Weak Vertical Surface Movement Caused by the Ascent of the Emeishan Mantle Anomaly


1. **Key Points:**
   - Neither significant surface uplift nor subsidence emerged during the ascent of the Emeishan mantle anomaly.
   - Entrained recycled dense oceanic crust is responsible for a reduced buoyancy of the Emeishan plume.
   - Prolonged surface subsidence through strong lithospheric flexure is caused by basalt load in the Emeishan province.

2. **Abstract:**
   Prevailing mantle plume models reveal that the roles of plume-lithosphere interactions in shaping surface topography are complex and controversial, and also difficult to test. The exposed and complete strata in the Emeishan large igneous province (LIP) recorded abundant paleoenvironmental information associated with preeruptions and syneruptions, attracting numerous workers to this province to test these models. Despite intensified research these models are still strongly debated. This study represents an extensive field investigation combining new and previously published data from the Emeishan LIP to further seek information on plume-induced topographic variations. Our results indicate that there are inconspicuous vertical motions of the surface topography during the ascent of mantle plume, and a significant surface subsidence occurred at the early stage of the volcanism that has a significantly positive correlation with the thickness of local lavas, and the topographic uplift emerged in the late stage of the volcanism. Our studies provide key geological and geochemical evidence that the ascent of the Emeishan plume is unable to drive a significant surface uplift, owing to the plume containing numerous entrained bodies of dense recycled oceanic crust (10–20%) that can significantly reduce plume buoyancy. The significant surface subsidence maybe linked to a significant loss of thermal buoyancy due to the release of heat, which, accompanied by rapid loading of numerous dense erupted lava and a strong lithospheric flexure, also lead to a later synchronous and significant surface subsidence in the Emeishan LIP.

3. **1. Introduction**

Large igneous provinces (LIPs) form as a result of vast outpourings of predominantly basaltic lava onto the Earth’s surface (Bryan & Ernst, 2008), and their formation is linked by many geologists to mantle plume activity (e.g., Richards et al., 1989). Classic mantle plume models predict that a hot, buoyant plume head should cause kilometer scale surface uplift prior to the onset of volcanic eruptions in these LIPs (Campbell & Griffiths, 1990; Richards et al., 1989; White & McKenzie, 1989). Whether uplift occurred or not can only be verified through joint observation and interpretation of the igneous record and interrelationship between sedimentation and erosion (e.g., Saunders et al., 2007). However, in many LIPs the predicted kilometer scale uplift is difficult to be verified from the geological record or even disputed (e.g., Czamanske et al., 1998). The Emeishan LIP was thought to be the best example of a continental LIP where plume-driven kilometer scale uplift occurred based on supposedly differential erosion from the center to the outer zone of the province and therefore providing strong support for the classic mantle plume model (He et al., 2003, 2006; Xu et al., 2004). However, several subsequent investigations revealed prevolcanic subsidence or no to insignificant uplift in the Emeishan LIP, rather than the proposed central kilometer scale lithospheric doming (e.g., Jerram et al., 2016; Sun et al., 2010; Ukstins-Peate et al., 2011; Ukstins-Peate & Bryan, 2008; Wignall et al., 2009; Zhu et al., 2014).

A lack of evidence for uplift was also proposed for the Wrangellia and Columbia River (USA) LIPs (Hales et al., 2005; Richards et al., 1991) and the Siberian Traps LIP, Russia (Czamanske et al., 1998). Through renewed and extensive field analyses a picture emerges that indicates plume head-induced uplift probably did not accompany the formation of many LIPs and therefore calls for alternative mechanism of formation. Based on numerical modeling, Leng and Zhong (2010) proposed a model ascribing the initial surface subsidence to the temporary ponding of the plume head below the 660 km discontinuity tens of million years prior to the onset of flood basalt eruptions, whereas synglobal volcanic subsidence may be due to loading of a large volume of erupted basalts. Current numerical thermochemical plume models ascribe (Dannberg & Sobolev, 2015; Sobolev et al., 2011) the absence of pronounced premagmatic uplift or negligible surface uplift in LIPs to a...
significant decrease in buoyancy, which is assigned to the presence of 15–20% of dense, recycled oceanic crust within an ascending mantle anomaly. However, this inference is still unproven requiring more detailed geological and geochemical evidence to reconstruct the plume-induced topographic evolution within a magmatic province.

