Geoscience Frontiers xxx (2017)

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Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

GEOSCIENCE FRONTIERS

Stagnant lids and mantle overturns: Implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics

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A R T I C L E I N F O

Article history:
Received 30 May 2016
Received in revised form
25 November 2016
Accepted 11 January 2017
Available online xxx

Keywords:
Archaean
Mantle-overturn
Stagnant-lid
Continental crust
Oceanic crust
Subcretion

A B S T R A C T

The lower plate is the dominant agent in modern convergent margins characterized by active subduction, as negatively buoyant oceanic lithosphere sinks into the asthenosphere under its own weight. This is a strong plate-driving force because the slab-pull force is transmitted through the stiff sub-oceanic lithospheric mantle. As geological and geochemical data seem inconsistent with the existence of modern-style ridges and arcs in the Archaean, a periodically-destabilized stagnant-lid crust system is proposed instead. Stagnant-lid intervals may correspond to periods of layered mantle convection where efficient cooling was restricted to the upper mantle, perturbing Earth's heat generation/loss balance, eventually triggering mantle overturns. Archaean basalts were derived from fertile mantle in overturn upwelling zones (OUZOs), which were larger and longer-lived than post-Archaean plumes. Early cratons/continents probably formed above OUZOs as large volumes of basalt and komatiite were delivered for protracted periods, allowing basal crustal cannibalism, garnetiferous crustal restite delamination, and coupled development of continental crust and sub-continental lithospheric mantle. Periodic mixing and rehomogenization during overturns retarded development of isotopically depleted MORB (mid-ocean ridge basalt) mantle. Only after the start of true subduction did sequestration of subducted slabs at the core-mantle boundary lead to the development of the depleted MORB mantle source. During Archaean mantle overturns, pre-existing continents located above OUZOs would be strongly reworked; whereas OUZO-distal continents would drift in response to mantle currents. The leading edge of drifting Archaean continents would be convergent margins characterized by terrane accretion, imbrication, subcretion and anatexis of unsubductable oceanic lithosphere. As Earth cooled and the background oceanic lithosphere became denser and stiffer, there would be an increasing probability that oceanic crustal segments could founder in an organized way, producing a gradual evolution of pre-subduction convergent margins into modern-style active subduction systems around 2.5 Ga. Plate tectonics today is constituted of: (1) a continental drift system that started in the Early Archaean, driven by deep mantle currents pressing against the Archaean-age sub-continental lithospheric mantle keels that underlie Archaean cratons; (2) a subduction-driven system that started near the end of the Archaean.

1. Introduction

Although plate tectonics is the fundamental unifying theory in the Earth sciences there is no consensus on when or how it began. Modern plate tectonics is often described as subduction tectonics because the pull of subducting slabs is the strongest plate driving force (Forsyth and Uyeda, 1975; Chapple and Tullis, 1977; Richardson, 1992; Bercovici et al., 2000; Anderson, 2001; Conrad and Lithgow-Bertelloni, 2002, 2004; Hamilton, 2007). The andesitic bulk composition of continental crust inspired proposals that continents grew by assembly of subduction-generated oceanic arc terranes, or by maturation of subduction zones into continental arcs (Taylor, 1967; Langford and Morin, 1976; Kelemen, 1995; Davidson and Arculus, 2006; Percival et al., 2006; Lee et al., 2007; Shirey et al., 2008; Polat, 2012; Arndt, 2013; Jagoutz and Kelemen, 2015). For genesis of Archaean continental crust,

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Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2017.01.005

volumetrically dominated by the TTG suite (Tonalite, Trondhjemite and Granodiorite: Martin, 1987; Moyen and Martin, 2012), some see a major role for garnet-facies melting of subducted oceanic crust in a hotter ambient mantle (Martin, 1986, 1993; Rapp et al., 1991; Arculus, 1999). It is also proposed that much of the juvenile input that feeds continental crustal growth through time was added through subduction-driven accretion of plume-generated oceanic plateau crust (Boher et al., 1991; Hill et al., 1992; Stein and Goldstein, 1996; Abbott et al., 1997; Albarède, 1998; Arculus, 1999; Benn and Kamber, 2009), with subsequent reworking and refining of the accreted juvenile plateau crust by ongoing or later subduction magmatism and terrane collisions. Given the paramount role proposed for subduction in these continental crustal growth scenarios it is vital to test these hypotheses by unambiguously identifying subduction products in the geological record. Correct identification of ancient arcs is particularly important, because other plate tectonic manifestations (ridges, transforms) have low-to-nil preservation potentials. Alternative non-plate tectonic subduction-less mechanisms for Archaean continental crust genesis involve remelting the base of magmatically or tectonically thickened basaltic crustal sections, or of delaminated lower crust (Campbell and Hill, 1988; Zegers and van Keken, 2001; van Thienen et al., 2004a,b; Smithies et al., 2005a; Bédard, 2006; Van Kranendonk et al., 2007b).

Today, it is possible to see robust volcanic arcs (arcuate chains of active volcanos) located above seismically detectable dipping oceanic slabs, and to directly measure convergence between upper and lower plates. Identification of subduction in the rock record, however, requires recognition in the field and laboratory of characteristic volcanic arc-related lithofacies and geochemical signatures, and that the rock facies that characterize fore-arc, arc, and back-arc environments should have the correct architecture (cf. Condie, 2015). This becomes increasingly difficult in the deep past due to degradation of the geological record (e.g. Goodwin, 1996; Myers, 2001; Cawood et al., 2013), leading to over-dependence on geochemical palaeotectonic classifications (e.g. Pearce and Cann, 1973; Pearce and Norry, 1979; Wood, 1980). Unfortunately, trace element signatures commonly used to identify arc magmas are mimicked by crustal contamination, making black-box classifications especially unreliable for ensialic basalts, such as the eponymous continental flood basalts and many Archaean basalts (e.g. Wang and Glover, 1992; Green et al., 2000; Pearce, 2008; Condie, 2015; Li et al., 2015).

