Geologic, geochemical, and geophysical consequences of plume involvement in the Emeishan flood-basalt province

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ABSTRACT

Prevolcanic kilometer-scale lithospheric doming in the Emeishan large igneous province, southwest China, allows us to evaluate the spatial and temporal consequences of uplift on the paleogeography, geology, geochemistry, and geophysics of the region. Systematic spatial variations are observed across the domal structure in the distribution and thickness of clastic and carbonate sediments, the extent of erosion, thickness, and chemistry of volcanic rocks, and the crust-mantle structure. These features, which are best explained by a mantle plume, may be used to track older plume sites in the geologic record.

Keywords: paleogeography, geochemistry, geophysics, plume-lithosphere interaction, Emeishan basalt.

INTRODUCTION

The plume hypothesis has been widely adopted to explain the formation of time-progressive ocean islands and large igneous provinces, such as oceanic plateaus and continental flood basalts (e.g., Morgan, 1971; White and McKenzie, 1989; Campbell and Griffiths, 1990; Coffin and Eldholm, 1994). This hypothesis is now challenged because some fundamental aspects predicted by the modeling of plumes are said to be lacking in classic regions like Iceland and Yellowstone (e.g., Foulger and Natland, 2003). Instead of invoking a ''bottom-up'' process, these researchers favor a ''top-down'' hypothesis (Anderson, 2001) for the formation of large igneous provinces, in which shallow lithospheric processes may fuel melt production. However, controversy prevails as to whether current resolution of seismic data is sufficient to detect small thermal anomalies such as mantle plumes (DePaolo and Manga, 2003; Foulger and Natland, 2003). It seems clear that there is not a plume at every hotspot and that there may be different types of hotspots rising from different levels of Earth's interior (Courtillot et al., 2003; Montelli et al., 2004).

Seismic investigations help trace mantle plumes in modern, active hotspots, but are of limited benefit in identifying ancient plumes, mainly because geophysics provides us with a snapshot of Earth's present-day structure. Consequently, the geologic ''footprint'' associated with thermal anomalies provides the clues to tracing ancient plumes. According to some theoretical models, prevolcanic lithospheric uplift is the most important criterion used to identify the presence of plumes (e.g., Campbell and Griffiths, 1990). Uplift is best recorded in the sedimentary record (Rainbird and Ernst, 2001) and in radial drainage patterns (Cox, 1989). The lack of such evidence, however, is an argument against the involvement of plumes in the formation of large igneous provinces (Czamanske et al., 1998; Sheth, 1999).

He et al. (2003) showed unambiguous evidence for a rapid crustal doming prior to the Emeishan flood volcanism (258–254 Ma) in southwestern China. Herein we use this domal structure as a new framework to examine several aspects of the Emeishan large igneous province, including (1) the middle Permian–Late Permian sedimentology, (2) the geochemistry of the volcanic successions, and (3) the seismic structure of the lithosphere to argue for a fossil mantle plume under this province.

SEDIMENTOLOGY AND PALEOGEOGRAPHY

To characterize the crustal processes prior to the Emeishan volcanism, we describe the nature of the strata underneath the basalts (i.e., the Maokou Formation; Fig. 1) and the basalt–sedimentary rock contact (He et al., 2003). Correlation and comparison of the biostratigraphy of the Maokou Formation reveal a systematic thinning of the strata beneath the Emeishan basalt; thinned carbonates are capped by a subaerial unconformity (Fig. 1), which in many cases is evident as karst paleotopography, zones of paleoweathering, and local and basal conglomerates. Provenance analysis of the clasts in the conglomerates indicates derivation from the uppermost Maokou Formation. Therefore, the stratigraphic thinning likely resulted from differential erosion due to regional uplift. Isopachs of the Maokou Formation further delineate an uplifted area with a roughly circular shape (Fig. 2), very similar to the crustal doming above an upwelling mantle plume predicted by theoretical modeling. Combining the extent of eroded Maokou limestone with erosion rates of 0.12–0.3 mm/yr (He et al., 2003) allows us to estimate the amount of uplift necessary to produce these relationships. We estimate the duration of the kilometer-scale uplift to have been <3 m.y. and its radius to have been >700 km. The extent of uplift is >1000 m in the core of the uplifted region (He et al., 2003). There is no known process on Earth, other than mantle plumes, that can form lithospheric domes 1000 km or more in radius and >1 km high within several million years.

