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Plate tectonics and continental basaltic geochemistry throughout Earth history

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ABSTRACT

Basaltic magmas constitute the primary mass flux from Earth's mantle to its crust, carrying information about the conditions of mantle melting through which they were generated. As such, changes in the average basaltic geochemistry through time reflect changes in underlying parameters such as mantle potential temperature and the geodynamic setting of mantle melting. However, sampling bias, preservation bias, and geological heterogeneity complicate the calculation of representative average compositions. Here we use weighted bootstrap resampling to minimize sampling bias over the heterogeneous rock record and obtain maximally representative average basaltic compositions through time. Over the approximately 4 Ga of the continental rock record, the average composition of preserved continental basalts has evolved along a generally continuous trajectory, with decreasing compatible element concentrations and increasing incompatible element concentrations, punctuated by a comparatively rapid transition in some variables such as La/Yb ratios and Zr, Nb, and Ti abundances approximately 2.5 Ga ago. Geochemical modeling of mantle melting systematics and trace element partitioning suggests that these observations can be explained by discontinuous changes in the mineralogy of mantle partial melting driven by a gradual decrease in mantle potential temperature, without appealing to any change in tectonic process. This interpretation is supported by the geochemical record of slab fluid input to continental basalts, which indicates no long-term change in the global proportion of arc versus non-arc basaltic magmatism at any time in the preserved rock record.

1. Introduction

Systematic changes in crustal composition and magma chemistry between the Archean and the present have long been advanced on the basis of geochemical, petrological, and field observations. Differences between Archean and post-Archean crust – including the preponderance of granite–greenstone terranes, high-Na Trondhjemite–Tonalite–Granodiorite (TTG) plutons, and ultramafic komatiite lavas in the Archean – have led to much discussion about the style and rate of Archean tectonics (Green, 1975; Hargraves, 1976; Wilson et al., 1978; Sleep, 1992; de Wit, 1998; Hamilton, 1998; Bédard, 2006; Pease et al., 2008; Condie and Kröner, 2008; Stern, 2008). One interpretational paradigm invokes the abundance of TTGs, komatiites, and apparent lack of preserved blueschists and ophiolites in the Archean along with vertical tectonic interpretations of dome-and-keel granite–greenstone terranes as evidence for a fundamentally different tectonic regime in the Archean (Hamilton, 1998; Bédard, 2006; Stern, 2008). In contrast, a more uniformitarian paradigm holds that qualitative differences between Archean and Proterozoic lithologies may be satisfactorily explained by secular changes in variables such as mantle temperature or water content in an essentially modern plate tectonic setting, backed by subduction-like geotherms and horizontal tectonic interpretations of, e.g., the Kaapvaal Craton and the Superior Province (Sleep, 1992; de Wit, 1998; Pease et al., 2008; Condie and Kröner, 2008).

Given conflicting structural models for Archean tectonics, some studies have instead used major and trace element geochemistry of Archean rocks to infer tectonic setting via modern associations (e.g. Atherton and Petford, 1993; Martin et al., 2005). Such approaches have been stymied by two fundamental problems: (1) geochemical signatures are often nonunique and may not have the same genetic implications 4 Gyr ago as today, and (2) systematic temporal variations in geochemistry can be dwarfed by the variance of the rock record at any one time. The resulting uncertainties have limited our ability to apply modern chemotectonic signatures (e.g. Pearce and Cann, 1973) to the Archean.

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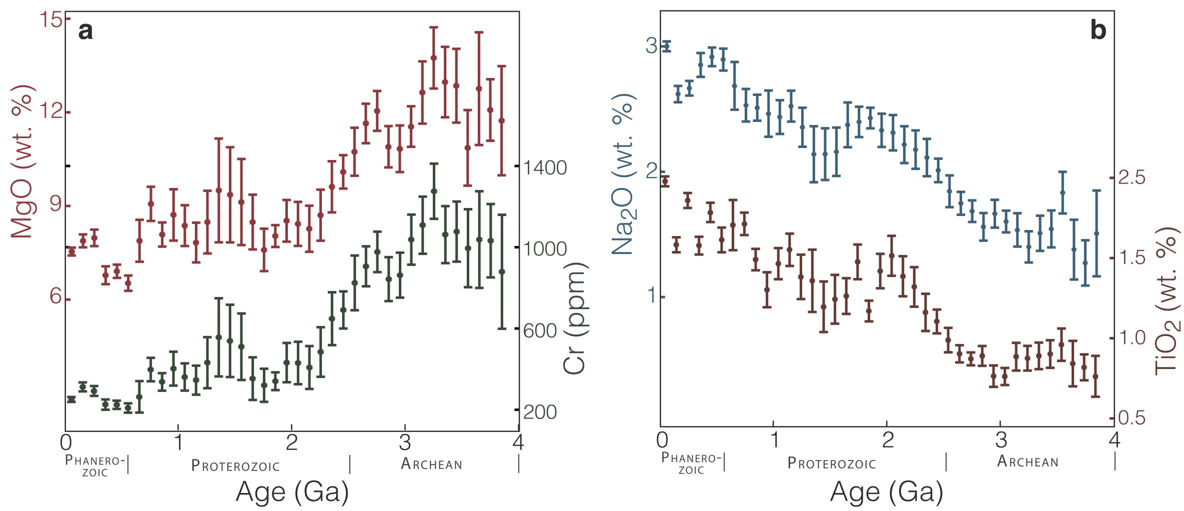

Fig. 1. Secular evolution of compatible (**a**) and incompatible (**b**) element abundances in basalt over the past 4 Ga, following the methods of Keller and Schoene (2012).

