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Earth and Planetary Science Letters 213 (2003) 391–405
www.elsevier.com/locate/epsl

Sedimentary evidence for a rapid, kilometer-scale crustal doming prior to the eruption of the Emeishan flood basalts

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Received 29 January 2003; received in revised form 2 June 2003; accepted 5 June 2003

Abstract

Biostratigraphic and sedimentologic investigations in 67 sections have been carried out for the Middle Permian Maokou Formation that immediately underlies the Emeishan flood basalts in southwest China. The results suggest a domal crustal thinning before the emplacement of the Emeishan large igneous province. Variably thinned carbonates in the Maokou Formation are capped by a subaerial unconformity, which is generally manifested by karst paleotopography, paleoweathering zone, or locally by relict gravels and basal conglomerates. Provenance analysis indicates that these gravels and conglomerates were mainly derived from the uppermost Maokou Formation. Therefore, the stratigraphic thinning likely resulted from differential erosion due to regional uplift. Iso-thickness contours of the Maokou Formation delineate a subcircular uplifted area, in accordance with the crustal doming caused by a starting mantle plume as predicted by experimental and numerical modeling. The duration of this uplift is estimated to be less than 3 Myr and the magnitude of uplift is greater than 1000 m. The sedimentary records therefore provide independent supporting evidence for the mantle plume initiation model for the generation of the Emeishan flood basalts.

Keywords: Emeishan flood basalts; sedimentary record; domal uplift; mantle plume

1. Introduction

The Emeishan flood basalt, an important large igneous province (LIP) in southwest China, occurred around the Permian–Triassic boundary [1–3]. Its possible synchronism with the Siberian Traps, another major flood basalt, and its relationship to massive extinctions around the Permian–Triassic boundary have attracted a number of recent studies [1–10]. Nevertheless, controversy remains as to the nature of the dynamic processes responsible for the generation of this massive igneous province (e.g., [11]). The currently available dynamic interpretation for the generation of the Emeishan basalts mainly includes: (a) a rift-based model and (b) a mantle plume initiation model. The rift model does not require a mantle plume to explain the genesis of the Emeishan basalts. The western Yangtze Craton was a passive

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doi:10.1016/S0012-821X(03)00323-6

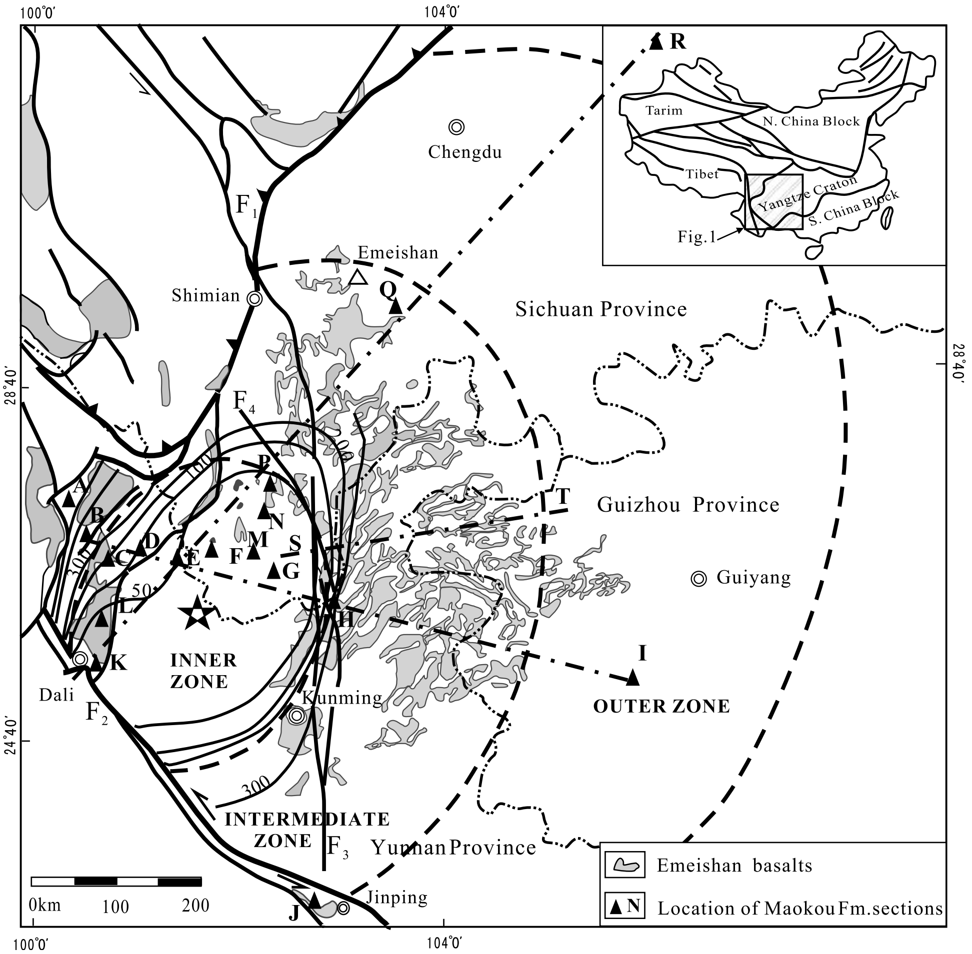

Fig. 1. Schematic geological map of the Emeishan large igneous province. Dash-dotted line: profiles across the Maokou Formation (A–I and K–R) and across the alluvial fan (S–T). Dashed line: estimated boundaries of the eroded zone, defining the inner zone, intermediate and the outer zone. Solid line: iso-thickness contours of the Maokou Formation. Numbers indicate the thickness in meters. Solid lines labeled with F indicate faults. F_1-Longmenshan thrust fault; F_2-Ailaoshan–Red River slip fault; F_3-Xiaojiang fault; F_4-Xichang–Qiaojia fault.

continental margin during the late Permian period. It is suggested that the Emeishan basalts were erupted as a result of lithospheric extension induced by the subduction of the Paleo-Tethyan oceanic plate underneath the Changdu micro-continents [12–15]. The 'Panxi rift' was the center of the Emeishan LIP. Since the middle 1990s, the mantle plume model has been increasingly adopted to understand the genesis of the Emeishan basalts. The supporting evidence includes the short duration of volcanism [3,17], the identification of high magnesian primary melts (MgO > 16%) and high potential mantle temperature (~1500°C) [1,2,17]. Trace element and Sr–Nd isotopic studies show a geochemical affinity to oceanic island basalts, thereby being consistent with their plume origin [2]. These previous studies mainly concentrated on the geochemical and petrologic ground and some inferences are thus model-dependent. The postulated plume model should be confirmed using other independent approaches.