The continuous and exposed strata in the Emeishan LIP recorded rare and complete paleoenvironmental information that can be used as a marker for subsidence and uplift of surface topography. Here we present results of extensive field analyses and combined this information with previous stratigraphic and geochemical data from the Emeishan LIP to explore surface topographic evolution in response to mantle plume activity during the prevolcanic and synvolcanic eruption phases. Based on these data we reaffirm the topographic subsidence of the Emeishan province and assign this to the entrainment of dense, recycled oceanic crust within an ascending mantle plume.

2. Geological Setting

The Emeishan LIP is located on the western margin of the Yangtze Craton in southwest China (Figure 1). The province covers an area of over 2.5 × 10^5 km^2 and includes an extrusive volume of mainly basalt of 0.3 × 10^6 km^3 (Ali et al., 2010), with the thickest units located in the west thinning toward the east and north. Radio-isotopic age data indicate that the main phase of magmatism occurred between 263 and 260 Ma (e.g., Liu & Zhu, 2009; see Shellnutt, 2014 for a compilation). Picritic lavas were mainly reported in volcanic successions of the western part of the Emeishan LIP, such as Dali, Lijiang, Binchuan, and Yongsheng, and these areas are considered to represent the center of the plume (e.g., Hanski et al., 2010; Kamenetsky et al., 2012; Zhang et al., 2006). This interpretation was also consistent with the spatial distribution of radiating mafic dyke swarms (Li et al., 2015). The Emeishan volcanic sequences unconformably overlie the late Middle Permian Maokou Formation and unconformably underlie Late Permian (western and eastern parts) and Triassic or Jurassic sediments (center) (He et al., 2003). The Permian sequences in south China have been extensively studied owing to their fossil fuel (oil, gas, and coal) potential (e.g., Feng et al., 1997; Wang et al., 1994), and therefore, only a brief summary is given below. Figure 2 provides, based on published data that we compiled, a diagram showing the Permian stratigraphy, sedimentary facies, and sea level changes in SW China. The Permian sequences consist of the lower Liangshan Formation, middle Qixia and Maokou Formations, and upper Lopingian sequence. The Early Permian Liangshan Formation is mainly composed of quartz sandstone with interbedded thin coal measures and minor limonite beds, which were formed in coastal to flat tidal environments. The Middle Permian strata, composed of the Maokou Formation and the underlying Qixia Formation, contains a large number of continuous marine reef fossils, representing a relatively stable carbonate platform with a sea water depth of ~20–50 m (Feng et al., 1997; Wang et al., 1994; Wang & Jin, 2000). The Lopingian sequence of the Late Permian strata (Xuanwei, Longtan, or Wujaping and Changxing Formations) is the most important coal-bearing unit in south China, consisting of multicolored sandstones, mudstones, and limestones, therefore representing alternating terrestrial and marine environments.

3. Methodology

3.1. Field Analysis

We carried out extensive field investigations in the Dali, Yongsheng, Yanyuan, and Panxian areas of the Emeishan LIP to further reconstruct a clear topographic variation model through detailed descriptions and critical evaluations of the sedimentary records during the prevolcanic and synvolcanic eruption phases. We compiled, based on our field analyses and combined with a thorough review of published regional papers, books and unpublished regional geological survey reports (several in Chinese) of the Emeishan volcanic sequences, a comprehensive data set of stratigraphic and lithologic logs, detailed information given in Tables S1–S5 in the supporting information.