Lithospheric uplift prior to the Emeishan volcanism may have been responsible for (1) the rapid sea-level fall recorded by a regression at the boundary between the middle Permian and Upper Permian rocks in the western Yangtze craton and (2) the generation of clastic deposits surrounding the apex of the domal structure during the Late Permian (Fig. 1). This sea-level fall has been linked to the end-Guadalupian mass extinction, characterized by the disappearance of fusulinids, echinoderms, brachiopods, and bryozoans (Hallam and Wignall, 1999). The loss of the marine habitat due to sea-level fall has been proposed as the major mechanism for this biocrisis (Hallam and Wignall, 1999). A complement is to link the extinction to the eruption of the Emeishan basalts (Courtillot and Renne, 2003; Zhou et al., 2002). It is possible that both sea-level change related to plume-induced crustal uplift and the Emeishan volcanism contributed to the end-Guadalupian extinction.

No significant extension during formation of the Emeishan large igneous province is supported by the presence of a vast carbonate platform (i.e., stable sedimentary environment, Feng et al., 1997), the lack of a Late Permian dike swarm (Ernst and Buchan, 2003), and the fact that the Emeishan basalts uncomfortably overlie the Maokou Formation (Fig. 1). A significant sublithospheric thermal anomaly (~1600 °C, compared to ~1300 °C of normal mantle) would be required to generate kilometer-scale lithospheric uplift in association with a melt

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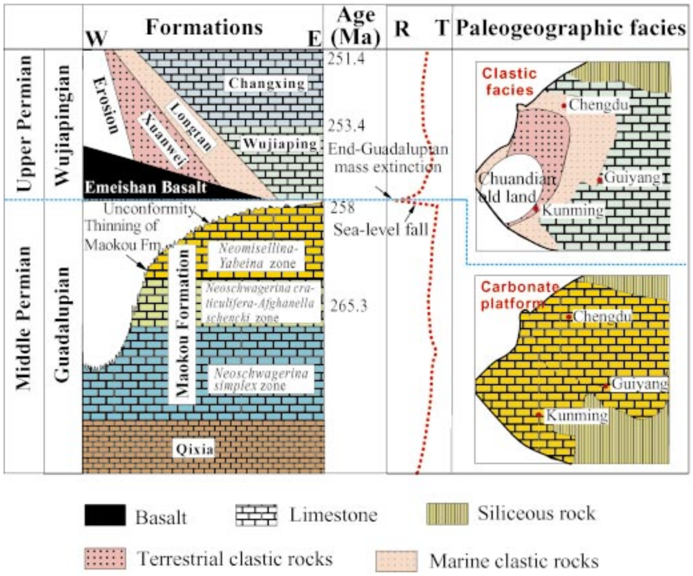

Figure 1. Changes in lithofacies, sea level, and paleogeographic pattern across boundary between middle Permian and Upper Permian rocks in Emeishan large igneous province. Three biostratigraphic units comprise Maokou limestone. Curve assigning thinning of Maokou Formation (from west to east) is after He et al. (2003). R—regression; T—transgression.