The mantle plume theory predicts a considerable lithospheric uplift and doming in response to anomalous thermal upwelling [18–23]. This uplift would leave recognizable effects on the sedimentation, such as localized shoaling, thinning of strata over the uplifted area and erosional unconformity between the basalts and underlying stratigraphic sequence [24]. These sedimentary patterns have been observed in many plume-related LIPs, thereby providing a reliable and independent means of identifying the role of mantle plumes in the generation of LIPs [25–27].

In order to better characterize the crustal processes prior to the eruption of the Emeishan basalts, the nature of the strata (i.e., the Maokou Formation) underneath the flood basalts and the contact between them are examined in this study. This paper presents evidence for domal differential thinning of the Maokou Formation in the west and central part of the Emeishan LIP. Other sedimentary features are also documented, which are very similar to those predicted by the mantle plume hypothesis. The sedimentary data therefore provide new and independent supporting evidence for the starting plume initiation model for the generation of Emeishan flood basalts. Finally, the location of the Emeishan plume head is defined on the basis of coincidence of the plume impact site and the core of the uplifted area.

2. Geological background

The Emeishan LIP is located in the western margin of the Yangtze Craton, SW China (Fig. 1). The Longmenshan thrust fault and the Ailaoshan–Red River slip fault are generally considered its northwestern and southwestern boundaries, respectively. The Emeishan basalts are exposed in a rhombic province of 250 000 km^2. Three sub-provinces have been divided in previous studies, namely the west, central and east parts of the Emeishan LIP (Fig. 1). The central part overlaps the 'Panxi paleorift zone' [28]. The thickness of the entire volcanic sequence in these sub-provinces varies considerably from over 5000 m in the west to a few hundred meters in the east. The province consists of dominant basaltic lavas and subordinate pyroclastic rocks. In the west sub-province, flows and tuff of trachytic and rhyolitic composition form an important member in the uppermost sequence [2,4,29]. The Emeishan volcanic successions unconformably overlie the late Middle Permian carbonate formation (i.e., the Maokou limestone) and are in turn covered by the uppermost Permian in the east and west, and the upper Triassic or Jurassic sediments in the central part (Fig. 2).

Paleomagnetic data have shown that the South China Block was situated at an equatorial position during the Permian period [30–32]. Since the early Permian, thick carbonate sequences began to deposit as a response to extensive transgression and basin subsidence [33–35]. The Permian strata in south China may be divided, in ascending order, into Liangshan (Lower Permian), Qixia and Maokou (Middle Permian), and Wujiaping and Changxing (Upper Permian) formations [36,37] (Fig. 2). The Liangshan Formation is mainly composed of various sandstones with only local appearance of thin coal sheets. In contrast, the Middle and Upper Permian strata in large parts of south China are almost entirely composed of limestone, indicating a sedimentary environment of carbonate platform [39,40]. However, the late Permian sedimentary rocks that capped the Emeishan basalts, especially in eastern Yunnan and western Guizhou, are somewhat lithologically different from the Wujiaping Formation. These late Permian clastic sequences are called the Xuanwei Formation (terrestrial clastic rocks) and the Longtan Formation (marine clastic rocks) (Fig. 2). The Middle and Upper Permian in the Upper Yangtze Craton was separated by an unconformity, which formed as a response of the 'Dongwu' movement. The latter was defined by Chinese geologists as a continent-forming event or crustal uplift at the transition between the Middle and Late Permian. This may suggest a fundamental difference in paleogeographic setting between the Middle and Late Permian. The Qixia and early Maokou stages of Middle Permian may represent a rising sea level stage or maximum marine incursion since the Late Paleozoic [38,39]. The regression commenced from the late Maokou stage and seawater withdrew entirely in south China at the end of the Maokou stage (Fig. 2). This regression was very rapid because the carbonate platform facies of the Maokou Formation