3.2. Calculating the Amount of Recycled Oceanic Crusts

We argue here that no significant uplift occurred prior to the onset of volcanism due to incorporation of dense recycled oceanic crust into the ascending mantle beneath the Emeishan LIP. Sobolev et al. (2005, 2007) proposed that melts derived from recycled and metamorphized oceanic crust (eclogite) interact with peridotite to form a hybridized pyroxenite mantle source. Olivine crystallizing from pyroxenite-derivate
melts have characteristically high Ni contents and high Fe/Mn ratios (Sobolev et al., 2005). Olivine from Emeishan picrites share these features (e.g., Fe/Mn = 66.3 ± 4.3) including low Ca content (Kamenetsky et al., 2012). Although the variation in Fe/Mn ratios of olivine can alternatively be interpreted by partial melting of a peridotite source under different pressure and temperature conditions (Matzen et al., 2017; Niu et al., 2011). Nevertheless, recent geochemical studies conclude that the Emeishan mantle source must have been enriched supporting our hypothesis of an involvement of a fertile pyroxenite mantle source for the Emeishan LIP (e.g., Ali et al., 2010; Liu et al., 2017; Ren et al., 2017). We therefore argue that the Fe/Mn ratios of olivine can be used to calculate a maximum proportion of pyroxenite-derived melt in the source through equation (S2) of Sobolev et al. (2007).

Figure 1. Simplified geological and paleogeographic map of the Emeishan LIP. (a) Permian paleogeographic map showing the location of the Emeishan LIP, base map from Ron Blakey (http://jan.ucc.nau.edu/~rcb7/260moll.jpg, accessed December 2015). The Emeishan LIP is located in the west part of the South China block during the Permian. (b) Simplified geological and Middle Permian (Qixia and Maokou Formations) paleogeographic map of the Emeishan LIP, based on Boven et al. (2002) and Ma et al. (2004), respectively. Paleogeographic map is made up of central Yunnan basement (light yellow), upper Yangtze carbonate platform (light blue), and Dian-Qian-Gui (Yunnan-Guizhou-Guangxi Provinces) carbonate basin (blue) during the Middle Permian. Green arcs represent Middle Permian marine reefs, and the locations are from Feng et al. (1997). Blue circles indicate pillow basalts, marine hydromagmatic deposits, and intercalated limestones in the early Emeishan volcanic sequences; and the data of Dali, Yanyuan, and Panxian areas are from this investigation and the others are based on Yunnan Geologic Bureau (1969), Sichuan Geologic Bureau (1976), and Ali et al. (2010). Red stars represent meter scale coastal-marsh sediments that are located between the Emeishan basalts and Maokou limestones.
Calculation of the amount of recycled oceanic crust involved in the formation of the Emeishan LIP was based on models and equations suggested by Sobolev et al. (2005, 2007). The following three parameters were considered in these calculations: (i) the proportion of pyroxenite-derived melt by the degree of melting of eclogite, (ii) the amount of eclogite-derived melt needed to produce hybrid pyroxenite from peridotite, and (iii) the degrees of melting of peridotite and pyroxenite (Sobolev et al., 2005, 2007). We used a compilation of olivine phenocryst data of the Emeishan picrites (Arguin et al., 2016; Hanski et al., 2010; Kamenetsky et al., 2012; Zhang et al., 2006) to calculate the amount of recycled oceanic crust based on equation (S3) of Sobolev et al. (2007) and under the following assumptions: (i) the maximum degree of melting of eclogite was 50%, (ii) 50% of peridotite was required to produce hybrid pyroxenite, (iii) a minimum degree of melting of pyroxenite of 50%, and (iv) degree of melting of peridotite ranged between 10% and 20%. Furthermore, a mean proportion of 38% of pyroxenite-derived melt was calculated based on the olivine phenocrysts data from early picritic lavas in the center of the Emeishan plume (including Lijiang, Dali, Yongsheng, and Binchuan) and equation (S2) of Sobolev et al. (2007).