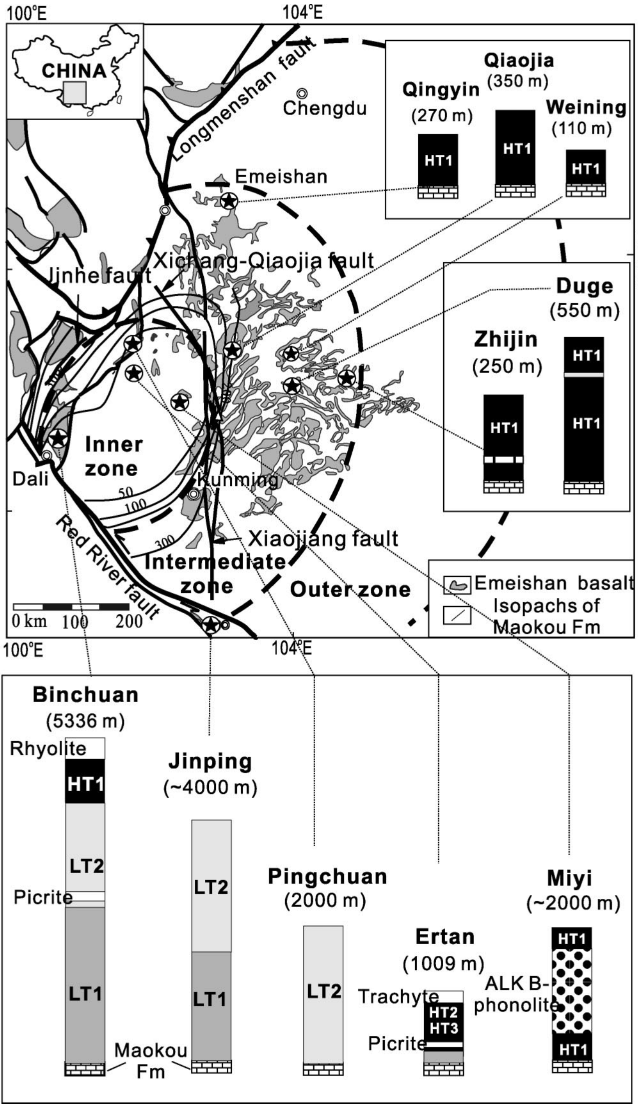

Figure 2. Distribution of Late Permian Emeishan basalts in southwestern China and stratigraphic variation of 10 representative lava successions. Also shown are isopachs of Maokou Formation that delineate subcircular domal structure formed prior to Emeishan volcanism (He et al., 2003). Dashed curves separate inner, intermediate, and outer zones of dome, which are characterized by varying extent of erosion of Maokou limestone. HT—high-Ti basalt; LT—low-Ti basalt; ALK—alkaline series. Classification of LT1, LT2, HT1, HT2, and HT3 and data are after Xiao et al. (2003) and Xu et al. (2001, 2003).

thickness of 15–25 km (see following), where lithospheric extension is minimal (e.g., McKenzie and Bickle, 1988). Late Permian paleogeography is defined by deposition on and off the circular uplift region (Fig. 1). For example, the distribution of Upper Permian terrestrial clastic deposits is largely confined to the domed area, and the shallow-marine limestones tended to be deposited in the areas beyond the uplifted area (Fig. 1). This observation and the circular sedimentary pattern strongly argue for a genetic link between plume-induced crustal uplift and the change in paleogeography across the middle Permian–Upper Permian boundary.

The domal structure associated with the Emeishan large igneous province can be divided into inner, intermediate, and outer zones (Fig. 2) in terms of the extent of erosion of the Maokou Formation. The inner zone, where the erosion of the Maokou Formation is most apparent, is considered the impact site of the rising plume head (He et al., 2003). The boundary of the inner zone is coincident with the Xiaojiang fault to the east, the Xichang-Qiaojia fault to the northeast, and the Jinhe fault to the northwest (Fig. 2). These faults are interpreted as syndoming structures because they controlled the very rapid deposition of clastic deposits in canyons and on alluvial fans. The extent of erosion is modest in the intermediate zone and is generally minor in the outer zone. Sedimentation in the areas beyond the Emeishan province, where the standard stratigraphic sequence of the Maokou Formation was established (Feng et al., 1997), was continuous throughout the Permian. Such a division of the domal structure is important because it provides a natural basis to subdivide the Emeishan large igneous province. Accordingly, the apex of the domed area may correspond to the plume head and the margins correspond to the plume peripheries.

SPATIAL VARIATION IN THE BASALT GEOCHEMISTRY

In this section we investigate compositional variations in the lavas from the center to the margin of the dome. For example, compositional variation would result from spatial zonation of mantle temperature that would lead to systematic variations in the degree of melting (Campbell and Griffiths, 1990). For this purpose, the volcanic stratigraphy at 10 locations in the inner and intermediate zones was sampled, and >350 samples were analyzed for major and trace element compositions (Xu et al., 2001, 2003; Xiao et al., 2003). The Jinping section was initially within the inner zone and was displaced to the present position by Cenozoic sinistral movement along the Red River fault (Xiao et al., 2003). Data compilation reveals a systematic change in basalt type from the inner to intermediate zones (Fig. 2). In general, the domed region of the Emeishan large igneous province comprises thick (2000–5000 m) sequences of dominant low-Ti volcanic rocks and subordinate picrites (Chung and Jahn, 1995), and high-Ti and alkaline lavas (Xu et al., 2001, 2003; Xiao et al., 2003). In contrast, thin sequences (<500 m) of high-Ti volcanic rocks mainly occur on the periphery of the domal structure (rock classification after Xu et al., 2001). Xu et al. (2001) showed that the high-Ti and low-Ti lavas require very different mantle conditions that are consistent with temperature variation across a plume head (Campbell and Griffiths, 1990). Application of rare earth element inversion techniques (McKenzie and O'Nions, 1991) reveals that the low-Ti lavas that originated at 60–140 km required 16% melting and mantle temperatures >1500 °C. In contrast, the high-Ti lavas were generated at 75–100 km during events of much smaller degrees of melting (1.5%) and at lower mantle temperatures (<1500 °C). Therefore, the transition from the low-Ti to high-Ti lavas, which is associated with a change in thickness of the volcanic rocks (suggestive of different melt-production rates), was likely accompanied by a decreasing thermal gradient. The predominance of the thick low-Ti lavas in the inner zone (Fig. 2) suggests that the mantle beneath the core of the domal structure underwent a larger extent of partial melting than that under the marginal area. This suggestion and the occurrence of picrites in the inner zone are consistent with a hotter mantle beneath the dome center than beneath the dome periphery. A likely scenario is that a plume head was present underneath the inner zone.