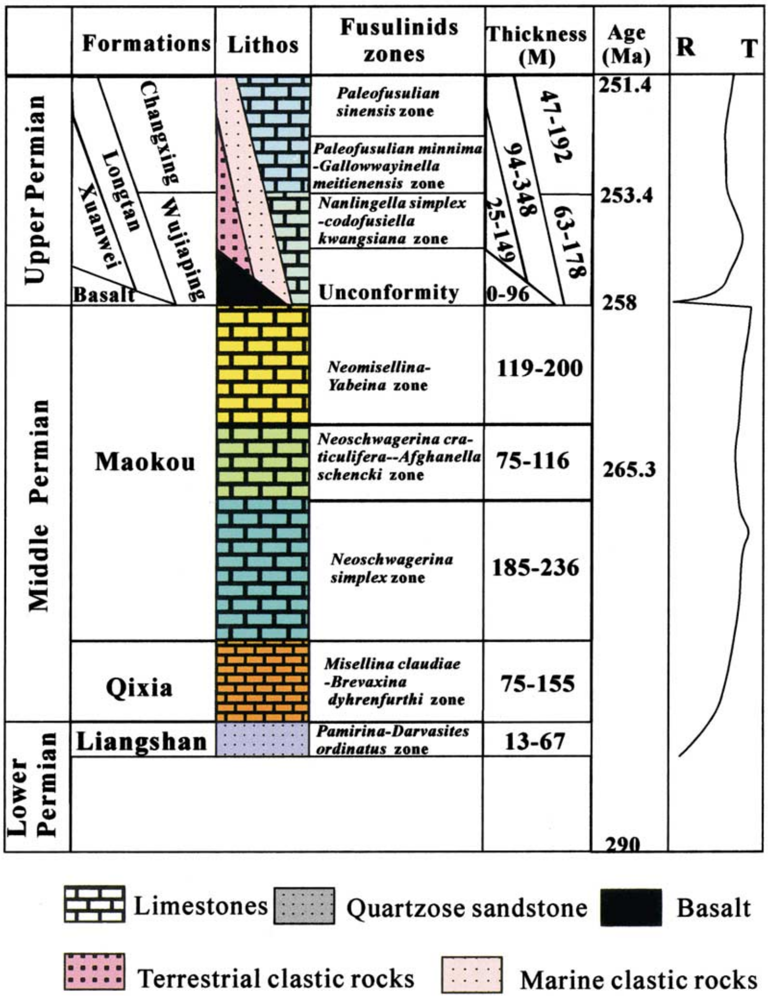

Fig. 2. Generalized Permian stratigraphy and division of fusulinid zones in the western Guizhou Province (the outer zone of the Emeishan LIP). Data compiled from [33,34]. Age scheme is after [36,37]. R-regression; T-transgression.

was changed suddenly to terrestrial clastic rocks in the Xuanwei Formation. The transgression began during or after the main eruption phase of the Emeishan basalts in the early Upper Permian. The course of this transgression was recorded in the west–east profile across the Emeishan LIP, in which the Xuanwei and Longtan formations progressively onlap the Emeishan basalts. However, in the central part of the Emeishan LIP, which was called Chuandian old land by Chinese geologists [36–39], the Emeishan basalts are unconformably covered by Upper Triassic or Jurassic sediments.

3. Stratigraphic thinning of the Maokou Formation in the Emeishan LIP

3.1. *Biostratigraphic units of the Maokou Formation*

The Maokou Formation underlying the Emeishan LIP mainly consists of medium-bedded to massive limestones. Its thickness ranges from 250 to 600 m with an average of about 350 m. Fossils in the Maokou Formation are abundant, including foraminifera, algae, brachiopods, ostracods, echinoderms, gastropods, bivalves and cor-

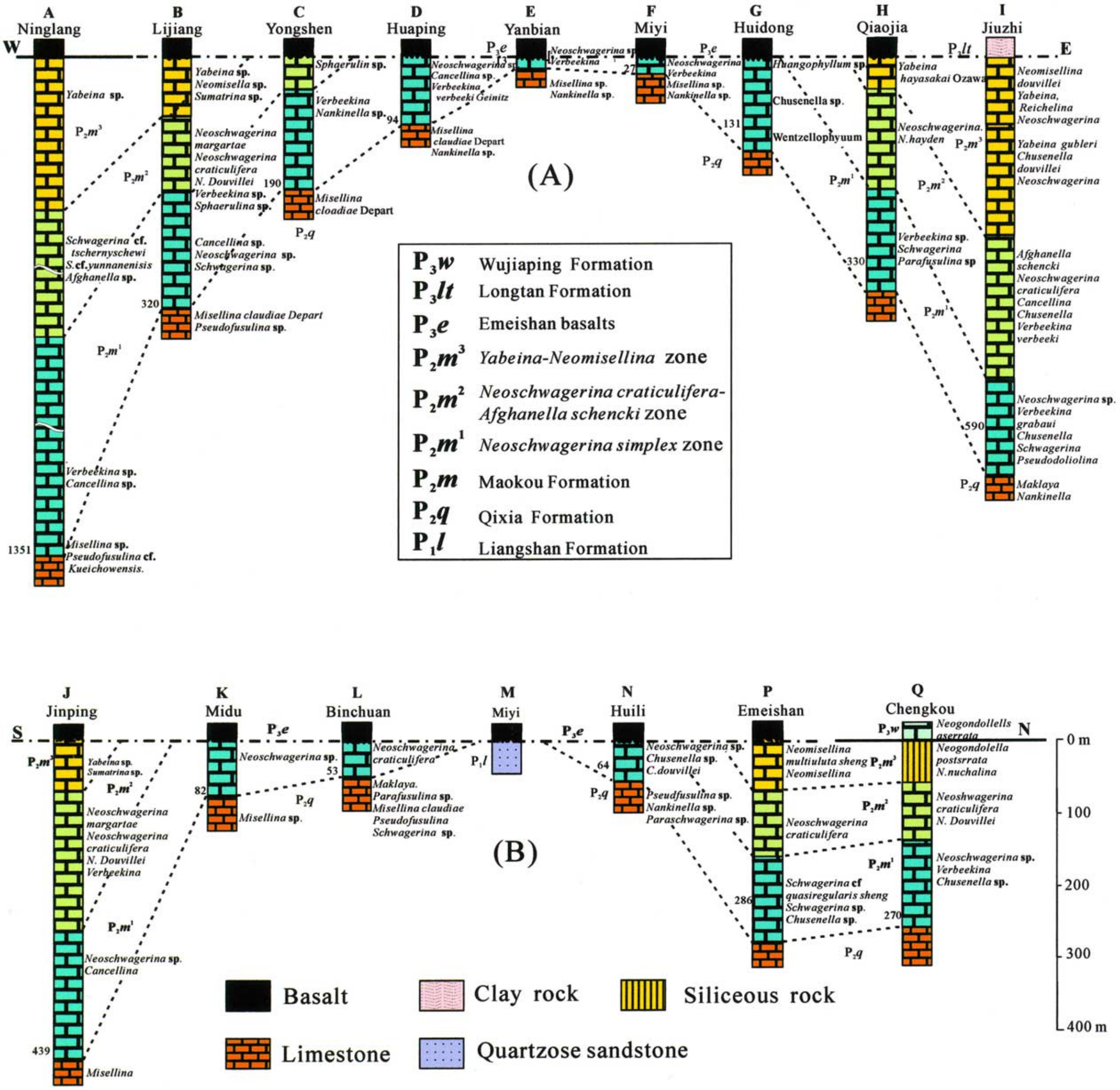

Fig. 3. Biostratigraphic correlation of the Maokou Formation in the Emeishan LIP. (a) Profile A–I, west–east oriented traverse across the Emeishan LIP. (b) Profile K–R, south–north oriented traverse across the province. The number near every section is the thickness of the Maokou Formation. The vertical scale is the same for each section except section A.

als. Also called the Maokou limestone by Chinese geologists, the Maokou Formation is widespread in south China and is a main constituent of the Permian carbonate platform [38,39]. The carbonate platform covers an area much larger than the Emeishan LIP. Based on petrologic characteristics of the limestone and associated fossil assemblages, seawater in south China in the Permian period is inferred to have been shallow and clean, and by implication the crust was stable at that time.

