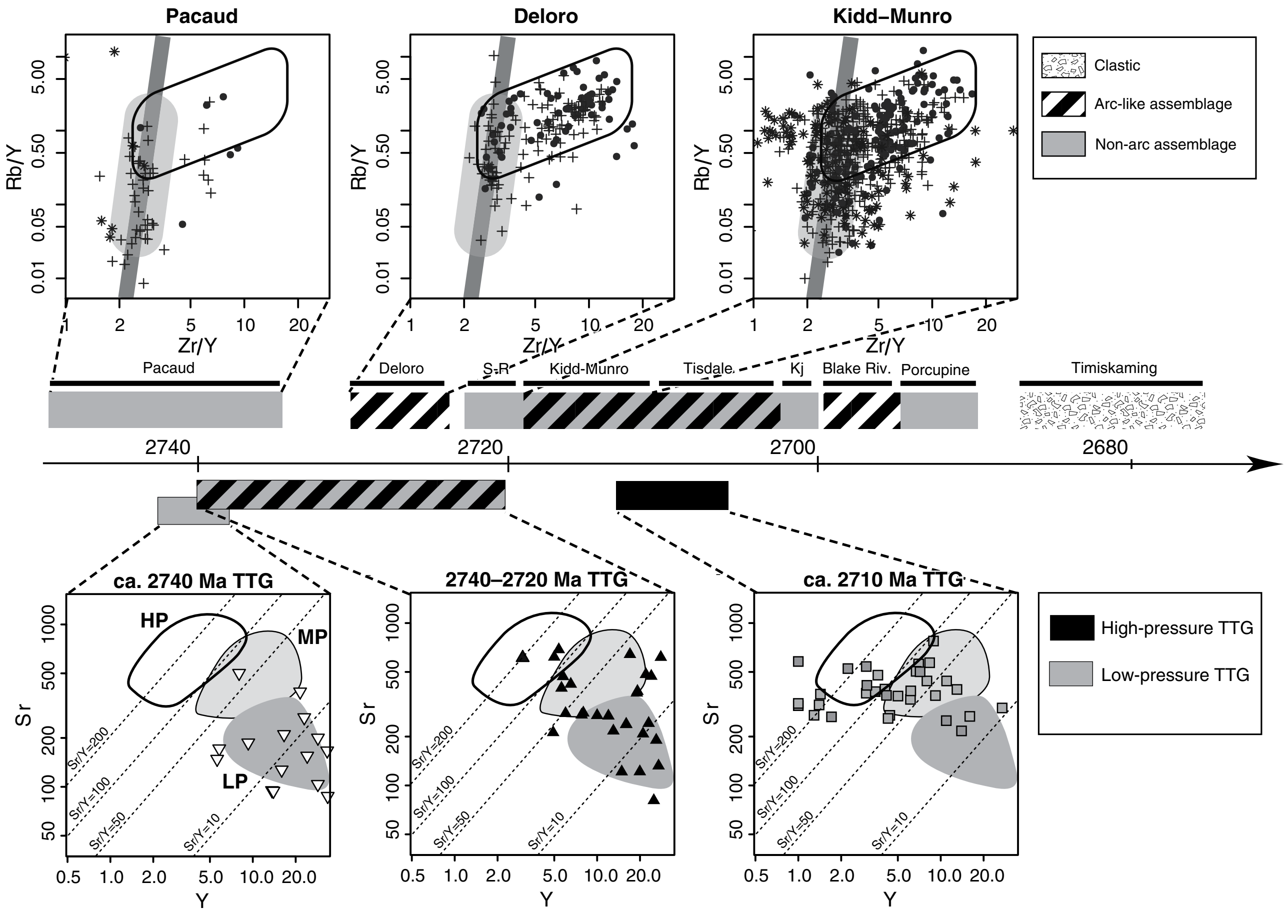

Figure 1. The succession of "arc" and "non-arc" events in the Western Abitibi, Canada (time line, middle, and top legend) is geochemically defined by (1) the nature of mafic (SiO_2 <62%) lava assemblages (top; data from http://www.discoverabitibi.com/, and Ayer at al. [2004]), and (2) concomitant (tonalites, trondhjemites, and granodiorites: TTG) plutons in the Kenogamissi complex, Abitibi greenstone belt (bottom; modified from Benn and Moyen, 2008). For mafic lavas, Rb/Y versus Zr/Y allows us to take into account X-ray fluorescence analyses from the database that lack a whole set of trace elements; Th/Yb versus Nb/Yb (see the Data Repository [see footnote 1]) show the same pattern. Symbols reflect the major element characteristics of the samples, based on Jensen (1976) classification: circles—calc-alkaline; crosses—komatiitic; stars—tholeitic. The main criteria used to classify an assemblage as "arc" or "non-arc" are (1) the position in these diagrams (omitting outliers); (2) the presence or absence of komatiites; and (3) the existence of intermediate to acid calc-alkaline lavas (not plotted here). (See details in Benn and Moyen, 2008; Kerrich et al., 1999a; Kerrich et al., 1999b; Sproule et al., 2002; Wyman, 2003; Wyman et al., 2002). Three examples (the "non-arc" Pacaud, the "arc" Deloro, and the "mixed" Kidd–Munro assemblage) are displayed; see Appendix DR1 (see footnote 1) for the whole stratigraphy. For plutonic rocks, the age determinations are slightly less precise and do not allow a perfect fit with the supracrustal stratigraphy. The ca. 2710 Ma plutons (synchronous with subduction-related lavas in the greenstone belt stratigraphy) belong to the low-HREE (high rare earth element), high-pressure group defined by Halla et al. (2009) and Moyen (2011), and are geochemically clearly different from older TTG. They are synchronous with the emplacement of the Kidd–Munro and Tisdale assemblages, which do contain an "arc" component. In contrast, ca. 2740 Ma low-pressure TTGs occur at the same time as the non-arc Pacaud assemblage. In between, the long-lived Gogama gneisses contain both low- and high-pressure components, and cover a time period corresponding to both the "arc" Deloro period, and the "non-arc" Pacaud.

