Earth and Planetary Science Letters 388 (2014) 1–8

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Did the formation of D″ cause the Archaean–Proterozoic transition?

Ian H. Campbell *, Ross W. Griffiths

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 6 November 2013
Accepted 23 November 2013
Available online 12 December 2013
Editor: C. Sotin

Keywords:
mantle plumes
Archaean–Proterozoic boundary
komatiites
picrites
plume temperatures
D″

ABSTRACT

The MgO content of the highest MgO plume-related komatiites and picrites remained constant at 32 ± 2.5% between 3.5 and 2.7 Ga, then fell to 21 ± 3% by ca. 2.0 Ga, a value similar to the present day value. Because there is a linear relationship between the liquidus temperature of dry magmas and their MgO content this observation implies that the temperature of mantle plumes changed little between 3.5 and 2.7 Ga, and then fell by 200–250 °C between 2.7 and 2.0 Ga to a temperature similar to that of present plumes. We suggest that Archaean plumes originate from the core–mantle boundary and that their temperature remained constant because the temperature of the outer core was buffered by solidification of the Fe–Ni inner core. At about 2.7 Ga dense former basaltic crust began to accumulate at the core and eventually covered it to produce an insulating layer that reduced the heat flux out of the core and lowered the temperature of mantle plumes. The temperature of mantle plumes fell as the dense layer above the core thickened until it exceeded the critical thickness required for convection. Because heat is transferred rapidly across the convecting part of the insulating layer, any further increase in its thickness by the addition more basaltic material has no influence on the temperature at the top of the layer, which is the source of Post-Archaean mantle plumes. We equate the dense layer above the core with the seismically identified layer D″. Our analyses suggest the drop in plume temperatures produced by a dense insulating layer above the core will be about 40% once it starts to convect, which is consistent with the observed drop inferred from the decrease in the MgO content of komatiites and picrites at that time.

1. Introduction

The Archaean and Proterozoic boundary marks what is arguably the most fundamental change in the evolution of the Earth. Archaean terrains have two main components: granites and greenstones. Granites are the most important component in all Archaean terrains, and in some cases, for example in much of India and Greenland, they dominate surface exposures. Although Archaean greenstone belts have variable stratigraphy all are dominated by basalts, normally in association with minor komatiites, especially low in the stratigraphy, where sedimentary rocks are rare or absent (e.g. Gresham and Loftus-Hills, 1981). The volume and frequency of mafic volcanism in Archaean greenstones are unmatched at later times. Basalts and komatiites become less abundant at higher levels in most greenstone sequences and are replaced by more evolved volcanic rocks such as andesites, dacites and rhyolites (Campbell and Jarvis, 1984). Sediments, principally felsic pyroclastic rocks, accompanied by lesser amounts of immature greywackes and shales, also become important at higher stratigraphic levels (Condie et al., 1970). Mature sediments are rare (Donaldson and Jackson, 1965). Extensive flat-lying platform sediments, with abundant mature sediments, typical of the Proterozoic, are also rare in the Archaean (Campbell and Jarvis, 1984). The increase in the abundance sedimentary rocks in Proterozoic supracrustal rocks is accompanied by a marked decrease in the abundance of mafic volcanic rocks.

The decrease in the basaltic volcanism at the Archaean–Proterozoic boundary coincides with drop in maximum MgO content of plume-related, high-MgO magmas from 32.5 ± 2.5% between 3.5 and 2.7 Ga to 21 ± 3% by 2.0 Ga (Campbell and Griffiths, 1992; Arndt et al., 2008), which implies a decrease in the maximum temperature of mantle plumes of ca. 250 °C (Campbell and Griffiths, 1992; Arndt et al., 2008; Lesher and Kamber, 2009). This drop coincides with decreases in the average thickness of the continental mantle lithosphere from 220 to 160 km (Drummond, 1988; Vinnik et al., 1996; Keller and Schoene, 2012), an increase in its average FeO content from 6.4 to 7.9% and a decrease in its average Mg# from 92.7 to 90.6 (Griffin et al., 1999). We will argue that the implied decrease in plume temperatures can be explained by an accumulation of dense former mafic crust above the core–mantle boundary (CMB), starting towards the end of the Archaean, which eventually became the seismically distinctive layer called D″ (Lay, 2007). Our hypothesis directly explains the decrease in mantle plume temperatures and volcanic activity between 2.7 and 2.0 Ga.