Fusulinid foraminifera are extremely abundant and evolved rapidly in the carbonate platform. This permits further division of the Maokou Formation. Three biostratigraphic units, from bottom to top, are *Neoschwagerina simplex* zone, *Neoschwagerina craticulifera-Afghanella schencki* zone and *Yabeina-Neomisellina* zone (Fig. 2). These biostratigraphic units are well correlated throughout south China [33–35].

3.2. Stratigraphic thinning of the Maokou Formation

A total of 67 sections of the Maokou Formation in the Emeishan LIP and its vicinity have been examined. Two representative profiles (Fig. 1) are described here in detail to illustrate the spatial variation in thickness and biostratigraphic units of the Maokou Formation in the Emeishan LIP. Profile A–I across the Emeishan LIP in west–east orientation includes nine sections (from west to east) at Ninglang, Lijiang, Yongshen, Huaping, Yanbian, Miyi, Huidong, Qiaojia and Jiuzhi (Figs. 1 and 3a). The thickness of the Maokou Formation in these nine sections is 1351 m, 320 m, 190 m, 94 m, 13 m, 27 m, 131 m, 330 m and 590 m, respectively. Profile K–R, which is in the N–S direction, includes seven sections at Jinping, Midu, Binchuan, Miyi, Huili, Emeishan and Chengkou (Figs. 1 and 3b). The thickness of the Maokou Formation in these seven sections is 439 m, 82 m, 53 m, 0 m, 64 m, 220 m and 230 m, respectively. It is clear from Fig. 3 that the Maokou Formation becomes progressively thinner towards the central parts of both profiles, while the thickness at each end of the profiles is typical of those of the Maokou Formation that are situated beyond the Emeishan LIP. The thinnest Maokou limestone is found in the central part of the Emeishan LIP. Such a stratigraphic thinning is correlated with progressive absence of certain biostratigraphic units towards the middle parts of each profile (Fig. 3). While all three biostratigraphic units of the Maokou Formation are present in the sections at the two ends of each profile (especially in Guizhou province), only the lowermost unit (i.e., *Neoschwagerina simplex* zone) is found in the sections in the central parts of the profiles (Fig. 3). The middle and upper units are totally absent in these sections (Fig. 3). This implies that the stratigraphic thinning is due to differential erosion or sedimentary absence. Although all three units are present in the section in eastern Yunnan province and southern Sichuan province, the uppermost unit is significantly thinner than in Guizhou Province. This may suggest a partial erosion of the Maokou Formation in these areas.

Integration of the data obtained from 67 sections of the Maokou Formation in south China provides insights into the spatial variation of the Maokouian biostratigraphic units. This is illustrated in terms of iso-thickness contours of the Maokou limestone (Fig. 1), which delineate a subcircular shape. Such a depositional pattern most likely resulted from domal differential erosion of the Maokou Formation. For convenience of description, the postulated doming area is divided into inner, intermediate and outer zones in terms of the extent of erosion. The inner zone, where the Maokou Formation is strongly eroded, encloses west Yunnan and south Sichuan, and is about 400 km in diameter (Fig. 1). In this zone, the two upper biostratigraphic units of the Maokou Formation (i.e., *Neoschwagerina craticulifera-Afghanella schencki* and *Yabeina-Neomisellina* zones) are supposed to have been eroded. The thickness of the remaining Maokou Formation is usually less than 100 m, mostly about 50 m (Fig. 1). In some localities, the Emeishan basalts cover directly the older sedimentary sequence, i.e., the Liangshan Formation, implying that both the Maokou Formation and the Qixia Formation may have been completely eroded.

The thickness of the Maokou Formation increases to 200–450 m in the intermediate zone, which includes large parts of east Yunnan and north Sichuan. In this 300 km wide zone (Fig. 1), the *Yabeina-Neomisellina*-bearing stratigraphic unit was partly eroded, with its remaining thickness varying between 10 and 80 m. In some instances, e.g., at Kunming and Dongchuan, the latter situated 200 km north of Kunming, the *Yabeina-Neomisellina* zone is totally eroded. A paleoweathering layer between the Early and the Late Permian is rare in the intermediate zone, probably because chemical dissolution and flowing water erosion act as dominant mechanisms of surface processes under tropical conditions.

The Maokou Formation in the outer zone

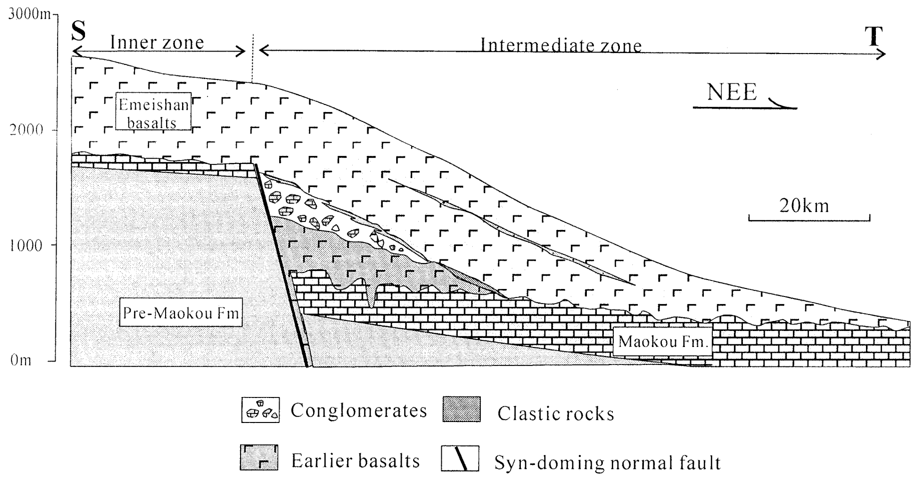

Fig. 4. West to east (S–T in Fig. 1) profile showing an alluvial fan beneath the Emeishan basalts in the northeastern flank of the domal structure.

