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Understanding cratonic flood basalts

Paul G. Silver *, Mark D. Behn [1], Katherine Kelley [2], Mark Schmitz [3], Brian Savage

Carnegie Institution of Washington, DTM, United States

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Abstract

The origin of continental flood basalts has been debated for decades. These eruptions often produce millions of cubic kilometers of basalt on timescales of only a million years. Although flood basalts are found in a variety of settings, no locale is more puzzling than cratonic areas such as southern Africa or the Siberian craton, where strong, thick lithosphere is breached by these large basaltic outpourings. Conventionally, flood basalts have been interpreted as melting events produced by one of two processes: 1) elevated temperatures associated with mantle plumes and/or 2) adiabatic-decompression melting associated with lithospheric thinning. In southern Africa, however, there are severe problems with both of these mechanisms. First, the rifting circumstances of several well-known basaltic outpourings clearly reflect lithospheric control rather than the influence of a deep-seated plume. Specifically, rift timing and magmatism are correlated with stress perturbations to the lithosphere associated with the formation of collisional rifts. Second, the substantial lithospheric thinning required for adiabatic decompression melting is inconsistent with xenolith evidence for the continued survival of thick lithosphere beneath flood basalt domains. As an alternative to these models, we propose a new two-stage model that interprets cratonic flood basalts not as melting events, but as short-duration drainage events that tap previously created sublithospheric reservoirs of molten basalt formed over a longer time scale. Reservoir creation/existence (Stage I) requires long-term (e.g. $\gg 1$ Ma) supersolidus conditions in the sublithospheric mantle that could be maintained by an elevated equilibrium geotherm (appropriate for the Archean), a slow thermal perturbation (e.g. thermal blanketing or large-scale mantle upwelling), or a subduction-related increase in volatile content. The drainage event (Stage II) occurs in response to an abrupt stress change in the lithosphere, which leads to the initiation and propagation of lithospheric dikes. Such a model accounts for the short eruption time of flood basalts, the evidence for lithospheric control of the eruptions, and the continued survival of cratonic lithosphere following these magmatic events. The most notable consequence of this model is that it implies the existence of large reservoirs of magma, comparable to the eruption volume of flood basalts that have been, and are still likely, present beneath stable continental lithopshere.

Keywords: flood basalts; craton; lithosphere

1. Introduction

From time to time, the Earth's surface is pierced by tremendous outpourings of basalt, the primary melt product of the Earth's mantle. These so-called flood basalts are unlike the basalts from arc volcanoes that decorate convergent plate boundaries, nor are they like

* Corresponding author.
E-mail address: silver@dtm.ciw.eu (P. G. Silver).
[1] Now at Woods Hole Oceanographic Institution, United States.
[2] Now at University of Rhode Island, United States.
[3] Now at Department of Geosciences, Boise State University, United States.

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basalts that are erupted along the globe-encircling length of mid-ocean ridges. They are indeed more akin to "floods", characterized by eruptions of millions of cubic kilometers of basalt that can spread over a large fraction of a continent with great rapidity—often in less than one million years. Flood basalts occur in both continental and oceanic settings, where they are termed continental flood basalts and oceanic plateaus, respectively. They are often associated with continental breakup, as in the case of Parana, Karoo, and Deccan flood basalts accompanying the breakup of Gondwanaland. Others are associated with rifting in stable cratons that does not lead to breakup, such as the Mid-Continent Rift in North America, or the Ventersdorp Rift of southern Africa. Their occurrence is not predicted by plate tectonics and consequently their origin remains enigmatic. What causes them to occur? How do they erupt so quickly? Where does the basalt come from?

Much of the thinking on the creation of flood basalts is based on the classic paper of White and McKenzie [1], which interprets flood basalts as melting events that are caused by one of two processes: (i) a high-temperature plume that serves to replace subsolidus sublithospheric mantle with supersolidus mantle, or (ii) the thinning of the lithosphere, thereby reducing the pressure of mantle material that is sitting just below the base of the lithosphere (Fig. 1A,B). The first of these is inspired by the plume hypothesis [2,3], that such outpourings are the result of deep, high-temperature plumes, while the second is an adaptation of the adiabatic-decompression melting model that so successfully accounts for the formation of mid-ocean-ridge basalts [4]. The combination of both of these mechanisms provides a reasonable explanation for flood basalts that are associated with breakup.

