Geoscience Frontiers xxx (2017) 1–15

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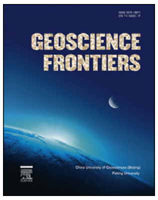
Geoscience Frontiers

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



Research paper

Do cratons preserve evidence of stagnant lid tectonics?

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ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form
1 February 2017
Accepted 10 February 2017
Available online xxx

Keywords:
Archean
Mantle overturn
Superior Province
Mantle plumes
Stagnant lid tectonics

ABSTRACT

Evidence for episodic crustal growth extending back to the Hadean has recently prompted a number of numerically based geodynamic models that incorporate cyclic changes from stagnant lid to mobile lid tectonics. A large part of the geologic record is missing for the times at which several of these cycles are inferred to have taken place. The cratons, however, are likely to retain important clues relating to similar cycles developed in the Mesoarchean and Neoarchean. Widespread acceptance of a form of plate tectonics by ~3.2 Ga is not at odds with the sporadic occurrence of stagnant lid tectonics after this time. The concept of scale as applied to cratons, mantle plumes and Neoarchean volcanic arcs are likely to provide important constraints on future models of Earth's geodynamic evolution. The Superior Province will provide some of the most concrete evidence in this regard given that its constituent blocks may have been locked into a stagnant lid relatively soon after their formation and then assembled in the next global plate tectonic interval. Perceived complexities associated with inferred mantle plume – volcanic arc associations in the Superior Province and other cratons may be related to an over estimation of plume size. A possible stagnant lid episode between ~2.9 Ga and ~2.8 Ga is identified by previously unexplained lapses in volcanism on cratons, including the Kaapvaal, Yilgarn and Superior Province cratons. If real, then mantle dynamics associated with this episode likely eliminated any contemporaneous mantle plume incubation sites, which has important implications for widespread plumes developed at ~2.7 Ga and favours a shallow mantle source in the transition zone. The Superior Province provides a uniquely preserved local proxy for this global event and could serve as the basis for detailed numerical models in the future.

1. Introduction

Cyclic or episodic geodynamics on Earth are suggested by the crustal growth record, despite potential issues related to preservational bias (e.g., Cawood et al., 2013). Cited types of evidence include episodic age spectra in orogenic granites and other rock types, Hf isotope–zircon U-Pb trends that intersect the mantle Depleted Mantle line at Hadean and early- to mid-Archean ages, and Os depletion ages in cratonic xenolith sulphides (Condie and Aster, 2010; Griffin et al., 2014; O'Neill et al., 2015). Other evidence, such as the preservation of ^{142}Nd anomalies in ~2.7 Ga lavas, is interpreted explicitly in terms of prior stagnant lid episodes (Debaille et al., 2013). Collectively, these observations favour alternating stagnant and mobile lid regimes on the early Earth.

Computer-based studies that examine plate tectonics versus stagnant lid or other geodynamic regimes on the early Earth (see Gerya, 2014 for a review) highlight a variety of possible controls on transitions between these regimes. The 2D petrological–thermomechanical modelling of Sizova et al. (2010), for example, identified an abrupt transition from "pre-subduction" regimes, where self-sustained subduction is not achieved despite an imposed convergence of plates, to recognizable subduction processes. The modelled transition occurred over a mantle temperature interval that is 175–160 K above present-day values, which allows for a variety of geodynamic possibilities where plate tectonics may emerge intermittently, or locally, on the Archean Earth. Rolf and Tackley (2011) undertook 3D spherical mantle convection modelling that showed increasing the ratio of cratonic lithosphere thickness versus oceanic lithosphere promotes plate tectonics whereas intermediate values promote episodic mobile-stagnant lid scenarios and small ratio values promote a stagnant lid regime. In reality, mantle thermal regimes and cratonic characteristics are related, as has been demonstrated by Rey and Coltice (2008) who found that the typical topography of cratons was unlikely to have exceeded 2500 m prior to the Neoarchean because this period

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

http://dx.doi.org/10.1016/j.gsf.2017.02.001
1674-9871/

Please cite this article in press as: Wyman, D., Do cratons preserve evidence of stagnant lid tectonics?, Geoscience Frontiers (2017), http://dx.doi.org/10.1016/j.gsf.2017.02.001

coincided with the crossing of a rheological threshold in the supporting lithosphere.

O'Neill et al. have approached the issue of Hadean and Archean geodynamics from the perspective of available evidence for episodic cratonic growth in the geological record (O'Neill et al., 2007, 2015; Griffin et al., 2014). Their recent models emphasize a cyclic behaviour through Earth's early history where a stagnant lid regime associated with heat retention in the mantle is interspersed with major crustal over turn events. They suggest that these brief plate tectonic-like intervals start when the convecting mantle breaks through the overlying lid. Massive mantle heat loss is inferred to result during these mobile lid intervals, which results in a new thin buoyant stagnant lid that resists subduction. None of the present models provide a clear picture of how such a cyclic regime may evolve, with diminished mantle temperatures, into the Neoarchean.

Feedback between new numerical models and geological observations can drive advances in our understanding of the early Earth's evolution although not necessarily in a steady progression. Geological context has already extracted intriguing insights from the limited Hadean record available. For example, Kamber (2015), Nutman (2001) and others have noted that most Hadean zircons are found in Neoarchean and Proterozoic sedimentary rocks. This distribution points to some form of isolation and storage of Hadean material and is clearly a fundamental constraint on the long-term evolution of some Hadean crust. By itself, this observation can only exclude certain models but if combined with enough other observations, then it may contribute to a cascade effect that brings us to consensus. This paper considers the cratonic record in an attempt to identify other features that might help to resolve geodynamic uncertainties.