(largely in Guizhou province) is 250–600 m in thickness. The erosion of the Maokou Formation was generally minor in this zone. However, an unconformity and a paleoweathering zone between the Maokou limestone and the Emeishan basalts are observed in many localities, implying a short sedimentary break between them. The paleoweathering zone mainly consists of pyrite-bearing clay rock, manganese and thin layers of coal, and siliceous rocks. Sedimentation in the areas beyond the Emeishan LIP was continuous throughout the Permian period [37]. In fact, the section at Jiuzhi (Section I, Fig. 3) is widely considered the standard stratigraphic sequence of the Maokou Formation [37].

4. An unconformity between the Maokou Formation and the Emeishan basalts

4.1. Relict gravels, basal conglomerates and alluvial fans

A number of observations suggest that the contact between the Maokou Formation and the Emeishan basalts was an erosion surface or an unconformity. The most convincing evidence is from relict gravels, boulders and basal conglomerates along the contact in some places in the inner and intermediate zones. Basal conglomerates are usually cemented by basaltic lavas, tuff and pyroclastics. The gravels are subrounded and subangular with a size of 5–30 cm. Abundant fusulinid fossils including *Yabeina* in these gravels strongly suggest that they are erosional products of the uppermost biostratigraphic units of the Maokou Formation. Basal conglomerates are cemented by tuff at Huidong, Sichuan Province. The clasts or gravels are also Maokou limestone that bears fusulinid *Neomisellina* and *Chusenella*. Again, this suggests that the thinning of the Maokou limestone in the Emeishan LIP was caused by differential erosion rather than by sedimentary breaks.

A layer of conglomerate of variable thickness is found underneath the main phase of the Emeishan basalts and above the earlier phase of basalts in the northeastern flank of the dome structure (i.e., in the intermediate zone; Figs. 1 and 4). It is distributed in an area 400 km in length and 30–70 km in width along the eastern boundary of the Xiaojiang fault (F_3 in Fig. 1) and the Xichang–Qiaojia fault (F_4 in Fig. 1). The basalt underneath this conglomerate layer is 160–485 m thick and may be related to the formation of syn-doming faults due to earlier uplift. In most cases, the conglomerates are cemented by basaltic lavas and subordinately by calcium, clay and tuff. The conglomerate layer is thickest (172 m) near the faults, becomes gradually thinner and finally disappears away from the faults (Fig. 4). The content and size of gravels in the conglomerate layer also change regularly from west to east in profile S–T (Figs. 1 and 4). Specifically, the conglomerates near the Xiaojiang and Xichang–Qiaojia faults are entirely composed of eroded materials from the uppermost Maokou limestone, whereas basalts occur as gravels in addition to the Maokou limestone in the areas distal from the faults. The size of gravels decreases gradually from 10–50 cm (up to 1 m) to 3–5 cm from west to east in profile S–T. This implies that the gravels are mainly derived from the inner zone. Clastic rocks above and in the conglomerate layer show some sedimentary structures such as cross-bedding, graded bedding, wavy bedding and planar laminations. All these observations lead us to propose that the conglomerate layer represents an alluvial fan, which was formed due to differential uplift of the blocks in the northeastern flank of the domal structure.

4.2. Karst relief on the top of the Maokou Formation

Since the Yangtze Craton was situated in the equatorial position in the Permian, surface erosion due to uplift under tropical climate conditions may result in a karst morphology as presently seen in southwest China. A number of observations suggest that karst paleotopography did develop on the unconformity between the Emeishan basalts and Maokou Formation underlying the Emeishan LIP area. (a) The contact between the Maokou Formation and the Emeishan basalts is uneven. The relief of the contact is usually several meters to 50 m high [40]. In some instances, the relief of the contact can be as high as 30 m in outcrop scale. An extreme example is found at Lunan county, Yunnan province, where the relief of the contact is up to 230 m high and 5000 m in length [40]. (b) More than 60 eroded carbonate caves or holes are found at Lunan county. These caves, in average size about 20×50 m, are filled with the Emeishan basalts, and were probably developed in a karst environment. (c) Stone forest-style karst is observed at Dali, Yunnan province. They are 1000–3000 m in length, several hundred meters in width and up to 100 m in height. (d) Limestone lenses or blocks are commonly found in the lower volcanic succession in southern Emeishan LIP. These lenses are randomly distributed in lavas and most of them have been metamorphosed to various degrees. They may originally have been gravels, boulders or blocks on erosion surfaces that were then trapped by lavas during eruption and flowing.

4.3. Paleoweathering crust and paleosols on the top of the Maokou Formation

The contact between the Maokou Formation and the Emeishan basalts (or the Xuanwei Formation) in the outer zone is mainly constituted of paleoweathering crust and paleosols. The paleoweathering zone contains pyrite-bearing clay rocks, manganese and thin layers of coal and siliceous rock. In some instances, kaolin and alumina ore deposits were formed on the uneven erosional surface. The weathering zone is hard to observe in the inner and intermediate zones probably because of chemical dissolution and erosion in carbonate areas with high elevation or altitude. Sedimentation in the areas beyond the three erosional zones was continuous throughout the Permian period.

