

U–Th–Pb fractionation in Archaean lower continental crust: Implications for terrestrial Pb isotope systematics

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Abstract

Pb isotopic compositions are reported for leached feldspars and whole rock samples of felsic to ultramafic, amphibolite to granulite facies xenoliths from the Bearpaw Mountains in the northern Wyoming Craton, Montana, USA. Two-point dates obtained for leached feldspar–whole rock pairs provide a record of Pb isotopic homogenisation at 1.6–2.1 Ga, during an inferred Palaeoproterozoic thermo-tectonic event. Model ages for leached feldspars, assuming single-stage melt extraction from depleted mantle, indicate formation of the protoliths from 2.8 to 4.0 Ga. The inferred timing of the Palaeoproterozoic high-grade metamorphism and extended Archaean crust formation is in agreement with available geochronological data for the Wyoming Craton. Following Palaeoproterozoic isotope resetting, the second stage of Pb isotope evolution suggests prolonged residence in a low U/Pb environment. Isotope resetting was apparently accompanied by a significant decrease in $^{238}\text{U}/^{204}\text{Pb}$ (μ -values), reflecting substantial loss of the highly incompatible and mobile element U and, by inference, other heat-producing elements. Geothermal considerations suggest that unstratified continental crust, as approximated by a “reconstituted” average xenolith composition from the Wyoming Craton, would have been thermally unstable at lower crustal levels at the time of formation and metamorphism, if abundances of heat-producing elements had been unaffected by the U–Th–Pb fractionation event. In contrast, differentiated continental crust comprising a chemically depleted lower layer and an enriched upper layer would have reached thermal stability at the time of high-grade metamorphism. On this basis, the Wyoming Craton xenoliths data are proposed as an approximation to the lower continental crust. In $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ space the xenoliths plot to the left of the meteorite isochron and above the depleted mantle evolution curve, in contrast to most previous data from lower crustal xenolith suites. Simple mass balance, using an average of the studied xenoliths from the Wyoming Craton as approximation to lower continental crust and published compositions for upper continental crust, yields a Pb isotopic composition of bulk continental crust that plots close to the meteorite isochron. Hence, it is proposed that Archaean lower crust, as exemplified by the Wyoming Craton xenoliths, displays the essential geochemical and isotopic requisites to be a major reservoir to balance the Pb isotope composition of bulk silicate earth.

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1. Introduction

The first terrestrial Pb isotope paradox refers to the fact that rocks from the accessible Earth (upper

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continental crust, continental flood basalts, continental and oceanic sediments, oceanic crust, ocean islands and, to some extent, lower continental crust) consistently show average Pb isotope compositions that plot well to the right of the 4568 Ma meteorite isochron with a μ ($^{238}\text{U}/^{204}\text{Pb}$) much greater than carbonaceous chondrites. This observation constitutes a cornerstone of chemical geodynamics and necessitates one or several 'hidden' reservoirs at depth, whose Pb isotope composition(s) plot(s) to the left of the meteorite isochron.

The role of core formation in producing a low μ , relatively high $^{207}\text{Pb}/^{206}\text{Pb}$ reservoir with an essentially frozen Pb isotope composition has been widely discussed since Allègre [1]. The relevance of the core as a solution to the first terrestrial Pb paradox depends critically on how effectively the core formation process scavenged Pb and the time scale of accretion and concomitant core formation. The view that the core is a significant Pb reservoir is historically linked to the preservation of 'initial' Pb isotope composition in sulphides from iron meteorites. Iron meteorites, however, have consistently very low unradiogenic initial Pb content, as demonstrated by the leaching experiments of Göpel et al. [2]. The core would have to be much richer in Pb than iron meteorites were it to play a significant role in the explanation of the first terrestrial Pb isotope paradox.

Regardless of the mass balance problem, maximum core formation periods inferred from Hf–W isotope systematics [3–5] are on the order of 30–45 Ma, much too short to explain the first terrestrial Pb paradox by core formation alone. Galer and Goldstein [6] and Murphy et al. [7] have shown that with core formation periods less than 85–100 Ma, one or several additional 'unradiogenic' Pb isotope reservoirs are required in the silicate Earth. Kramers and Tolstikhin [8] arrived at a similar conclusion using a sophisticated transport forward model. By comparing the model results with Pb isotope compositions of average sediment and average MORB (Mid-Ocean-Ridge-Basalt), these authors demonstrated that for various accretion–core formation intervals unradiogenic Pb in the core could at most account for 30% of the first terrestrial Pb isotope paradox. In view of the combined evidence the existence of silicate Earth reservoir(s) plotting to the left of the 4568 Ma meteorite isochron appears unavoidable. The two most likely candidates are the lower continental crust (LCC) and recycled material in the mantle.

The LCC is known to be poor in radioactive heat-producing elements (mainly U, Th, K) from geothermal observations that are only consistent with over-proportional abundance of K, Th and U in upper continental crust [9]. Whether this heat flow constraint for low U and

Th concentrations in the LCC can be extended to imply low U/Pb and Th/Pb ratios has been discussed for some time [8,10–12] but, as pointed out by Murphy et al. [7], the key problem in assessing this possibility is the paucity of reliable Pb isotope data for representative LCC lithologies of Archaean age. In particular, it is the time-integrated U/Th/Pb evolution stored as Pb isotope ratios, rather than inferences made from measured elemental ratios, that provides a robust measure of the LCC with regard to the first terrestrial Pb isotope paradox.

The impetus behind the present study is to expand the existing LCC Pb isotope database not only for whole rocks, but also for leached feldspars so as to gain information about the timing of potential U and Th loss and to discuss the relevance of these new data for chemical geodynamics.

2. Geological setting and samples

The igneous rock suite of the Bearpaw Mountains in north-central Montana (Fig. 1) was emplaced into >45 km thick continental crust of the Archaean Wyoming Craton (hereafter abbreviated as WC) [13]. These volcanic and plutonic rocks have been dated at 50–54 Ma [14] and form part of an extensive Eocene high-K magmatic province [13]. Detailed accounts of the geology, petrology and geochemistry of the Bearpaw Mountain magmatism were presented by Hearn [15] and McDonald et al. [13]. Minettes and latites, the main extrusive rock-types, contain a varied suite of upper mantle and lower crustal xenoliths. The crustal xenoliths range from ultramafic to felsic but, like other lower-crustal xenolith suites [16], the population is dominated by mafic compositions. Peridotitic xenoliths representing WC lithospheric mantle architecture from beneath the Bearpaw Mountains were studied by Downes et al. [17].

Crustal xenoliths selected for this Pb isotope study are angular to sub-rounded and range from <2 cm up to 25 cm in diameter. Contacts to the host rock are sharp indicating that interaction with, or penetration by, the host lavas was minimal. The xenoliths were collected from previously un-sampled localities. The majority of samples are massive, with only few exhibiting centimeter-scale compositional layering. Petrographically, the xenoliths show mostly equigranular-to-inequigranular granoblastic microstructures that are compatible with the achievement of thermodynamic equilibrium.

The mafic lithologies can be subdivided into an eclogite to high-pressure granulite facies assemblage (garnet + clinopyroxene + plagioclase \pm rutile \pm hornblende \pm quartz) and an intermediate-pressure two-

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