uniquely short-lived compared to their modern counterparts, and requires a geodynamic explanation.

GEODYNAMICAL MODELS OF ARCHAEAN SUBDUCTION—WHY SUBDUCTION WAS DIFFERENT IN THE ARCHAEAN

The primary cause for potentially different tectonic styles in the Archaean is the change in the thermal regime on Earth (van Hunen et al., 2008). The Archaean mantle was hotter than today, and cooled by ~100 K/G.y., as evidenced by liquidus temperatures and MgO contents of basaltic lavas through time (Abbott et al., 1994; Herzberg et al., 2010). This resulted in (1) more extensive mantle partial melting, and (2) reduced plate strength. More melting gave more (oceanic) crustal production: a 200–300 K hotter mantle resulted in a 15–23-km-thick crust (van Thienen et al., 2004). Near the surface, crustal material is significantly less dense than mantle material, and this adds to the buoyancy of oceanic lithosphere. Because today's plate tectonics is primarily driven by negative buoyancy of downgoing slabs, Archaean plates might have been difficult to subduct, although eclogitization of basalt might help (van Hunen and van den Berg, 2008). As mantle rock weakens by about one order of magnitude for every 100 K temperature increase, plates were likely weaker by up to 2–3 orders of magnitude.

In an attempt to capture the effects of this combination of processes on the characteristics of Archaean subduction, we performed a series of numerical model calculations for various mantle temperatures, ranging from today's mantle temperature to 300 K warmer. The details of the model setup are further elaborated in the Data Repository. Figure 2

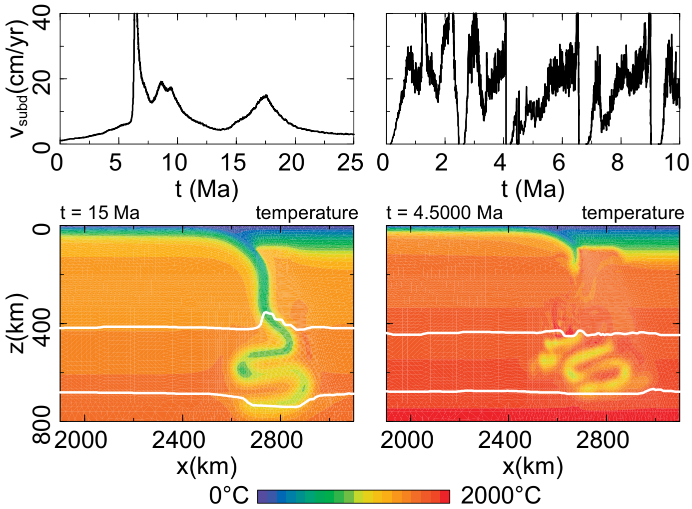

Figure 2. Numerical model calculations for subduction dynamics through time. Left: Subduction velocity (top) and subduction dynamics (bottom) for the present-day mantle potential temperature and 7-km-thick oceanic crust, illustrating a coherent, continuously subducting slab. Right: Subduction in a 200 K hotter mantle with a 15-km-thick oceanic crust. A weaker slab results in intermittent subduction due to frequent slab break-off events. Further details about the model calculations are provided in the Data Repository (see footnote 1) and in van Hunen and van den Berg (2008).