To obtain meaningful temporal trends from the heterogeneous rock record, one productive approach has been to prioritize quality over quantity, for instance obtaining a well-constrained primitive magma composition by tracing a liquid line of descent from samples that have only fractionated olivine (Herzberg et al., 2010), or by focusing on the composition of carefully screened and geologically well-understood suites of samples Condie and O'Neill (2010); Condie et al. (2016). For instance, using 33 primary melt solutions culled from a dataset of 1500 "non-arc" basalt analyses, Herzberg (Herzberg et al., 2010) found primary magma temperatures consistent with a smooth trend in mantle potential temperature from ∼1530 °C in the Eoarchean to ∼1350 °C today, along a similar trend to the models of Korenaga (2008).

If, however, one obtains a sufficiently extensive, representative sample dataset, an alternative inclusive approach becomes possible. Given a perfectly representative sample set of the continental crust, the compositional average of this set has unique physical significance corresponding to the bulk composition of the crust — that is, the composition that would result from physically homogenizing the entire crust. Consequently, changes in the average composition of new igneous crust contain information about the processes of crust formation: at long time scales, changes in the mean reflect secular variation in fundamental terrestrial parameters such as mantle potential temperature, crustal thickness, and tectonic mechanism of crust formation. A continuous temporal record of average crustal geochemistry would thus allow for the critical examination of temporal variations in such Earth system parameters and, consequently, the extrapolation of modern geologic processes back through Earth history in a conditional application of uniformitarianism. However, the quantification of systematic changes in mean crustal composition has been impeded by the difficulty of obtaining a representative sample population given the vast heterogeneity produced by magmatic processes, along with persistent questions about sampling and preservation bias Rudnick and Gao (2014).

Recently, increasing availability of large geochemical datasets, such as EarthChem, Georoc, and Navdat, has provided a new opportunity to quantify crustal composition by employing a greatly enlarged sample set. Our previous work (Keller and Schoene, 2012) has taken advantage of these freely-available datasets to construct and analyze a ∼70,000-sample whole-rock geochemical record of secular crustal evolution over the past 4 Ga, using weighted bootstrap resampling to obtain maximally representative temporal trends. First-order results revealed smooth decreases in compatible element abundance and increases in incompatible element abundance in basaltic samples (Fig. 1), along with some indication of more discontinuous processes at the end of the Archean. While many indications of geochemical variation across the Archean–Proterozoic boundary were specific to the felsic record, changes in the estimated degree of average mantle melting and in basaltic La/Yb ratio circa 2.5 Ga suggested an analogous transition in the mafic record as well (Keller and Schoene, 2012).

Given the petrological complexities involved, previous work has not presented any definitive conclusions on the origin and significance of this potential transition in the mafic record. However, many additional geochemical constraints are available due to the breadth of the underlying dataset. In order to better understand the implications of the new record of crustal evolution provided by statistical geochemistry, we focus here on the ∼30,000-sample mafic subset of our database (defined as 43–51 wt.% SiO_2, generally including komatiites but excluding many ultramafic cumulates), here termed basaltic *sensu lato*. As the product of 4 Ga of partial mantle melting, this mafic record preserves the most direct account of mantle conditions through time, and provides the necessary foundation for any interpretation of subsequent processes of crustal differentiation. Our analysis of this record combines weighted bootstrap resampling with major- and trace-element geochemical modeling. This analysis allows us to study global variations in the process and setting of basaltic magma production over geologic time, in turn providing insight into the style and existence of plate tectonics throughout Earth history.

2. Weighted bootstrap resampling

In order to minimize sampling bias and accurately propagate temporal and compositional uncertainties to obtain an optimal estimate of the compositional distribution of Earth's exposed crust, we followed the weighted bootstrap resampling method of Keller and Schoene (2012), summarized in Appendix A and Supplementary Figs. 1–6. As in our previous work, this technique was applied to a ∼70,000-sample record of crustal whole-rock major and trace element geochemistry, including ∼67,000 samples from the EarthChem repository, ∼2,500 samples from Condie and O'Neill (2010), and ∼1500 from Moyen (2010) including age estimates and geospatial sample locations for each sample. Although outliers were not rejected categorically, the dataset was manually screened to identify suspicious data patterns and exclude any physically implausible data (e.g. concentrations <0 or $>100\%$). We consider only samples collected from the present-day continental crust (i.e., excluding MORB and OIB except where naturally ob-