2. Plate versus stagnant lid tectonics in the Neoarchean

2.1. Persistent arguments against Archean plate tectonics

A common view, or "quasi-consensus" of geologists and geomodellers is that something approaching modern-style plate tectonics became prominent between 3.2 and 2.7 Ga (Stern et al., 2016). For most workers, acceptance of this view does not exclude the penecontemporaneous presence of upwelling thermal or thermochemical mantle plumes. To some extent, the definition of what constitutes plate tectonics is the cause of dissent from the prevailing view. For example, Stern et al. (2016) referred to "deep subduction" as a key feature, whereas many others consider subduction of any sort to be the main criteria and argue in any case for a gradual transition to modern plate tectonic styles (Gerya, 2014).

The absence of Archean blueschists has been cited frequently as evidence against plate tectonics (e.g., Bédard, 2006; Hamilton, 2011; Stern et al., 2016). A wide range of responses have been provided as counter arguments, including subduction occurring along hotter mantle gradients or the possibility that Archean high MgO rocks were not suitable for development of blueschist mineral assemblages (Palin and White, 2016 and references therein). Other workers claim that Archean paired metamorphic belts of low-dt/dP and high-dT/dP have in fact been identified (e.g., van Hunen and Moyen, 2012). If such paired belts represent accretionary origins situated at the margins of late Archean cratons, then most were likely to have been subsequently subjected to collisional orogens and transformed beyond recognition. An alternative and more durable type of evidence for the subduction cold finger effect is suggested by the occurrence of diamonds in Neoarchean shoshonitic lamprophyres derived from shallow mantle depths and requiring a perturbation of the mantle geotherm in a mantle wedge by shallow subduction to permit diamond stability (Wyman et al., 2006; Smart et al., 2016). The term "shallow subduction" used here does not refer to the flat, wedge-less, scenario of the type proposed by Smithies et al. (2003).

Many workers have pointed out that geochemistry alone cannot distinguish between plate tectonics and alternative Archean geodynamic scenarios. Although Archean mantle plume events have been often argued on the basis of komatiites alone, very few authors in recent decades have suggested Neoarchean plate tectonic models based on the existence of a single rock type. When suites of associated rocks are considered in terms of the spatial and temporal context, and include mantle-derived varieties, then it is much more difficult to generate multiple viable geodynamic scenarios. This is particularly true where those rock suites include boninites and lamprophyres (Kerrich et al., 1998; Wyman et al., 2002), which most workers agree require wet upper mantle magmas and volumes of H_2O that cannot be provided by sagduction or drip tectonics (e.g., Rollinson, 2007). A version of the "geochemical" argument against Neoarchean plate tectonics has been an emphasis on the paucity of typical andesites in greenstone belts of that age (e.g., Bédard, 2006). This argument has always ignored models that invoke slab melting as a common product of Archean subduction, which implies a mantle wedge environment that is distinct from the ones associated with most younger andesites. It also requires rejection of the most common interpretation of the "sanukitoid" suite, which is generally attributed to mantle wedge or lithospheric sources that have been metasomatised by slab melts (Martin et al., 2009). Recent re-evaluations of the processes that generate post-Archean andesites provide other insights. If "relamination" via the return of subducted sediments in diapirs to the base of the crust is a major process in the formation of younger andesites (Hacker et al., 2011; Marschall and Schumacher, 2012), then there are obvious reasons why such rocks were rare prior to ~2.7 Ga: the process requires stable emergent crust as a sediment source that was not common until the end of the Archean (Flament et al., 2008). Maunder et al. (2016) suggested yet another complication, which is that under Archean conditions mafic rocks rather than sediments may have been relaminated. The end result is similar to the Archean slab melting model (Martin, 1999) in that it results in broadly "adakitic" magmas.

One alternative geodynamic model proposed by Moore and Webb (2013) for pre-plate tectonic Earth invokes heat pipes, which are "conduits that transfer heat and material from the base of the lithosphere to the surface" (p. 501). These authors envisage heat pipe volcanism as a global process that generated constant resurfacing and may have dominated Earth prior to the onset of plate tectonics that they accept emerged at around 3200 Ma. If, however, Archean boninites do represent the melting of depleted upper mantle that has been re-enriched mainly by hydrous fluids, then the 3.8–3.7 Ga Isua examples are difficult to reconcile with the heat pipe model. Cooled crustal material, possibly hydrated, is rapidly advected downward in the Moore and Webb (2013) model as new volcanic layers are added at surface. It seems likely that in this burial process water would be driven upwards into overlying sequences to generate intra-crustal melting. There also appears to be no place in the model for a region of upper mantle that is chemically analogous to the depleted mantle wedge in a (proto-) arc setting. Heat pipe processes have been invoked for other planets in the solar system (Moore and Lenardic, 2015) and in the case for Earth, Moore and Webb (2013) applied the concept based on the consensus view regarding the onset of plate tectonics rather than deriving the date from their model. If the evidence for a form of subduction at 3.8 Ga becomes widely accepted, then it could perhaps still be argued that the geodynamic transition period they envision corresponds to the Hadean-Archean boundary.

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