A second major criterion used to identify ancient arcs is evidence for compressional tectonics (terrane thrusting, nappes, regional folding and shearing); on the assumption that horizontal tectonics is equivalent to plate tectonics. Mapping and structural studies have recognized compressional horizontal tectonics and terrane assembly in Archaean accretionary orogens (Van Kranendonk et al., 2002; Percival et al., 2004; Tomlinson et al., 2004; Smithies et al., 2005b; Nutman and Friend, 2007, 2009; Boily et al., 2009; Windley and Garde, 2009; Czarnota et al., 2010; Kisters et al., 2010; Chardon et al., 2011; Hickman and van Kranendonk, 2012; Leclerc et al., 2012; Polat et al., 2015). On the other hand, compelling evidence for vertical tectonics in Archaean granite greenstone terrains, typically with shear sense indicators indicating ascent of granitoid domes and coeval development of pinched supracrustal synclines, has led to increasing acceptance of sagduction/partial convective overturn as an important Archaean intra-crustal redistribution and maturation process (Mareschal and West, 1980; Hickman, 1984; Choukroune et al., 1995; Chardon et al., 1996, 1998; Collins et al., 1998; Bailey, 1999; de Bremond d'Ars et al., 1999; Van Kranendonk et al., 2002, 2004, 2007a, 2009; Bédard et al., 2003, 2013; Robin and Bailey, 2009; Lin et al., 2013; Thébaud and Rey, 2013; François et al., 2014; Kamber, 2015; Wiemer et al., 2016). Although vertical tectonic models have long been viewed as the an-Archic antithesis of plate tectonics, this is a false dichotomy as the two tectonic styles are not mutually exclusive, and evidence for coeval vertical and horizontal tectonics is now recognized in the Archaean record (Lin, 2005; Van Kranendonk, 2010, 2011a; Bédard et al., 2013; Lin et al., 2013; Harris and Bédard, 2014a,b). So the key question is not whether there was vertical *or* plate tectonics in the Archaean, but whether horizontal tectonics necessarily requires modern-style plate tectonic driving forces?

Bédard et al. (2013) and Harris and Bédard (2014a,b) argued that the distinctive Archaean rock associations, structures and geochemical signatures are best explained if continental drift started very early in Earth's history (ca. 3.9 Ga), long before active subduction (ca. 2.5 Ga), allowing horizontal tectonics and terrane accretion to occur throughout the Archaean in the absence of subduction. They argued that Archaean continental drift (like modern continental drift) is primarily the result of a traction force exerted by mantle flow on the Archaean-age sub continental lithospheric mantle (SCLM) keel that underlies cratons (cf. Forsyth and Uyeda, 1975; Bokelmann, 2002a,b; Bokelmann and Silver, 2002; Eaton et al., 2004; Conrad and Lithgow-Bertelloni, 2006; Eaton and Frederiksen, 2007; Husson et al., 2012; Kaban et al., 2015). Harris and Bédard (2014a,b) corroborated this hypothesis by documenting Himalayan-style orogenesis and extrusion tectonics on Venus, a planet lacking subduction zones and spreading ridges, implying that horizontal tectonics and continental drift cannot simply be equated to uniformitarian plate tectonics. Instead, Harris and Bédard (2014b) proposed that plate tectonics today is constituted of two systems: (1) a bottom-up continental drift system driven by mantle currents that started in the Early Archaean; and (2) a top-down subduction-driven system that began near the Archaean/Proterozoic boundary. In this discussion paper, the Archaean subduction-less continental drift model is combined with existing (and some new) field, structural, metamorphic and geochemical data, and with concepts emerging from recent thermo-mechanical models, so as to develop an overarching non-plate tectonic hypothesis of Archaean geodynamics and magmagenesis.

The debate about how and when plate tectonics began is handicapped by terminological ambiguities and imprecision. I argue that many differences of opinion regarding Archaean tectonics and magmagenesis can be resolved if a formal distinction is made between active subduction and passive subcretion/imbrication. I also suggest that although the upwelling zones of Archaean mantle overturns are plume-like in their physics, they differ from modern plumes in scale, longevity and possibly source chemistry. The definitions of reworking and recycling from Hawkesworth et al. (2010) are slightly modified. Crustal reworking: the remobilization of pre-existing crust (mafic or felsic) by partial melting or erosion at sites within the crust. Recycling: the introduction of crust (either oceanic or continental) into the mantle by whatever process (subduction, delamination or foundering), making it available for resampling by younger mantle melting events.

2. Active subduction

Active subduction of oceanic lithosphere characterizes many convergent margins and is a fundamental part of plate tectonics today. The purpose of the review that follows is to provide a point of comparison for putative Archaean analogues, so as to show how pre-2.5 Ga convergent margin environments may have differed from modern ones.

Active Subduction is a process by which oceanic lithosphere descends in an organized manner as a coherent slab into the mantle

Please cite this article in press as: Bédard, J.H., Stagnant lids and mantle overturns: Implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics, Geoscience Frontiers (2017), http://dx.doi.org/10.1016/j.gsf.2017.01.005