In cratonic environments and in the absence of breakup, the necessary lithospheric thinning could be caused by either stretching of the lithosphere [1], or through some form of convective instability and lithospheric delamination, such as that advocated for Tibet (e.g. [5,6]). The latter process would account for regions where there is little surface indication of the required lithospheric stretching needed for adiabatic decompression, although such models predict uplift following delamination. Cratonic southern Africa represents a particularly stringent test of these two mechanisms. There have been several massive outpourings or intrusions of continental basalts in the Precambrian of southern Africa, and thanks to the results from the recent Kaapvaal Project [7], it is now possible to examine the characteristics of these magmatic events in unprecedented detail. This information is in the form of new analyses of crust and mantle xenolith suites (chronology, geothermobarometry) from southern Africa's numerous kimberlite pipes, as well as new seismic constraints on the structure of the crust and upper mantle provided by the associated Southern African Seismic Experiment.

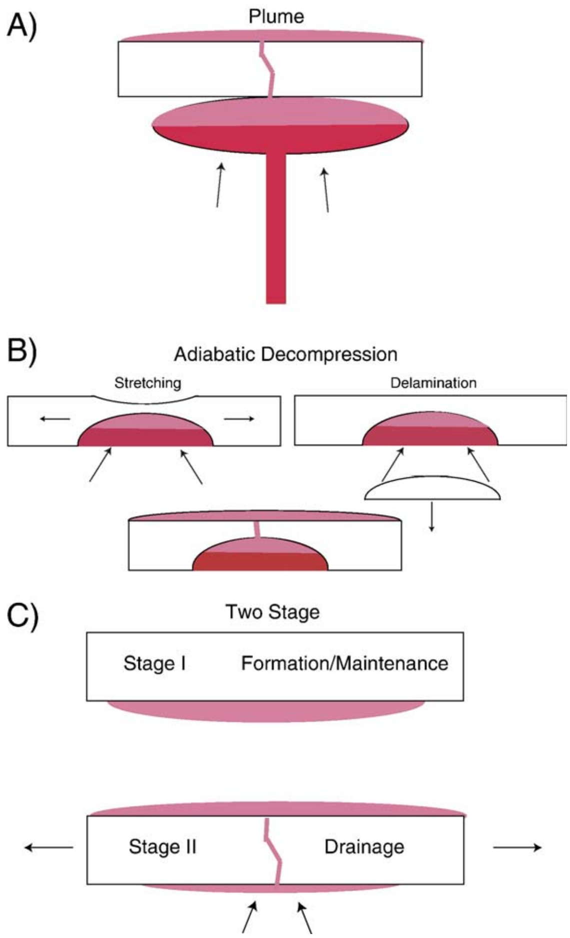

Fig. 1. Schematics of various models for continental flood basalts. Red zones denote areas of elevated temperature or volatile content, pink zones are molten. (A) Plume model. (B) Adiabatic-decompression-melting model. (C) Two-stage formation/drainage model.

2. Cratonic flood basalts in southern Africa

We consider the occurrence of 4 large magmatic events (Table 1, Figs. 1 and 2) spanning the time period 1.8–2.7 Ga: Ventersdorp (2.71 Ga), Great Dyke (2.57 Ga), Bushveld (2.06 Ga), and Soutpansberg Trough (1.88 Ga). The Ventersdorp is commonly regarded as a flood basalt covering much of the Archean Kaapvaal Craton [8–11]. The Bushveld, the world's largest layered igneous intrusion, has been referred to as the intrusive equivalent of a flood basalt, given its extensive volume and short duration [8,12]. The 500-km-long Great Dyke is likely the eroded remnant of a large igneous province.