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Earth and Planetary Science Letters 247 (2006) 143 – 156
EPSL
www.elsevier.com/locate/epsl

The Yellowstone hotspot in space and time: Nd and Hf isotopes in silicic magmas

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Received 6 May 2005; received in revised form 20 March 2006; accepted 19 April 2006
Available online 9 June 2006
Editor: K. Farley

Abstract

Over the course of its 16 m.y. history, the Yellowstone hotspot has produced silicic magmas exhibiting systematic, and often sympathetic, variations in isotopic and chemical composition, temperature and frequency of eruption. Nd and Hf isotopic ratios vary systematically from initial eruptions at ~16 Ma, contemporaneous with basaltic volcanism in eastern Oregon and Washington, to the present day Yellowstone Volcanic Plateau. Nd and Hf isotopic ratios co-vary and span the range of most terrestrial samples, reflecting mixing of mantle and crustal sources. Earliest erupted silicic magmas were hot (in excess of 1050 °C), relatively less evolved and have isotopic ratios within the range of contemporaneous Columbia River flood basalts. The transit of the hotspot across the lithospheric boundary between the western accreted oceanic terrain and the Precambrian craton at 15 Ma is marked by shifts in ε_{Nd} from +4 to −11 and in ε_{Hf} from +10 to −10. The duration of the transit yields a crustal magma source diameter of ~70 km. In the interval from 14 to 9 Ma, ε_{Nd} systematically increases from −11 to −7, recording a minimum increase in the mantle component from 5% to 30%. The mantle component could be twice as great, depending upon the isotopic composition of crust and mantle reservoirs. In this same interval, peak temperatures of ~1000 °C occurred at 9 Ma. The last 8 m.y. are characterized by less frequent eruption of lower temperature (830–900 °C) and more compositionally evolved magmas.

Keywords: neodymium; hafnium; isotope ratios; Yellowstone; hotspot; silicic magma; rhyolite; mantle plume

1. Introduction

Hotspots provide a window into the earth's interior and yield information on the differentiation of the earth, the persistence of long-lived geochemical heterogeneities in the Earth's mantle, and geodynamic processes that recycle outer portions of the earth into its interior. Additionally, because hotspots originate at sublithospheric depths, they play an important role in plate tectonic theory and provide key reference points in assessment of relative plate motions. Hotspots are distinguished by their anomalous thermal character, a pronounced geoidal anomaly, a linear space- and time-transgressive volcanic history, and often, a geochemically distinct volcanic record.

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doi:10.1016/j.epsl.2006.04.030

The Yellowstone hotspot (YHS) is of interest because it is located on a continent and offers the opportunity to examine the interrelationship of coupled mantle and crustal igneous processes. Among continental hotspots, the Yellowstone hotspot is amenable to study because it is young, active, and the relative plate motion between the North American plate and the localized mantle heat source is sufficiently rapid so as to leave a well-defined hotspot trace. In addition, the Yellowstone plateau has been the locus of some of the most voluminous production of silicic magma on the planet in the Quaternary.

The YHS has been the focus of investigation for several decades and there continues to be disagreement as to its origin and evolution. Fundamental questions remain including whether or not the hotspot is the result of a mantle plume, and if so, where the plume first impinged on the North American lithosphere. The nature of the source of silicic magmas is speculative, and the mass and thermal contributions from the mantle are poorly constrained, although they are critical factors in crustal growth and maturation. A question of particular importance is whether large silicic provinces represent new material from the mantle or the recyling of older continental material. The ages of volcanic events and their distribution bear on the debate about the relative roles of plate motion and crustal extension in governing the apparent migration rate of the hotspot. In order to address these questions we have measured Nd and Hf isotopic ratios in glass from silicic tuffs erupted over the past 16 m.y. history of the hotspot.

2. Geologic background

2.1. The Yellowstone hotspot

Numerous lines of evidence support a hotspot origin for the Yellowstone system including extraordinarily high heat flow, a pronounced 1000 km diameter geoid anomaly, and a parabola of active seismicity and tectonism in the Yellowstone Plateau/Eastern Snake River Plain [1,2]. The pronounced topographic decline to the west of the Yellowstone Plateau that defines the Snake River Plain can be modeled as the response of cooling lithosphere that has additional loading from injection of mantle-derived basalt into the crust [2,3]. Finally, for the last 12 m.y. the 500 km track of time-progressive silicic volcanism extends continuously to the NNE, approximately antiparallel to the velocity vector of the North American plate.

Despite these features, there is a lack of consensus regarding the mechanism for the origin and evolution of the time transgressive track of the Yellowstone hotspot. A number of workers advocate a mantle plume origin to account for the hotspot track [1,2,4,5] as well as for the voluminous basaltic volcanism in the Columbia Plateau that was contemporaneous with early YHS volcanism [6–10]. A recent model incorporating details of temporal migration of basalt eruptive centers in Oregon and Washington advocates a plume origin for both the voluminous mafic volcanism as well as the ensuing volcanism along the Snake River Plain [11]. In this interpretation initial volcanism is widespread resulting from the arrival of a plume head. The narrower path of the Snake River Plain is interpreted as the tail of the plume that was sheared off from the head by the westward moving continental lithosphere. An alternative plume model places the plume head under the western Snake River Plain with volcanism spreading laterally east and west to account for the YHS and the space–time progression of volcanism on the High Lava Plains of Oregon [12]. Elevated $^3He/^4He$ ratios in fluids and minerals, with values as high as 16 RA [13–17], suggest that there is a component in the YHS magmatic system that has its origin deeper than the outgassed upper mantle. Early-erupted silicic tuffs from the Yellowstone hotspot system are contemporaneous with flood basalt volcanism on the Columbia Plateau [18], and early (16–15 Ma) Yellowstone hotspot rhyolites and Columbia River basalts have similar Nd isotopic ratios [19]. These same flood basalts have He and Ne isotope signatures characteristic of mantle plume sources [20].

Those objecting to the plume model advocate a shallow mantle origin for the hotspot and point to the role of preexisting crustal structures and the inability to image a deep low velocity anomaly beneath the current location of the hotspot at Yellowstone National Park [21–24]. However recent seismic imaging reveals a low velocity structure in the upper mantle beneath Yellowstone National Park that extends to the transition zone at a depth of 660 km [25]. Although the isotopic data presented here do not specifically resolve the plume issue, the data do indicate that the silicic volcanism of the Yellowstone hotspot is driven by a focused, sub-lithospheric thermal anomaly.

2.2. Geologic setting

The earliest eruptions of silicic fallout tuffs in our study occurred around 16 Ma contemporaneous with voluminous eruptions of basalt in Washington and Oregon. Early centers of silicic volcanism include the High Rock Desert of northwestern Nevada (16.5–15.4 Ma [26–29]), the High Lava Plains of Oregon