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Research Paper

Metamorphic consequences of secular changes in oceanic crust composition and implications for uniformitarianism in the geological record

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ABSTRACT

Cooling of the Earth's mantle since the Meso-Archean is predicted by thermal and petrological models to have induced a secular change in the composition of primary mantle-derived magmas – and thus bulk oceanic crust; in particular, suggesting a decrease in maficity over time. This hypothesis underpins several recent studies that have addressed key geological questions concerning evolving plate tectonic styles, the rates and timing of continental crust formation, comparative planetology, and the emergence of complex life on Earth. Major, minor, and trace element geochemical analyses of (meta)mafic rocks preserved in the geological record allows exploration of this theory, although no consensus currently exists about the magnitude of this change and what compositions – if anything – constitute representative examples of Paleo-, Meso-, or Neo-Archean primitive oceanic crust. In this work, we review the current state of understanding of this issue, and use phase equilibria to examine the different mineral assemblages and rock types that would form during metamorphism of basalt of varying maficity in subduction zone environments. The presence (or absence) of such metamorphic products in the geological record is often used as evidence for (or against) the operation of modern-day subduction-driven plate tectonics on Earth at particular time periods; however, the control that secular changes in composition have on the stability of mineral assemblages diagnostic of subduction-zone metamorphism weakens such uniformitarianistic approaches. Geodynamic interpretations of the Archean metamorphic rock record must therefore employ a different set of petrological criteria for determining tectonothermal histories than those applied to Proterozoic or Phanerozoic equivalents.

1. Introduction

"By explaining past changes by analogy with present phenomena, a limit is set to conjecture, for there is only one way in which two things are equal, but there is an infinity of ways in which they could be supposed different." – Hooykaas (1963).

Basalt is the most widespread rock on the Earth's surface today (Nielsen and Fisk, 2010), and investigations of Phanerozoic, Proterozoic, and Archean terranes worldwide suggest that it has been similarly abundant throughout geological time (Condie, 1981; Furnes et al., 2014). As oceanic crust is produced via decompression melting of mantle peridotite at divergent plate margins (McKenzie and Bickle, 1988), its structure and composition can provide critical first-order constraints on the geochemical and petrophysical properties of the Earth's interior (Vervoort and Blichert-Toft, 1999). Even basalts produced in intraplate geodynamic scenarios, such as above the heads of mantle plumes, can provide critical information about the thermal and petrological properties of the Earth's shallow interior (Campbell and Griffiths, 1990). Identifying primary magmas or otherwise relatively unaltered components of oceanic crust in the geological record is thus of prime importance, as such discoveries would help to resolve many major issues in solid-Earth geoscience, such as constraining the thermal evolutions of the mantle over time and deducing whether or not plate tectonics operated during the Archean (e.g. Davies, 1992; Hamilton, 1998, 2003; Stern, 2005; Van Hunen and Moyen,

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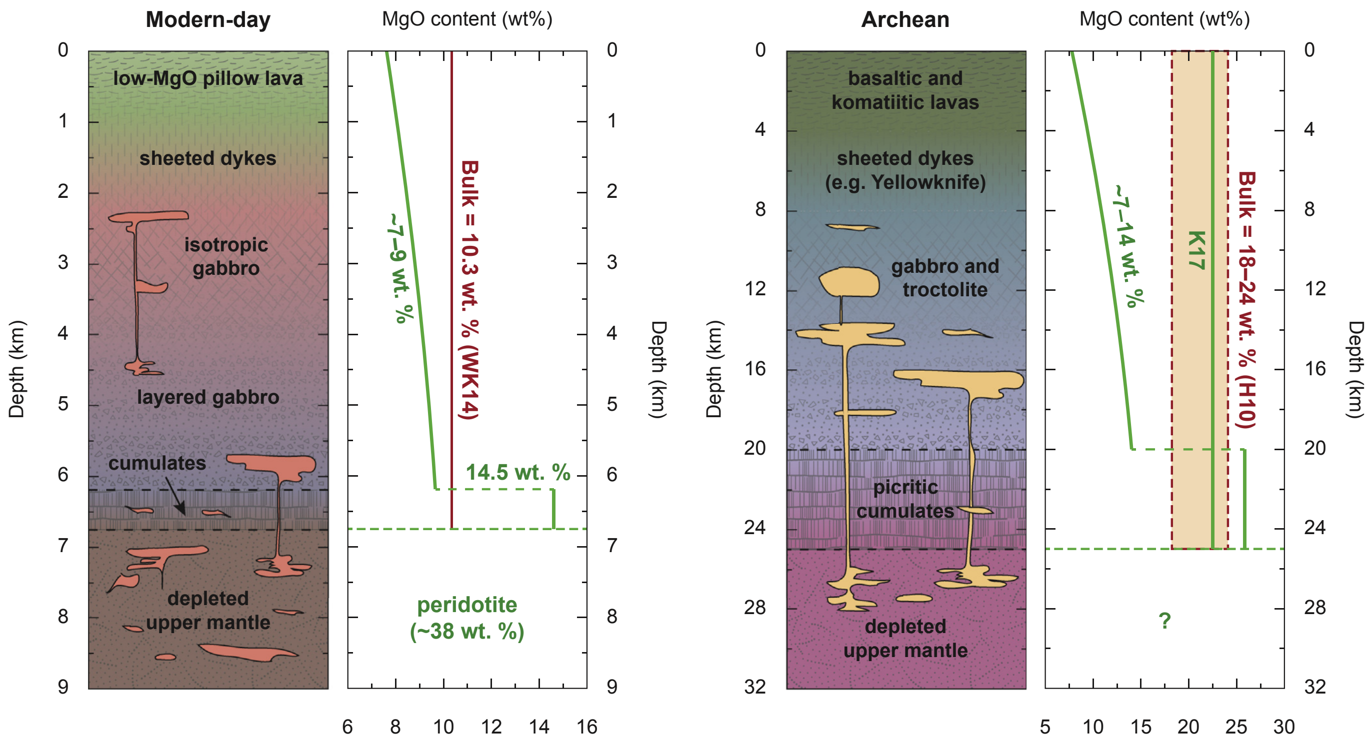