4.4. Summary

The above observations suggest that the thinned Maokou Formation is capped by an unconformity, which may have resulted from subaerial chemical and physical weathering and erosion. The exposure of the Maokou marine carbonates under subaerial conditions was probably due to uplift. The unconformity is regional and restricted to the Upper Yangtze Craton, and is not observed in the lower Yangtze and South China Block. The unconformity is mainly expressed by relict gravels, basal conglomerates, alluvial fans and karst relief in the inner and intermediate zones, and by paleoweathering crust and paleosols in the outer zone.

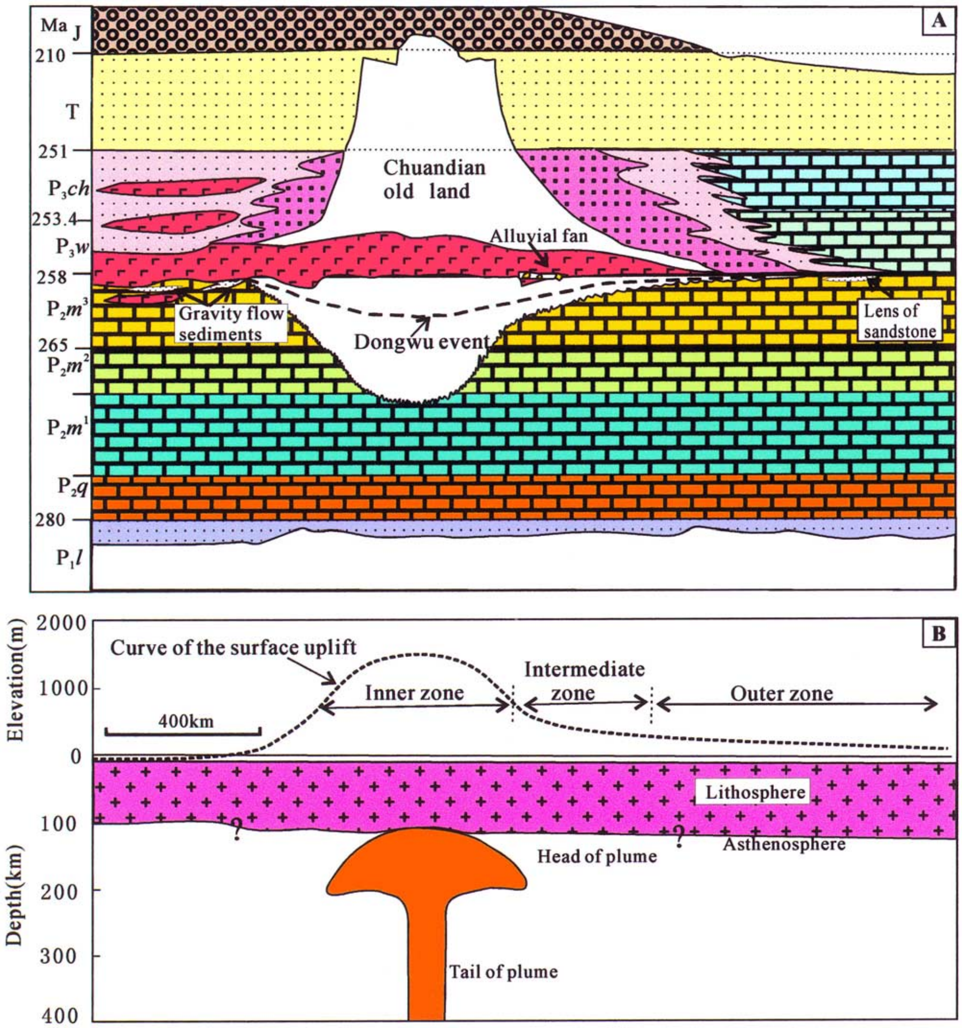

Fig. 5. (a) Diagram showing the chronostratigraphic correlation of the Permian across the Emeishan LIP. The legends are the same as in Fig. 3. It is suggested that a domal uplift, a local unconformity, karst and gravity flow sediments at the end of the Maokouian stage and the domal uplift continued until the end of the Triassic. (b) A sketch showing the surface uplift due to the Emeishan mantle plume prior to the eruption of the Emeishan basalts.

5. Discussion

5.1. Pre-eruptive crustal doming uplift

The spatial correlation of the biostratigraphic units of the Maokou Formation immediately beneath the Emeishan basalts suggests a domal stratigraphic thinning. The iso-thickness contours of the Maokou Formation further outline a subcircular region (Fig. 1), strongly indicating a domal crustal uplift prior to the eruption of the Emeishan basalts. Similar sedimentary patterns have been documented in the North Sea Basin [41] and in the Shaler Supergroup, northern Canada [25]. Such stratigraphic features all have been interpreted as results of differential crustal uplift, which is postulated to be the consequence of thermal or dynamic doming by a starting mantle plume [24].

The crustal uplift inferred from the stratigraphic records was likely responsible for the regression of seawater starting in the western Yangtze Craton since the end of the Maokou stage (Figs. 2 and 5). With progressive uplift, sea level decreased, eventually leading to the emergence of marine carbonates above sea level in the uplifted areas. This variation in sedimentation is corroborated by the change from carbonate platform facies in the Maokou Formation to terrestrial clastic facies in the Xuanwei Formation (Fig. 5). Subaerial exposure of marine carbonates in the uplifted areas, especially in the inner and intermediate zones, would allow for chemical weathering and erosion, particularly in a tropical climate during the late Permian. In the Emeishan case, this is manifested by an unconformity that capped the Maokou Formation. In many instances, this unconformity developed karst paleotopography, basal conglomerates and locally paleosols. Evidence for pre-eruptive doming may also be preserved in conglomerates and sandstones that underlie the Emeishan flood basalts. It is interesting to note that the clastic rocks are mainly distributed in the flanks of the domal structure (Fig. 1). More importantly, alluvial fans covering an area 400 km in length and 30–70 km in width are identified in the northeastern flank of the dome structure (Fig. 4). The location of these large alluvial fans to the east of the Xiaojiang fault and the Xichang–Qiaojia fault suggests that their formation was probably controlled by these syn-doming faults. The differential movement along the faults may have resulted in considerable relief contrast between the inner and intermediate zones, a condition favorable for erosion in the inner zone and deposition of eroded materials in the intermediate zone. This mechanism explains the predominant Maokou limestone gravels in the alluvial fans close to the syn-doming faults and the anomalously large dimension of the fans. Thus we conclude that the gravels, conglomerates and alluvial gravel fans at the domal flanks probably resulted from the plume-related differential uplift (Fig. 5).