4. Results

4.1. Coastal Tidal-Lagoonal Records at the Base of the Emeishan Volcanic Succession

Our field analyses concentrated on the Dali area within the Emeishan central zone, where the exposed and thick volcanic succession contains many intercalated sedimentary layers (Figure 3). In several sections, a
few meter-thick mudstones, sandstones, and shales with coal beds and limestone lenses directly overlying or close to the boundary between the Maokou limestone Formation and Emeishan volcanic succession contact were observed (Figures 4 and 5). (i) At the Shuanglang section (Dali City of Yunnan Province), ~ 1.5 m thick gray-black mudstones with volcanic clasts and intercalated coal and tuff beds were exposed at the base of thick lavas and approaching the top of the Maokou limestone, implying deposition within a supratidal environment. However, at Shuanglang we found no evidence that basaltic pillow lavas were directly
overlying the Maokou limestone as reported by Zhu et al. (2014). (ii) At the Wase section (about 15 km east of Shuanglang, Dali City of Yunnan Province), Sun et al. (2010) reported the contact between the Maokou Formation and the overlying Emeishan volcanic rocks, which consists of lower gray silty shales with sponge spicules filling in the isolated hollows (25 cm relief and 1 m diameter) on the top of Maokou limestones and upper bright red mudstones with volcanic clasts. Sun et al. (2010) considered that the hollows are dissolution basins by plant roots and spiculitic shale formed a restricted lagoonal facies. The bright red mudstones reflect a supratidal setting, similar to Shuanglang. (iii) At the Shangcang section (Binchuan County of Dali City, Yunnan Province), the contact between the Maokou limestone formation and Emeishan volcanic succession is over ~ 5 m thin-bedded yellow-green and yellow-white calcareous siltstones, containing minor gypsum and salinization clays in interlayers of calcareous siltstones, where horizontal bedding and plastic deformation bedding are displayed. These sedimentary features are may be related to a lagoonal setting under muddy water at the Shangcang. (iv) At the Jiexiang section (Midu County of Dali City, Yunnan Province), ~ 3.5 m thick intercalated sedimentary layers are composed of lower sandstone with limestone lenses and upper tuffaceous sandstone at the base of lavas, probably in a tidal setting.

Figure 4. Field images of representative sedimentary and volcanic lithologies recording the geological history prior to the onset of numerous flood basalt eruptions in the center and outer regions of the Emeishan LIP. (a) White-yellow tuff, gray-black mudstone, and coal bed with pyroclastic rocks at the base of lavas at the Shuanglang of Dali area (central). (b) Thin coal beds at the base of lavas in Panxian county (outer). (c) Yellow-green and gray-white argillaceous sandstone (including limestone lenses) and tuffaceous sandstone at the bottom of lavas at the Jixiang of Dali area (central), (e and f) are partial enlargements of Figure 4c. (d) Yellow-green and yellow-white argillaceous sandstone on the top of the Maokou Formation, Shangcang of Dali area (central). Locations are shown in Figures 1 and 3.
In the outer zone, we compiled five previous measured stratigraphic sections on the contact between the Early Permian Maokou Formation and Emeishan volcanic succession and carried out a field investigation in Panxian area at the eastern part of the Emeishan LIP. (i) At the Luoxi section (Puge County of Sichuan), ~0.7 m thick yellow-green fine conglomerates directly overlie the Maokou limestone, and the subsequent stratigraphy consists of gray calcareous siltstones with argillaceous limestone lenses, gray-black argillaceous limestones, gray and yellow sandy shales with lenticular carbonaceous shales including fossil plant fragments, and gray-green shales from base to up (Sichuan Geologic Bureau, 1965). (ii) At the Yiduoyun section (Kunming City of Yunnan Province), the contact is ~1 m gray clay rocks with a few centimeters thick limonites and kaolins at the base (Yunnan Geologic Bureau, 1990). (iii) At the Liuhong section (Meigu County of Sichuan Province), ~0.9 m thick gray-yellow carbonaceous clay rocks and gray-black mudstones contain intercalated black shales (~3 cm thick) and fossil plant fragments, and there is a few centimeters thick weathering crust on the top of the Maokou Formation (Sichuan Geologic Bureau, 1972). (iv) At the Waduanshan section (Emei City of Sichuan Province), the base is composed of lower gray clay rocks and argillaceous limestones (~1.3 m thick) with intercalated lenticular coal layer (~10 cm thick) and black shale, and upper gray-black mudstones and sandstones containing fossil plant fragments and intercalated carbonaceous shales and thin coal layers (~0.7 m thick) (Sichuan Geologic Bureau, 1971a). (v) At the Chaojiaying section (Shuicheng County of Guizhou Province), the contact is ~2.5 m brown-yellow, purple, and gray clay rocks with a few centimeters thick limonites and kaolins at the base (Guizhou Geologic Bureau, 1973b), similar to the Yiduoyun section. (vi) At the Zhudong section (Panxian County of Guizhou Province), we found two coal layers (~10–20 cm thick) were close to the top of the Maokou limestone and in sharp contact with basal basalt lavas. Small pillow basalts (a few centimeters in diameter) below these coal layers suggest that extrusion of lavas occurred under water before the formation of coal layers. This may imply a possible small uplift before the onset of numerous volcanic eruptions.