* Corresponding author.
E-mail address: Ian.Campbell@anu.edu.au (I.H. Campbell).

0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.11.048

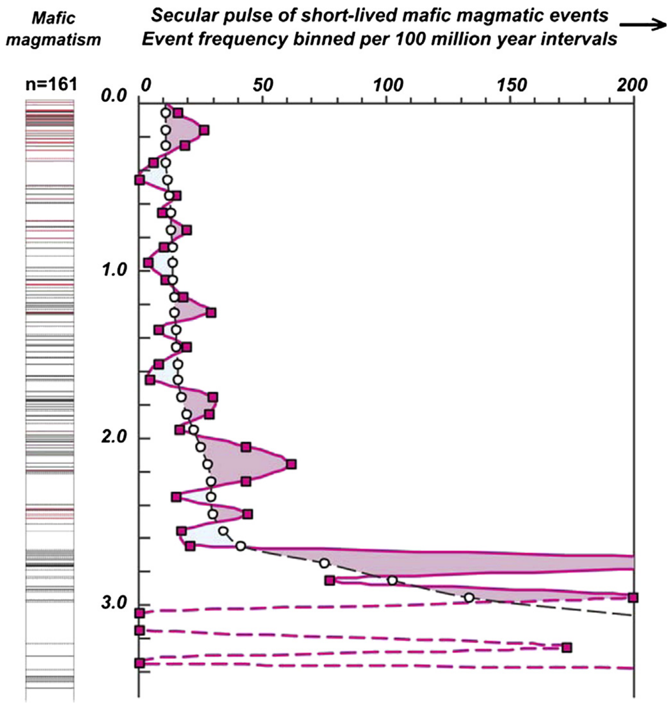

Fig. 1. Secular variation in the frequency of large short-lived igneous events, which are assumed to represent large igneous provinces. The squares represent data binned over 100 Myr intervals (moving point average) and normalized by the area of the preserved continental crust. The bar chart shows the individual events (after Ernst and Bleeker, 2010).

Indirectly it may explain the decrease in the average thickness between the Archaean and Proterozoic mantle lithospheres and why the Archaean mantle lithosphere has a lower FeO content and higher average Mg#.

2. Secular change in the frequency of plume activity

Flood basalts and oceanic plateaus, the melting products of mantle plume heads, erupt over short periods of time, typically less than a million years (Richards et al., 1989; Campbell and Griffiths, 1990). As a consequence, the frequency of short-lived basaltic volcanic activity can be used as a proxy for the frequency of plume-related flood basalt events (Ernst and Bleeker, 2010). The change in frequency of short-lived volcanic events, normalized to crustal preservation area, is illustrated in Fig. 1. Although the record beyond 3.0 Ga is questionable, due to the limited area of preserved crust older than this age, it is clear that there is a spectacular decline in plume activity at the end of the Archaean and that there is little plume activity between 2.6 and 2.3 Ga. Significant plume activity restarts between 2.3 and 2.0 Ga but the peak is much smaller than the 2.7 Ga peak.

