Re-evaluating plume-induced uplift in the Emeishan large igneous province

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Numerical and fluid dynamic modelling predicts that mantle plumes should generate a broad domal uplift (>1,000 km wide, 500 to ⩾1,000 m high) preceding volcanism in large igneous provinces. The Emeishan large igneous province (southwest China) has been offered as the best example of plume-induced uplift, where kilometre-scale pre- and syn-volcanic relief was interpreted to develop in response to the impingement of a plume head. Here, we document voluminous mafic hydromagmatic deposits and submarine extrusions that formed during the initiation and early stages of the Emeishan large igneous province: these deposits were previously interpreted to be alluvial fan sediments shed from a pre-volcanic domal high. The abundance of such deposits—consisting of variable proportions of marine limestone and basaltic fragments—strongly suggests that the bulk of this province was emplaced at sea level. Evidence for dynamic pre-volcanic uplift as predicted by plume models is lacking, and such a lack may be the more general case. Any positive relief that developed was more likely the result of the formation of a volcanic edifice and rapid accumulation of the volcanic pile.

Many authors have argued that, on the basis of numerical and fluid dynamic models, a fundamental prediction of the mantle plume hypothesis should be that when a buoyantly rising plume head impinges on overlying continental lithosphere it flattens to form a disc up to 2,500 km across, which results in significant and observable pre-volcanic uplift[1–10]. Numerical modelling indicates that maximum domal uplift is $1,000 \pm 500$ m (refs 4,5,9), over a radius of about 200 km, with decreasing, but still significant uplift, extending out to about 400 km radius[8]. Documenting dynamic uplift in response to mantle plumes is difficult for many igneous provinces[11] and the Emeishan large igneous province (LIP) in southwest China has been critical in this documentation, providing field evidence of pre-volcanic, kilometre-scale lithospheric doming in response to mantle plume impact on the lithosphere[8,9,12–14]. Southwestern China shows relative continuity of deposition through the Permian period, and robust base-level constraints are provided by the active shallow-water carbonate platform (20–50 m water depth)[13] that extended beyond the limits of the Emeishan LIP. Two critical pieces of evidence used to infer Emeishan domal uplift are (1) variably thinned carbonates of the underlying Maokou Formation and (2) clastic deposits interpreted to be alluvial fan conglomerates shed from a domal high[12,13]. An upper estimate of plume-induced uplift magnitude, about 1,000 m, was inferred from the geometry of the alluvial fan conglomerates[10].

Physical volcanological studies of LIPs provide eruptive process and palaeoenvironment constraints[15] that can be used to test predictions for the extent and magnitude of pre-volcanic kilometre-scale domal uplift. Mafic volcaniclastic deposits yield a sensitive record of eruption and emplacement environments and are capable of recording subtle variations in tectono-volcanic evolution not found in effusive lava flow morphology or stratigraphy[15,16]. This study re-evaluates the clastic deposits of the Emeishan LIP to constrain better the tectono-volcanic evolution of flood basalt emplacement and directly address the model-driven interpretations of mantle-plume-induced, kilometre-scale pre-volcanic uplift.

GEOLOGICAL FRAMEWORK

The Emeishan LIP is located on the western margin of the Yangtze craton in southwest China, with an estimated area of $\sim 2.5 \times 10^5$ km and an estimated preserved extrusive volume of $\sim 0.3 \times 10^6$ km^3 (ref. 17) (Fig. 1). Sensitive high-resolution ion microprobe U/Pb ages indicate that it is about 260 Myr old[18], equivalent to the Middle–Late Permian boundary and the end-Guadalupian mass extinction event[19,20]. The earliest phase of flood basalt eruption was restricted to the northeastern part of the province, and lavas vary from 160 to 485 m in thickness[12,13]. This is overlain by a layer of deposits described as conglomeratic with gravel- to boulder-sized volcanic and limestone clasts with abundant fossiliferous material[12,13]. In other parts of the province, this clastic deposit directly overlies the Maokou Formation limestones and underlies the main flood basalt lavas[12]. The clastic unit forms a wedge in the northeastern part of the province, up to ~170 m thick, 30–80 km wide and 400 km in length, with limestone blocks up to 1 m in the thickest part of the deposit and fining to 3–5 cm diameter in the thinner, distal deposits[12,13] (Figs 1 and 2). This clastic wedge was interpreted to be alluvial fan conglomerate formed in response to pre-volcanic domal uplift and erosion of the Maokou Formation. The Xichang–Qiaojia fault (Fig. 1), forming the western border of the clastic wedge, was interpreted to be a doming-generated normal fault that provided extra faulted topography for erosion and generation of coarse clastic