In summary, sediments immediately underlying the Emeishan lavas in the central and outer zones of the Emeishan LIP are mainly composed of siltstones, mudstones, and shales, generally ranging in thickness from ~1 m to ~5 m. These sequences are representative of muddy coastal to tidal-lagoonal settings present at the onset of numerous volcanic eruptions.

4.2. The Relationship Between Marine Lithologies and Early Lavas

Numerous investigations now demonstrate that the early Emeishan volcanism occurred at shallow marine or near sea levels from the central to outer zones (Figure 1) (e.g., Jerram et al., 2016; Sun et al., 2010; Wignall et al., 2009; Zhu et al., 2014). This is most evident in the Dali area of the Emeishan province (Figure 3). Based on our field analyses, at the Dali, Yanyuan, and Panxian areas, we also found several pillow basalts, marine...
4.3. The Terrestrial Record of Late Stage Lavas

We conducted the field analyses of lavas for four areas, including Dali City, Yanyuan County, Yongsheng County, and Panxian County. Here the total thickness of late stage lavas is less in comparison to those of the early stage lavas. The late stage lavas contain many thick intercalated tuffaceous rock and tuff layers.
(Figures 9a, 9d, and 9e), and their cumulative thicknesses may be up to one third of all late volcanic rocks. In Dali, Yongsheng, and Yanyuan areas, the late-stage lavas have terrestrial intercalated beds, such as yellow siltstones and mudstones and purple mudstones, which were described at different stratigraphic positions (Figures 9a–9d). Particularly in Panxian area, we found fossil plant fragments in volcaniclastic rocks as a direct evidence for late volcanism within terrestrial environments (Figure 9f). The presence of many intercalated terrestrial beds including plant fossils within late volcanic rocks suggests that the late volcanism occurred in a terrestrial environment.