Figure 1. Schematic cross sections through modern-day and (interpreted) Archean oceanic crust and upper mantle. Modern-day structure, petrology, and MgO contents are from White and Klein (2014), and Archean structure and petrology are after Foley et al. (2003) and Nair and Chacko (2008). Bulk MgO content for Archean crust is after Herzberg et al. (2010) (H10), and two compositional profiles discussed by Klein et al. (2017) (K17) and in this study, are shown by thick green lines.

2012; Turner et al., 2014; Ernst, 2017; Ganne and Feng, 2017; Wade et al., 2017).

Continued improvements to quantitative chemical analysis techniques in recent years—alongside advances in large-scale data archiving and distribution—have heralded the rise of Big Data within the geological community (Kattge et al., 2014). Centralized, public-access repositories containing an extensive range of petrological analyses of rocks and minerals (e.g. EarthChem[1]) allow straightforward processing of vast amounts of information. Indeed, several recent studies have analyzed large databases of Proterozoic and Archean metabasalt bulk-rock compositions to examine the extent of secular variations in major, minor, and trace element geochemistry, and elucidate the geodynamic settings of formation of the parental mafic magmas (Keller and Schoene, 2012; Furnes et al., 2014; Condie et al., 2016; Ganne and Feng, 2017). These studies, however, have produced differing opinions on the extent to which the petrology and structure of primary mafic oceanic crust and/or mid-ocean ridge basalt (MORB) has evolved over geological time, which are predicted by models of the mantle's thermal history to be significant (Abbott et al., 1994; Korenaga, 2008; Herzberg et al., 2010; Ziaja et al., 2014).

Nearly all basalts in the Precambrian rock record have undergone some degree of metamorphism (Gill, 1979), sometimes in subduction zones at high-pressure/low-temperature (HT–LP) conditions, or alternatively in collisional orogens along notably hotter geothermal gradients (e.g. Brown, 2007). Secular changes in primary mantle-derived magmas, bulk oceanic crust, and/or MORB compositions will thus have distinct petrological consequences on the metamorphic rock type produced in each tectonic setting (e.g. Palin and White, 2016). Thus, there is a need to define the mineral parageneses that are expected to form in different mafic rocks at these variable *P*–*T* conditions, which will allow more informed evaluation of the rock record and can provide greater insight into how metamorphic processes and products may have evolved throughout Earth history (e.g. Grambling, 1981; Sandiford, 1989; Komiya et al., 2002; Martin and Moyen, 2002; Brown, 2007; Bradley, 2011; Zhai and Santosh, 2013; Dyck et al., 2015; Weller and St-Onge, 2017; Nicoli and Dyck, 2018).

In this paper, we first summarize the theory behind secular change in bulk oceanic crust and MORB composition, and discuss the extent to which metabasic rocks preserved in the geological record validate these predictions. We then present the results of phase diagram analysis and interpretation demonstrating the petrological consequences of such compositional changes at *P*–*T* conditions characteristic of modern-day, and early and late Archean subduction zones. Finally, we discuss the implications of this theoretical secular change on uniformitarianism-based approaches to interpreting the geological record, and the onset of modern-day subduction-driven plate tectonics.

1.1. Predicted secular change in bulk oceanic crust and uppermost MOR basalt compositions

It has long been known that the Earth has undergone cooling since its formation (Thomson, 1862; See, 1907; Patterson, 1956); however, the absolute magnitude and rate of this temperature change over time is poorly constrained. Conceptual models for this thermal evolution fundamentally rely upon the balance at any point in time between internal heat production from the decay of radiogenic elements, and the loss of heat by mantle convection and surface volcanism (Breuer and Spohn, 1993). The present-day ratio of heat production to heat loss—the convective Urey ratio—is estimated to be 0.23 ± 0.15 (Korenaga, 2008), and can be

[1] http://www.earthchem.org/.