summarizes the typical model results, in which the subduction process for a Phanerozoic setting is compared to an Archaean setting (with an assumed 200 K hotter mantle). The Phanerozoic model illustrates continuous subduction with a typical 5–10 cm/yr convergence rate, representative for today's subduction. The Archaean setting displays a different behavior, as slabs frequently break off from the trailing plate and sink down into the transition zone. This change in subduction behavior is a consequence of several effects: (1) the thicker oceanic crust creates a larger tensile stress between the buoyant crust near the surface and the dense (eclogitic) crust at depth; (2) due to the larger average subduction velocity, oceanic plates are younger and therefore thinner and weaker when arriving at the trench; (3) a weaker mantle leads to more vigorous sublithospheric small-scale convection and subsequent lithospheric thinning (van Hunen et al., 2005); (4) the thick, intrinsically weaker oceanic crust leads to a reduced integrated strength of the subducting plate; and (5) the weaker mantle provides less support for the sinking slab. This combination of effects leads to weaker slabs that cannot maintain the encountered tensile stresses during subduction, and therefore frequently yield in the form of slab breakoff. Such breakoff would lead to a temporal loss of slab pull, and a period in which subduction would be absent or very slow, with no or very little volatile input in the mantle, and subsequent magmatic quiescence.

These results suggest a subduction episodicity of a few million years, but the exact duration of break-off events is somewhat uncertain. The duration of modern, continental collision-triggered events is a topic of significant debate, with estimates ranging from a few million years up to 20 m.y. (Andrews and Billen, 2009; Duretz et al., 2011; van Hunen and Allen, 2011). This is controlled by a range of geodynamical parameters, most of which are unconstrained for the generic Archaean scenario studied here.

DISCUSSION AND CONCLUSION

The use of a geochemical "arc" signature as a marker of subduction is debatable. Firstly, a range of petrogenetic processes can yield "arc" signatures (Bédard et al., 2010; van Hunen and Moyen, 2012), and burial of mafic rocks in the mantle is not the only option; however, the close temporal association of distinct types of rocks, all with some kind of arc affinity, suggests that this petrogenetic scenario is still the most likely on a regional scale (Smithies et al., 2005). Secondly, the burial of mafic rocks in the mantle can occur in nonsubduction environments (e.g., by delamination of the mafic crust; Bédard, 2006), but in these models, it is unclear how hydrous rocks are transported down. We acknowledge, however, that geochemistry puts only weak constraints on the size and shape of the buried parcels of mafic rocks. Thirdly, there may be preservation issues such that some time slices could be missing, therefore creating an apparent episodicity. However, in the Abitibi case (as in most other examples cited), we do have a continuous or nearly continuous stratigraphic record, without long breaks (Fig. 1; see the Data Repository). Therefore, we can confidently state that no known event of "arc" magmatism in the Archaean lasted longer than a few tens of millions of years.

Cessation of arc magmatism can occur for reasons other than slab breakoff. (1) During modern subduction of oceanic buoyant plateaus, magmatism ceases temporarily due to flattening of the subducting slab. Such a mechanism, however, is not likely to be viable in an Archaean, hotter mantle (van Hunen et al., 2004). (2) Modern subduction stops with continental collision, and the same probably occurred in the Archaean as well. Depending on the intermediate ocean size, Phanerozoic collision intervals varied from a few to several hundred million years (i.e., a much larger range than observed in the Archaean rock record), and applying this mechanism to the observed short-lived "arc" signature would suggest a dramatic change of the size of ocean basins throughout Earth history. The mechanism of spontaneous, frequent slab breakoff of weak slabs in a hotter Earth is more appealing, because it only requires a (well-accepted) change in mantle temperature to explain the difference between Archaean and modern subduction dynamics. It does provide an elegant explanation to the classical interleaving of both "arc" and "plume" rocks in Archaean rock sequences (i.e., plume-arc interaction; Wyman et al., 2002).

We do not know when the plate tectonics–style of convection started on Earth, with estimates ranging from nearly 4.5 Ga. down to 2 Ga (or even later according to some authors; Stern, 2005). Our work suggests a way to evolve a single-plate, stagnant lid style of tectonics into modern plate tectonics. Early subduction events in a hot mantle were small and short. As the mantle cooled down, the size and duration of the downwellings increased, and they evolved into proper, permanent subduction. This short-term episodicity may have been superimposed to a longer-term periodicity (100 m.y.), related to episodic mantle overturns (Davies, 1995), supercontinent formation and breakup (Silver and Behn 2008), or to intermittent plate locking (O'Neill et al., 2007). Therefore, plate tectonics may not have "appeared," but rather matured, over a long period of time (perhaps of several gigayears), during which subduction became progressively more widespread, efficient, and stable.

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