5.1.1. Timing and duration of pre-eruptive uplift

Determination of the timing and duration of mantle plume-related crustal uplift is critical for testing models that describe plume dynamics, plume–lithosphere interactions and generation of flood basalts. Conglomerates on the erosional surface, in alluvial fans and limestone blocks (lenses) in the lower lava successions contain fossils that are identical to those found in the uppermost Maokou Formation. Therefore, the domal uplift likely started after, or was coeval with, the deposition of the *Yabeina-Neomisellina*-bearing biostratigraphic unit (i.e., the uppermost of the Maokou Formation). The change from regression to transgression at the boundary between the Middle and Upper Permian (Fig. 2) may have resulted from plume-induced crustal uplift induced by plume impact and subsequent thermal subsidence probably due to cooling of the plume. This interpretation implies a very rapid crustal uplift (within a few Myr). The uplift probably ended in the beginning of the Late Permian ($\sim$258 Ma) because new transgression and depositional onlap started at that time (Fig. 5). The duration of pre-eruptive uplift can be roughly estimated by using the eroded thickness of the Maokou Formation and erosion rates under appropriate climate conditions. The average thickness of the Maokou Formation prior to and after erosion is $\sim$350 m and $\sim$50 m in the core of uplift, respectively [33]. Thus the average thickness of the eroded Maokou limestone is about 300 m. By taking the average erosional rate in a subtropical climate (i.e., 12–30 mm/100 years [40]), we estimate the duration of uplift to be about 1–2.5 Myr. An even shorter duration is expected if the following factors are taken into account. (a) A higher erosional rate is expected because the Emeishan LIP was situated at the equator during the Permian. (b) The sediments of the upper Maokou Formation may not have been completely solidified.

5.1.2. Dimension and extent of uplift

According to the spatial distribution of the Maokou Formation and of the unconformity between the Emeishan basalts and the Maokou limestone, the uplifted area is inferred to cover near entirely the upper part of the Yangtze Craton. It corresponds to an area 800 km in radius (Fig. 1). The extent of the uplift is dependent upon the location of the stratigraphic section relative to the apex of the uplift (Fig. 5b). The minimum estimates on the extent of uplift can be deduced from the eroded thickness of the strata at a given site. This reasoning suggests that the minimum extent of uplift in the inner, intermediate and outer zones is about 300 m, 100 m and 0 m, respectively. The magnitude of uplift in the inner zone could be ∼500 m because in some places, the Emeishan basalts directly cover the Liangshan Formation, which suggests the total erosion of the Maokou and Qixia formations (∼500 m thick). With similar reasoning, an estimate of 300 m is obtained for the intermediate zone. Further constraints on the extent of uplift can be inferred from the geometry of the alluvial fan in the northeastern flank of the domal structure. As shown in Fig. 4, the maximum thickness of the conglomerate layer and underlying basalts in the alluvial fan is ∼600 m. The uplift in the inner zone must be greater than 900 m (the height of the alluvial fan plus the magnitude of uplift in the intermediate zone) to have a relief contrast for the development of the alluvial fan in the intermediate zone. Taking into account the maximum thickness (∼500 m) of the eroded strata in the inner zone, we suggest that total uplift in the Emeishan LIP was greater than 1000 m, although an accurate estimate is not possible at this stage.

5.2. *Implication for a plume origin of the Emeishan flood basalts*

Fluid dynamical and numerical modeling [19–21] argues that flood basalts and LIPs originate from plumes, and these plumes rise from the D″ region just above the core–mantle boundary due to thermal and gravitational instabilities. When a mantle plume impinges on the lithosphere, the surface of the Earth should be elevated, producing roughly circular uplifts; the doming area may reach a diameter of 1000–2000 km, with 500–2000 m of relief depending on the viscosity of the plume head [20]. Therefore, an important question related to plume models of LIPs is whether uplift and extensional deformation precede magmatism as predicted by experimental and numerical models [20,21]. The lack of such evidence in some LIPs has been cited as an argument against the plume model [42,43].

The data presented in this study provide unambiguous sedimentary evidence for domal uplift that preceded volcanism in the Emeishan LIP. The uplifted region has a subcircular shape (Fig. 1), rather than a linear elongation (along the Panxi rift zone) as would have been expected for the rift-based model. The diameter and extent of the uplifted dome are estimated to be ∼1600 km and >1000 m, respectively, and the uplift took place within a period of less than 3 Myr. So far, 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. Griffiths and Campbell [20] predicted uplift of 500–1000 m when a temperature excess of 100°C was used, whereas Farnetani and Richards [21] predicted that flood volcanism is associated with 2–4 km of uplift assuming a temperature excess of 350°C. As the amount of uplift is directly related to plume temperature, the observation in the Emeishan LIP implies that the potential temperature of the plume is 150–200°C greater than that of the upper mantle (i.e., 1450–1500°C). A similar thermal anomaly has been inferred from the rare earth element inversion model [2]. More importantly, the chronological relationship between uplift and volcanism and the dimensions of the uplifted dome are virtually identical to those predicted by experimental and numerical modeling involving a starting mantle plume [19–21]. This thus provides the best evidence in favor of the plume model for the formation of the Emeishan LIP. The plume-induced uplift correlates with the sudden change from carbonate platform facies to terrestrial clastic facies in the western Yangtze Craton at the transition between Middle and Upper Permian (Fig. 2). While the thermal uplift associated with a starting mantle plume can nicely account for the rapid, pre-volcanism domal uplift, it cannot explain the persistent crustal elevation in the 'Chuandian old land' over at least 45 Myr (Fig. 5), because the thermal uplift associated with a new plume is largely transient [20]. Signs of erosion and weathering have been observed on the top of the basalts in this area. Magmatic underplating was the likely mechanism for keeping this area elevated for a prolonged period [18]. Supporting evidence for magmatic underplating in the Emeishan LIP comes from recent seismic tomographic data, which reveal a thick (ca. 20 km) high-velocity lower crust ($V_p = 7.1–7.8$ km/s) in the west Yangtze Craton [44]. To reconcile the composition of primary picritic plume melts with the dominant basaltic composition of the erupted lavas, crystal fractionation must occur when the primary picritic magmas pond at the crust–mantle boundary [45]. Cumulates such as olivine and pyroxene would form the high-velocity layer at the base of the crust [46].