4.4. The Amount of Pyroxenite-Derived Melt and Recycled Oceanic Crust

The geochemical signature of Emeishan igneous rocks (e.g., high Zr concentration in basalt, high Re/Os ratios in dyke, and linear arrays of the Pb isotope ratios in melt inclusions) strongly implies that recycled oceanic
crust has been involved in the formation of this LIP (e.g., Ali et al., 2010; Hou et al., 2013; Ren et al., 2017). We calculated the proportion of pyroxenite-derived melt (Figure 10 and Table S6) and the amount of recycled oceanic crust possibly entrained in the Emeishan plume applying the model proposed by Sobolev et al. (2007) to published data of high-forsterite (~80–90) olivine phenocrysts (data from 924 samples) hosted in the early picrite lavas (Dali, Lijiang, Binchuan, and Yongsheng areas in the center of the Emeishan plume). Our results show that the amount of pyroxenite-derived melt is at a mean proportion of 38%, and that of incorporated recycled oceanic crust ranges between 10% and 20%. These results are comparable to values obtained for low-forsterite (~50–70) olivine crystals of the Siberian LIP (46% and 10%–20%) (Sobolev et al., 2011).
5. Discussion

5.1. Prolonged and Inconspicuous Surface Subsidence Prior to the Onset of Volcanisms

The coastal to tidal flat environments recorded in the Emeishan LIP of Liangshan stage (Early Permian) transformed into a shallow sea carbonate platform at the beginning of the Qixia stage. This change may be attributed to regional transgression because of the presence of Liangshan quartz sandstone observed throughout south China (e.g., Ma et al., 2004; Wang et al., 1994; Wang & Jin, 2000), which is much larger than the area of the Emeishan LIP (Figure 1a). During the entire Middle Permian, the continuous fossil records of marine reefs imply that the regression was very slow under the relatively stable crust (Feng et al., 1997; Wang et al., 1994; Wang & Jin, 2000). Thus, topographic changes are inconspicuous in the Emeishan LIP during a period of time of over 20 million years before the onset of volcanism, rather than significant surface subsidence (Jerram et al., 2016).

For a purely thermal plume with a negative Clapeyron slope (e.g., $\gamma = -3.0 \text{ MPa/K}$), the mantle model shows that the plume head ascends through the lower mantle and arrives at the 660 km phase boundary before the onset of volcanic eruptions. This ascent deflects the phase boundary upward owing to the plumes high

Figure 9. Field images of volcanic rocks and sedimentary records during the late eruptions in the center and outer parts of the Emeishan LIP. Intercalated terrestrial deposits, tuffaceous rocks, and tuffs (e.g., siltstone and mudstone) in the late eruptions, widely distributed in Yongsheng (a and b), Dali (c), Yanyuan (d), and Panxian (e) areas. (f) Photomicrograph (reflected light) showing fossil plant fragments in basaltic tuff of late volcanism from the Panxian area. For locations please see Figure 1.
temperature and thus generates a negative buoyancy, resulting in a surface subsidence that lasts for over 10 million years and reaches to ∼100 m (Leng & Zhong, 2010). However, our results show that the Emeishan plume contains a substantial amount of dense recycled oceanic crust (eclogite). Eclogite has a lower density than peridotite just below the 660 km discontinuity to compensate this negative buoyancy, leading to inconspicuous topographic changes from the prediction of Dannberg and Sobolev (2015), which is consistent with our findings.

5.2. Weak Surface Uplift Prior to the Onset of Numerous Volcanic Eruptions

Our extensive field-based observations were combined with previously published data, which includes various sandstones and mudstones with thin coal layers and minor limonites (only a few meters) intercalated between the Emeishan basalts and Maokou limestones. These lithologies are widely distributed in the central and outer zones of the Emeishan LIP (Figure 4), suggesting that a muddy water tidal-lagoonal setting in the center of the Emeishan LIP and a muddy water tidal setting in the outer zone prevailed at the onset of numerous volcanic eruptions. Furthermore, at Xiongjiachang of Zhijing County (Guizhou Province) on the outer boundary of the Emeishan LIP (Figure 1), early basaltic lavas are in sharp contact with the shallow marine platform carbonates on top of Maokou Formation, indicating the emplacement of early basaltic lavas in a marine setting (Sun et al., 2010; Wignall et al., 2009). Therefore, we propose that a clean and shallow water oceanic reef environment forming at the carbonate platform of Maokou stage (Feng et al., 1997; Wang et al., 1994) turned into a muddy water coastal tidal-lagoonal setting in the central and outer zones of the Emeishan LIP, in response to the onset of extensive volcanic activity associated with the Emeishan plume (Figure 11). This scenario reflects weak surface dynamic uplift prior to the onset of numerous flood basalt eruptions in the Emeishan LIP, probably to depths of a shallow sea (∼200 m). Considering the effect of the regression on the Emeishan LIP (Figure 3), this estimated uplift should represent a maximum height for dynamic uplift caused by the Emeishan plume.