There are additional observations that require complexity in this simple thermal-zonation model. Specifically, within the inner zone sections, high-Ti—HT1 and HT2-HT3—lavas occur in the uppermost parts of the Binchuan and Ertan sections, respectively, and a thick sequence of evolved alkaline lava (hawaiite to phonolite) occurs between high-Ti lavas in the Miyi section (Fig. 2). It is possible that these high-Ti and alkaline lavas are relatively young compared to low-Ti lavas and reflect the waning of plume-related volcanism (Xu et al., 2001). However, to date we have no age constraints on lavas in these three sections. Nevertheless, low-Ti, HT2-HT3, and alkaline lavas occur exclusively in the inner zone, and they were subject to significant crustal contamination (Xu et al., 2001, 2003). These factors may be related to a larger degree of thermal remobilization of the lithosphere above the plume head compared to that above the plume periphery.

SEISMIC DATA AND CRUST-MANTLE STRUCTURE

Seismic data provide insights into the nature of the lithosphere, in particular the character of the transition between the crust and upper mantle. In relation to the domal structure outlined here, there is a gradual decrease in crustal thickness from the center to the margin of the dome (Fig. 3A). The crustal thickness in the inner zone ranges from 55 to 64 km (average 61.5 km), which is considerably thicker than that beneath eastern China (<35 km), a typical nonrifted continental margin (Menzies et al., 2002). The crust in the intermediate zone is also relatively thick, ranging from 38 to 54 km (average 45 km), but is thinner than in the inner zone. The data in the outer zone are sparse but define a range of 35–43 km (Fig. 3A). This seismic result is consistent with the petrogenetic model, indicating that melt production was higher in the inner zone.

Seismic tomographic modeling reveals that the lower crust in the inner zone has a high seismic P-wave velocity ranging from 7.1 to 7.8 km/s (Fig. 3B; Liu et al., 2001). The thickness of this high-velocity lower crust is as much as 25 km (average 20 km), similar to that of high-velocity lower crust reported from volcanic rifted margins associated with large igneous provinces (Menzies et al., 2002). Although tomographic data are not available for other zones of the domed area, other investigations suggest that the crust outside of the inner zone is relatively thin (<45 km) and that the high-velocity layer is generally absent (Cui et al., 1987). Different crustal structures are therefore suggested for the inner and intermediate zones of the domed area. It is interesting to note that the outline of the high-velocity lower crust according to seismic data coincides with the domal structure defined on the basis of sedimentary rocks.

Furthermore, the tomographic results (Liu et al., 2001) reveal a lens-shaped, fast upper mantle (seismic velocity, $Vp = 8.1–8.6$ km/s) below the high-velocity lower crust (Fig. 3B). The western and eastern margins of this seismically anomalous body correspond to longitudes of 100.8°E and 102.8°E, respectively, which agree well with the geographic location of the inner zone (Fig. 3). It is the spatial proximity of the high Vp body and the inner zone that leads us to suggest that this body might represent the residues left after extensive melt extraction from the plume head. Strongly refractory (olivine rich) mantle is low in density, which translates to high compressional velocities. In addition, the high Vp body is at a depth of >100 km (Fig. 3B), where garnet is stable. An assemblage of olivine and garnet with subordinate pyroxenes would have a characteristically high seismic velocity (Farnetani et al., 1996).