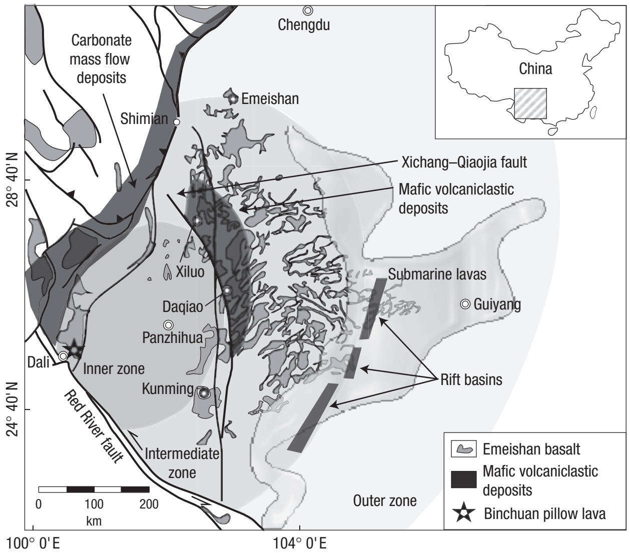

Figure 1 Geologic map of the Emeishan LIP in southwest China. Schematic geologic map of the Emeishan LIP showing the distribution of mafic volcaniclastic deposits; the inset shows the location of the Emeishan LIP in China. A second sampled section with mafic volcaniclastic deposits is located at Xiluo. Grey shaded areas at the periphery of the LIP illustrate the areal extent (after He *et al.*[13]) of rift basins, carbonate mass flows and submarine lavas with intercalated syn-volcanic marine limestone[35]. Pillow lavas at Binchuan (star near Dali) are located in the core of inferred domal uplift. Grey shading on the map represents inferred zones of differential uplift: inner, middle and outer (after He *et al.*[12,13]).

material, as well as acting as a conduit for the early flood basalt magmas. Carbonate platform deposition continued in the Upper Permian following emplacement, and around the peripheries, of the Emeishan LIP (Wujiaping and Changxin formations), totalling up to 370 m in thickness[12].

The late Middle Permian Maokou Formation immediately underlies the Emeishan LIP and is a bedded to massive, fossiliferous limestone generally ranging in thickness from 250 to 600 m (ref. 12). The Maokou Formation, and the underlying Quixia Formation, are the main constituents of the Middle Permian carbonate platform in south China, representing a clean, shallow water (20–50 m depth) oceanic reef environment that formed in response to extensive transgression and basin subsidence from the early Lower to Upper Permian[21,22]. The Maokou Formation has been divided into three biostratigraphic units on the basis of fusulinid foraminifera: lower (*Neoschwagerina simplex*), middle (*Neoschwagerina craticulifera–Afghanella schencki*) and top (*Yabeina-Neomisellina*) and 16 composite sections were interpreted to show thinning and preferential erosion of the upper biostratigraphic units[12]. An area of thinned Maokou Formation ~800 km in radius was defined that formed the basis for delineating circular uplift within the Emeishan LIP. Mantle-plume-induced uplift was estimated assuming an average thickness of ~350 m for the Maokou Formation, an inferred erosion of up to 500 m and adding the thickness of the clastic wedge and underlying lavas (~600 m). The uplifted area was broken into three zones on the basis of the amount of inferred erosion (Fig. 1): an inner zone (0–200 km radius) with pre-volcanic uplift of 300 to >1,000 m; a middle zone (200–425 km) with uplift of 100–800 m; and an outer zone (425–800 km) with minimal uplift (0–250 m). The clastic deposits between the upper Maokou Formation and the main phase of Emeishan flood basalt eruption were interpreted by He *et al.*[12]