The relatively small size of basaltic lavas exposures ($> 250\,000$ km^2 in comparison with $1\,000\,000$ km^2 for normal LIPs) and relatively thin volcanic sequences in some localities have cast some doubt on the viability of the plume model in the Emeishan case [11]. However, it should be pointed out that some statements expressed in [11] are based on non-representative observations and thus need reconsideration. For instance, the lava successions described by Thompson et al. [11] are only from a restricted area. The lava sequence thickness does reach in excess of 5000 m in the western part of the Emeishan LIP [2]. It should be pointed out that the Emeishan basalts are remnants of an igneous province that was subjected to intensive destruction and erosion [5,47,48]. It is clear from Fig. 1 that a smaller but significant part of the Emeishan LIP and dome has been displaced to the southeast, together with Indochina extrusion along the Red River fault. Total strike-slip has been estimated to be in the order of 500–1000 km [49,50], so the currently accepted surface exposure value of $\sim 250\,000$ km^2 is only a minimum estimate [2].

The spatial variation of the effect of mantle uplift may be dependent upon the location of the stratigraphic section relative to the inferred center of the plume [22]. The apex of the uplift is likely coincident with the center of the postulated mantle plume. Accordingly, the center of the Emeishan plume is inferred to be located in the inner zone of erosion, i.e., at the central and partly western Emeishan LIP. This is in good accordance with the conclusion reached independently through petrologic studies [2].

5.3. *Plume head model versus extension model*

Whether LIPs are the result of plume impact [19–21] or plume incubation [22,51] has been the focus of recent discussions [51]. In the plume head model [19,52], a large plume head, originating at the core–mantle boundary, rises beneath the lithosphere and flattens to form a disk about 2000 km across when it reaches the top of its ascent, leading to an uplift of 500–1000 m, followed by volcanism. Melting of the plume head occurs as a consequence of adiabatic decompression. In the extension-plume model, White and McKenzie [22] suggested that volcanism is triggered by lithospheric extension and plumes originate from the upper mantle–lower mantle boundary [53]. Rifting prior to volcanism, which is required by the plume incubation model, is not evident in the Emeishan case. Lithospheric extension was very limited in the Emeishan LIP during the late Permian, and the previously so-called Panxi rift zone needs re-assessment. In fact, the sequence of uplift and volcanism in the Emeishan LIP is the same as that predicted by [19]. This, along with the inferred rapid crustal uplift (< 3 Myr) and short duration of the Emeishan basaltic volcanism [3,16], suggests that the plume impact model may be suitable for the Emeishan LIP. Griffiths and Campbell [20] suggested that significant uplift begins 10–20 Myr before the onset of volcanism when a viscosity of 1×10^{20} Pa/s was used. The modeled timing of uplift produced by a plume head depends on the assumed viscosity for the top of the upper mantle [20]. In the Emeishan case, an uplift in < 3 Myr would imply a much lower viscosity of $< 5 \times 10^{19}$ Pa/s, almost an order of magnitude lower than the estimates for the average viscosity of the upper mantle [54]. The low viscosity allowed the Emeishan plume to rise very rapidly from the depth to the base of the lithosphere. This is in accordance with Larsen and Yuen [55], who have suggested that upwelling speed of a mantle plume may exceed 10 m/yr and spreading of plume materials at the lithosphere base may be accomplished within a couple of million years.

6. Conclusions

1. Systematic biostratigraphic correlation and examination of 67 sections of the Maokou Formation immediately underneath the Emeishan basalts reveals a significant domal thinning in the Emeishan LIP. The thickness contours of the Maokou Formation outline the subcircular area of uplift. This domal uplift immediately preceding eruption of the basalts is consistent with predictions from numerical modeling and is interpreted as a consequence of thermal or dynamic doming by a mantle plume that generated the Emeishan flood basalts.
2. A number of observations suggest that the contact between the Maokou Formation and the Emeishan basalts is an unconformity, which includes basal conglomerates, paleoweathering crust and karst paleotopography, typical of erosion features under tropical conditions. The spatial variation of the unconformity lends further support to domal uplift prior to emplacement of the Emeishan basalts.
3. The duration of this uplift is estimated to be less than 3 Myr and the magnitude of uplift is greater than 1000 m in the core of the uplift. This may be the first example for pre-volcanic kilometer-scale uplift in a Phanerozoic LIP. The rapid uplift suggests that plume impact rather than plume incubation was responsible for the formation of the Emeishan LIP. The magnitude of uplift implies that the plume head temperature is 1450–1500°C.
4. The extent of stratigraphic thinning and the unconformity suggest that the center of the Emeishan plume was located at the western and central Emeishan LIP, an inference also reached by independent petrologic studies [2].

Acknowledgements

I. Campbell, C. Farnetani, R. White and V. Courtillot are thanked for their careful and constructive reviews which substantially improved the paper. We gratefully acknowledge the financial support from the Chinese Academy of Sciences (KZCX2-101), the National Natural Science Foundation of China (40234046) and the Chinese Ministry of Science and Technology (G1999043205). This paper was completed while Y.G.X. was a visiting scientist at the National Taiwan University, which is supported by the NSC of Taiwan.***[VC]***

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