3. Secular change in the temperature of the mantle

Mantle convection, like convection in any material that can be treated as a fluid, is driven by density anomalies that originate in boundary layers (Davies, 1999). The Earth's cool, upper boundary layer is the oceanic lithosphere, which cools over time until its density becomes greater than that of the underlying mantle causing it to sink as a ridged plate. The hot, lower boundary, at least early in Earth's history, is the core–mantle boundary. Heat conducted from the core into the overlying mantle heats the boundary layer above the core so that it becomes lighter than the overlying mantle and provides the source of buoyancy that drives mantle plumes. Sinking slabs are therefore zones of anomalously cold

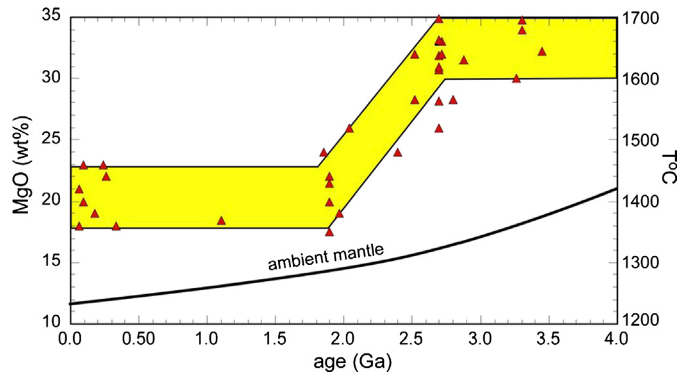

Fig. 2. Variation in the maximum MgO content of fine-grained and spinifex textured plume-related rocks with time. The secular cooling curve for the ambient mantle (Davies, 1999) is relative to the eruptive temperature of modern MORB, which is taken to be 1220 °C, so as to be compatible with the eruptive temperatures of komatiites and picrites. Liquidus temperatures have been calculated from MgO contents assuming $T(°C) = 1000 + 20x\text{MgO}$ (Arndt et al., 2008). Data from Campbell and Griffiths (1992), Arndt et al. (2008), Lesher and Kamber (2009), Hanski et al. (2004), Zhang et al. (2006).

mantle whereas rising plumes are zones of anomalously hot mantle. Numerical modeling suggests that, away from sinking slabs and rising plumes, variations in the mantle's potential temperature are small, no more than a few 10's of degrees (Davies, 1999; Davies and Davies, 2009); we refer to that temperature as the ambient mantle temperature.

3.1. Secular change in the temperature of mantle plumes

The potential temperature of the modern mantle, which is the temperature of the mantle extrapolated adiabatically to a pressure of one bar, is 1350 ± 50 °C (Lee et al., 2009; Courtier et al., 2007). The highest degree of melting of normal upper mantle with this potential temperature occurs at Mid Ocean Ridges (MOR), where the maximum MgO content of a dry magma is 10.3% MgO (Jenner and O'Neill, 2011). Dry magmas, with MgO contents well above this value must originate from anomalously hot parts of the mantle. That is they must come from mantle plumes (Jarvis and Campbell, 1983).

The change in the maximum MgO content of plume-related komatiites and picrites as a function of time is illustrated in Fig. 2 and the data used to construct the figure are given in Supplementary Table S1. We have considered only maximum MgO content because our aim is to show how the temperature of the plume's boundary layer source has changed with time, and temperatures estimated from the highest MgO komatiites and picrites are most representative of that source. As a plume ascends through the mantle some of it can cool and it can entrain the cooler adjacent mantle the plume passes through, which is unrelated to the plume's boundary layer source. Furthermore ascending plume magmas can pond and fractionate in the crust or become contaminated by continental crust as they ascend. Magmas produced by partial melting of cooler parts of the plume, those that have undergone fractional crystallization and those that have become contaminated by continental crust during their ascent, yield lower MgO magmas, which in turn yield lower calculated temperatures that are not representative of the plume's boundary layer source.

Mantle cooling curves inferred from compilations of large numbers of MgO analyses of basalts, picrites and komatiites, which do not classify the analyzed material as arc, plume or MORB (e.g. Keller and Schoene, 2012), or recognize that plumes can entrain ambient mantle as they ascend, are not useful for our present purpose. Preserved Archaean and Proterozoic basalts are dominated by plume and arc magmas. The MgO content of primary plume