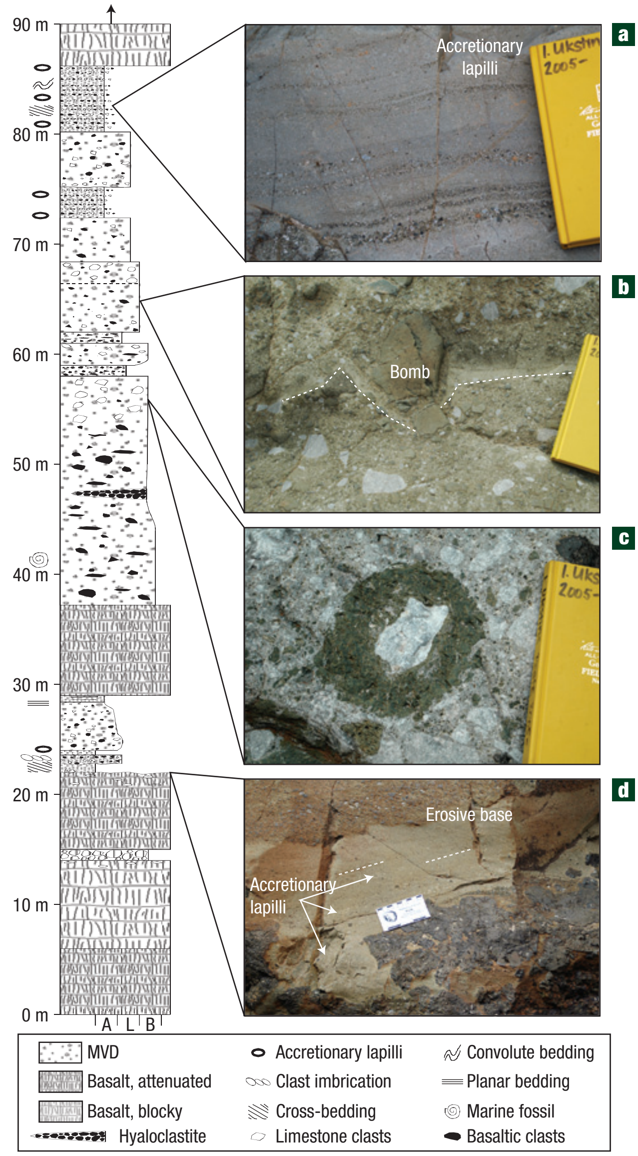

Figure 2 Stratigraphy of mafic volcaniclastic deposits, Daqiao. Rock lithologies are: lava and mafic volcaniclastic deposits (MVDs), with clast size distribution of A = ash, L = lapilli and B = block/bomb. Volcanostratigraphic column represents textural variations in lava flows and MVDs through the Daqiao section. **a**, Fine-grained, fining-upwards sequence of basaltic pyroclastic surge deposits with accretionary lapilli. The notebook is 19 cm long in all photographs. **b**, Basaltic bomb with bomb sag in underlying thin (~3 cm) fine-grained basaltic ash layer. **c**, Limestone-cored basaltic bomb in breccia dominated by angular limestone fragments. **d**, Autobrecciated lava flow top with overlying accretionary lapilli-bearing tuff filling interstices and forming lag deposits in topographic lows. The ruler in the centre of the photo is 8 inches long.

to record an erosional unconformity formed in response to the pre-volcanic doming.

Domal uplift is not the only interpretation of the thickness variations in the Maokou Formation as indicated by He *et al.*[12] (their Fig. 3). The regional variations equally reflect syn-depositional normal faulting that resulted in greater thicknesses of limestone accumulation towards the unstable margins of the Yangtze craton. Clear thickening of *Neoschwagerina* zones occurs towards the craton margins, and is unrelated to any later uplift, erosion and truncation inferred by He *et al.*[12]. The same lateral thickening trends are mirrored in siliciclastic and limestone formations that overlie the Emeishan flood basalts[13]. The thickest limestone sections (1.35 km) along the western craton margin also correspond to a region of carbonate mass flow deposition at the top of the Maokou Formation, previously interpreted to have formed in response to normal faulting, and narrow, deeper marine rift basins developed along the southeastern margin[13] (Fig. 1). An issue not addressed in previous studies is that Himalaya-related deformation increases westwards across the region complicating the Emeishan stratigraphy through faulting and steep tilting.

Modern reefs show significant primary relief (tens of metres: for example, reef flat versus lagoonal and inter-reef) such that the uneven contact between the Maokou limestone and Emeishan flood basalts may reflect natural topography rather than erosion and karst formation. An important constraint is that all carbonate-bearing clastic sedimentary deposits immediately beneath the Emeishan flood basalts across the inferred inner and intermediate uplifted zones were deposited in a marine environment[13]. Any karst formation may have more recent origins given the subaerial tropical exposure of the limestones since the Mesozoic era. Karst formation also provides no constraint on the magnitude of uplift, only subaerial exposure.

EVIDENCE FOR VOLUMINOUS HYDROMAGMATIC VOLCANISM

The Daqiao section of the Emeishan LIP is located 200 km northeast of Kunming and proximal to the core of maximum inferred pre-volcanic domal uplift (Fig. 1). This section (Fig. 2) contains a complete record of the early stages of volcanic activity from the initial basaltic lavas overlying Maokou limestone through the clastic section interpreted as alluvial fan conglomerates[12], to the main stage of flood basalts. The oldest lavas are 8–10-m-thick pahoehoe and a'a sheet flows totalling 22 m, and medium-grained to megacrystic (up to 3 cm) plagioclase-phyric and glomerophyric basalts (Fig. 2 and Supplementary Information). Interstices in the vesicular autobrecciated top of the uppermost lava are infilled with a tan fine-grained basaltic ash with abundant accretionary lapilli of up to 2 cm in diameter (Fig. 2d and Supplementary Information). This basal accretionary lapilli tuff is overlain by an erosive-based, low-angle cross-stratified matrix-supported basaltic lapilli tuff with imbricated, blocky angular basalt and limestone fragments from 0.5 to 4 cm in diameter (Fig. 2d).