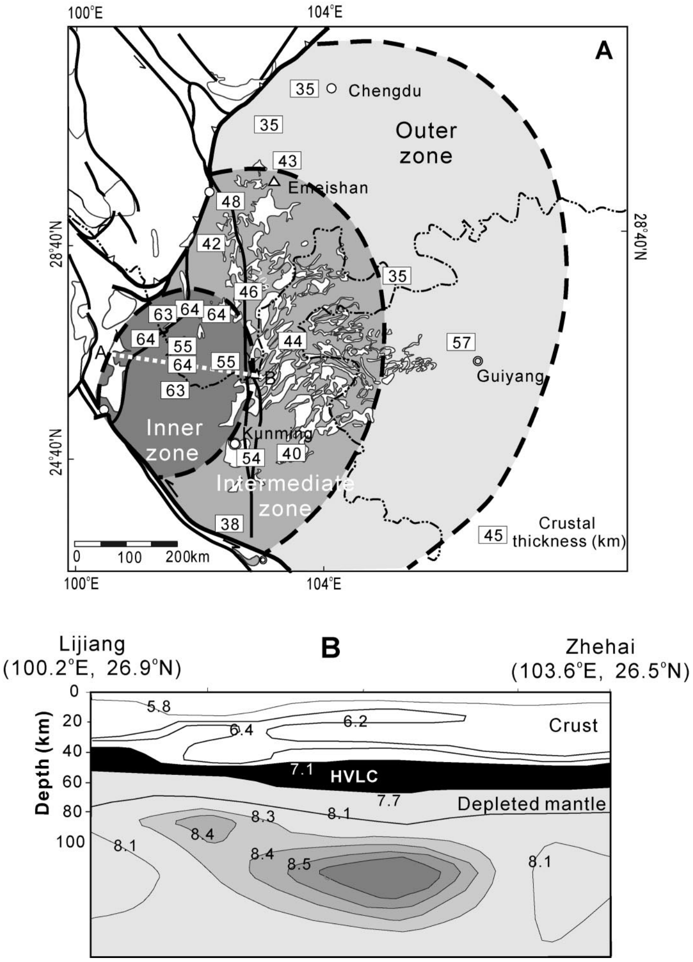

Figure 3. A: Crustal thickness data plotted over domal area of Emeishan large igneous province. Data sources: Zhang et al. (1988), Yuan (1995), and Liu et al. (2001). B: Seismic velocity (*V*p) structure of lower crust and upper mantle along profile A–B shown in A (modified after Liu et al., 2001). HVLC—high-velocity lower crust.

A genetic link between the crust-mantle structure and a mantle plume is thus inferred. The thicker crust in the inner zone reflects high melt production resulting from the higher temperature in the central part of the plume and uplift of lithosphere above the plume head that triggered relatively high amounts of decompression melting (Fig. 4). High melt production may lead to cooling and fractionation of melts at the crust-mantle boundary, thereby creating cumulate rocks that form the high-velocity lower crust (Farnetani et al., 1996).

FOSSIL MANTLE PLUME IN THE EMEISHAN LARGE IGNEOUS PROVINCE

While a heated debate rages around the existence of mantle plumes, this study provides compelling evidence for a fossil mantle plume beneath the Emeishan flood-basalt province of southwest China. Sedimentologic and paleogeographic data show unequivocal evidence for a lithospheric doming event prior to the Emeishan volcanism. In turn this analysis provides a unique framework within which to interpret data from many disciplines. Systematic geochemical and geo-

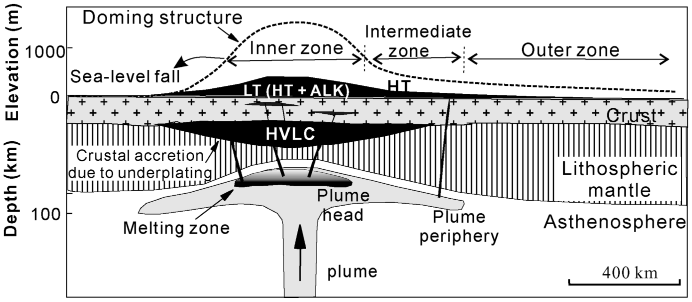

Figure 4. Surface uplift, generation of Emeishan basalts, and crustal accretion in context of upwelling of mantle plume. HVLC—high-velocity lower crust; HT—high-Ti basalt; LT—low-Ti basalt; ALK—alkaline series.

physical variations and geologic observations in and around the Emeishan large igneous province are best explained in terms of plume involvement in flood volcanism. Specifically, the consequences of plume-lithosphere interaction (Fig. 4) include (1) sedimentologic evidence for kilometer-scale, prevolcanic uplift and/or doming, including thinning of marine carbonates, a marine to subaerial transition, local provenance of clastic sediments, and a marked erosional unconformity, evident as paleo–karstic surfaces on the marine carbonates; (2) a domal structure (700 km radius) active for 3 m.y.; (3) variations in the thickness of volcanic rocks across the domal structure; (4) variations in flood-basalt geochemistry from the center to the edge of the domal structure (such that picrites are restricted to the core of the dome) that are interpreted as high-temperature melts in the center and lower-temperature melts at the edge; (5) gradual decrease in crustal thickness from the center to the margin of the dome; and (6) the presence of a high-velocity region of upper mantle at a depth of ~100 km and high-velocity lower crust (15–25 km) immediately beneath the domal structure consistent with significant melt production and possible underplating and/or intrusion into the lower crust.

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