This result does not concur with the classic mantle plume model. According to the prediction of this model, the hot mantle plume can generate a substantial surface uplift in the center of the plume through thermal buoyancy (e.g., Campbell & Griffiths, 1990; Richards et al., 1989; White & McKenzie, 1989). However, our geochemical model calculations based on olivine phenocryst data indicate that the Emeishan mantle anomaly could have entrained a substantial amount of dense recycled oceanic crust, between 10% and 20%. The calculated volume of recycled oceanic crust can significantly reduce plume buoyancy, because the bulk rock density of recycled oceanic crust is significantly greater than the ambient peridotite mantle under the high-pressure environment (Kennett et al., 1995; Ono et al., 2001).

The amount of recycled oceanic crust in the Emeishan plume is similar to that proposed for the Siberian LIP (10%–20%) where, similar to the Emeishan province, no significant premagmatic uplift on the Siberian craton can be inferred from the sedimentary cover and from the prediction of numerical thermochemical plume
modeling (Sobolev et al., 2011). Although the locus of a rising mantle anomaly and hence uplift in Siberia were proposed to be centered in the West Siberian Basin (Saunders et al., 2005). Dannberg and Sobolev (2015) further developed this numerical model for different types of thermochemical plumes and considered that the initial excess temperature and volume of plume have also a profound impact on plume-induced topographic uplift, apart from fraction of eclogite in the plume.

Ali et al. (2010) derived a mantle potential temperature of around 1560°C for the mantle source of the Emeishan basalt based on analyses of a large number of olivine from picrite lavas. Based on this we assume that the Emeishan plume has an average excess temperature of ~ 210 K in the upper mantle, slightly lower than that predicted for the Siberian Traps mantle for which a mantle potential temperature of 1600°C and corresponding excess temperature of ~ 250 K are predicted (Sobolev et al., 2011). Giving these parameters a best fit of the Emeishan plume is obtained by the model of a small plume with an initial excess temperature of ~ 550 K (Figure 12) that transports a high eclogite content. This plume rises in a subadiabatic lower mantle and ponds in a depth of 300–400 km of the upper mantle that can generate a secondary plume. Due to mixing in the asthenosphere, the secondary plume has a lower average excess temperature (~ 210 K) and fraction of eclogite (~ 12%) than a primary plume (~ 280 K, ~ 14%, respectively) with the same initial excess temperature in the lower mantle when it reaches the base of the lithosphere, but the plume head volumes of both are approximately the same size at the base of the lithosphere. As a result, it generates a surface uplift of ~200 m mainly within ~ 1 Ma prior to the onset of volcanic eruptions, which is consistent with our inferred results based on our field analyses of the geologic records. However, with the same excess temperature this uplift is significantly lower than expected from a purely thermal plume. Taken together, our study provides important geological and geochemical evidence supporting the current numerical thermochemical plume model for the Emeishan province (Dannberg & Sobolev, 2015; Sobolev et al., 2011).

5.3. Significant Surface Subsidence During the Eruptions of Early Lavas

Pillow basalts, marine hydromagmatic deposits, and intercalated limestones were described at different stratigraphic positions in the early thick lavas from central to outer areas of the Emeishan LIP, and the height of
marine records in lavas increases together with the thickness of local lavas. In the Dali and Jianshui areas, the maximum height of marine records is as high as ~ 3,300 m and ~ 1,850 m, respectively. However, the inconspicuous topographic changes before volcanic eruptions cannot provide a possible environment for forming such high marine records in the Emeishan volcanic successions, even without considering the weak uplift approaching numerous volcanisms. Therefore, the marine records that can be found at such a high stratigraphic horizon are most likely due to the continuous and significant surface subsidence in the syneruptions of the early stage. If so, the height of marine records roughly reflects amplitude of surface subsidence in early lavas, which increases together with the thickness of local lavas, as shown in Figures 7 and 8.

This initial surface subsidence may be related to a significant loss of thermal buoyancy, because the hot plume head may release significant heat when the Emeishan LIP starts erupting. However, the negative chemical buoyancy could remain in the Emeishan plume with numerous eclogites, especially if chemically heavy plume material gets attached to the lithosphere. Furthermore, the loading from erupted lavas can also trigger the surface subsidence in the syneruptive stage from the subsidence model of Leng and Zhong (2010). Their model, in which 2 km thick basalt loads with a radius of 300 km and 50 km effective elastic thickness of the lithosphere were assumed, suggests that the basalt loads can trigger a significant surface subsidence through strong lithospheric flexure in the center, close to the thickness of basalts, and an inconspicuous surface subsidence.

Figure 12. Plume initial excess temperature in the lower mantle versus excess temperature in the upper mantle (a), plume composition (b), and premagmatic surface uplift (c) for different plume initial volumes and mantle temperature profiles (modified after Dannberg & Sobolev, 2015). Siberian and Emeishan data are from Dannberg and Sobolev (2015) and this study, respectively. Black solid lines in Figures 12a and 12c represent an excess temperature (~ 210 K) of the Emeishan plume in the upper mantle and an estimated uplift of 200 m based on our field analyses of the geologic records, respectively. Gray-shaded area in Figure 12b indicates eclogite range in the Emeishan plume. Small plumes have initial volumes of $1.22 \times 10^8$ km$^3$ and large plumes $3.71 \times 10^8$ km$^3$ that are used in the numerical modeling of Dannberg and Sobolev (2015).
subsidence at the periphery (Leng & Zhong, 2010 their Figure 5b). However, the late lavas contain numerous intercalated low-density volcanic and sedimentary rocks that could prevent continued surface subsidence due to greatly reducing lithospheric load. The accumulation of low-density volcanic rocks generated a terrestrial environment in later volcanic eruptions of the Emeishan LIP.

6. Conclusions

We conclude that (i) the ascent of a high-temperature plume head in the lower mantle, arriving at the 660 km phase boundary, could not have triggered a significant topographic change from prediction model of Dannberg and Sobolev (2015), which has been confirmed by our field-based analyses of the geologic record in the Emeishan LIP; (ii) the Emeishan plume containing a substantial amount of dense recycled oceanic crust (up to 10%–20%) had the ability to significantly reduce its own buoyancy, which led to only a weak surface uplift at the onset of numerous volcanic eruptions that is consistent with numerical thermochemical plume modeling and with our own field observations of the geologic records; (iii) the negative chemical buoyancy in the Emeishan plume with numerous eclogite can trigger an initial surface subsidence when the thermal buoyancy of plume may be significantly reduced by the release of heat during the early stage of numerous eruptions; (iv) a strong flexure of the lithosphere, accompanied by rapid loading of dense erupted lava during the early stage, also lead to a later synchronous and significant surface subsidence of the area of the Emeishan LIP; and (v) late volcanism generated numerous low-density volcanic rocks, which played the key role in ceasing the surface subsidence of the early stage and produced a terrestrial environment through continued accumulation of volcanic rocks. Our detailed work based on the Emeishan LIP offers important geological insights and geological framework to test prevailing mantle plume models in other LIPs, which may ultimately shed new light on the importance of lithospheric rheology and important role of lithosphere in the complex mantle-lithosphere interactions.

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References