The overlying volcaniclastic units are highly diverse in composition and morphology: beds range in thickness from <1 m up to 20 m and contain varying amounts of basaltic lava and limestone fragments from >90% limestone to >90% basalt. The sequence is dominated by limestone clasts at the base and grades up-section to a volumetrically greater basaltic component; clast compositional grading is strongly reflected in unit colour variance from grey to brown (Figs 2,3 and Supplementary Information). Basaltic and massive to fossiliferous limestone fragments range from <1 mm up to 50 cm in size. Blocky plagioclase-phyric, glomerophyric and massive to vesicular lava clasts are similar to lavas underlying the mafic volcaniclastic deposits. Many beds, however, contain attenuated dense, glassy mafic juvenile clasts, suggesting a primary volcaniclastic origin. These basaltic fragments exhibit structures such as a fluidal morphology (see the Supplementary Information) or limestone clasts forming indentations (Fig. 3b), indicating that these were molten or ductile on deposition. Preservation of these morphologies suggests little or no remobilization followed initial emplacement. Thin-section observation confirms a wide variety of volcanic clast textures from blocky (vesicular to massive glassy fragments and crystalline basaltic and gabbroic lithic clasts) to fluidal glassy clasts with vesicular to ductile and welded textures (Fig. 3d and Supplementary Information). This range of petrographic textures and vesicularity indicates that hydromagmatic eruptions ejected molten magma as well as fragments of previously erupted lava occurring as young country rock[23]. Bombs and cored bombs are abundant, and range from basaltic with ductile impact structures and bomb sags developed in underlying bedded units to cored bombs with both basaltic and limestone lithic fragment cores (Fig. 2b,c). Fine-grained units become more abundant towards the top of the section, and contain sharp and planar 1 to >10 − cm-thick beds defined by normally graded basaltic and limestone lithic fragments (0.2 to ∼1 cm), abundant accretionary lapilli (5 mm to 3 cm in diameter) and fine-grained basaltic ash (Fig. 2a and Supplementary Information). Upper fine-grained, tan lapilli-tuff deposits (volcaniclastic rock terminology of White and Houghton[24]) with no visible limestone fragments in hand sample react vigorously to weak HCl acid, reflecting the presence of silt to fine-sand-sized particles as observed in thin section (see the Supplementary Information). Importantly, free fossils of shell and crinoid are also found within these clastic deposits (Fig. 3d and Supplementary Information), indicating these organisms were not bound and lithified at the time of volcanic eruption.

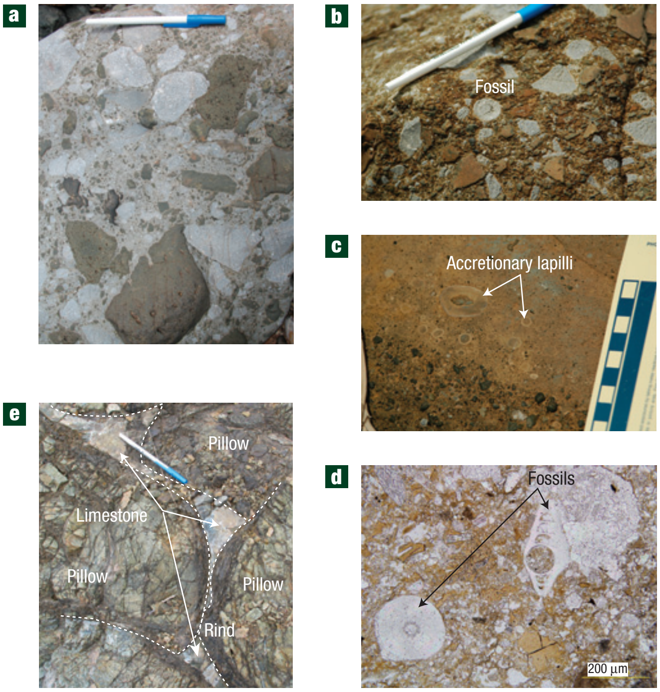

Figure 3 Textural features of Daqiao mafic volcaniclastic deposits and Binchuan pillow lavas. a, Clast-rich breccia bed with blocky to variably attenuated basaltic clasts and blocky limestone clasts (Daqiao). Note indentation and deformation of basalt clast by limestone fragment. The pen is 15 cm long in all photographs. **b**, Basaltic breccia with angular basaltic and limestone clasts. The round limestone fragment in the centre of the photo is a crinoid stem (Daqiao). **c**, Accretionary lapilli (up to 3 cm) with coarse-grained ash and basaltic lithic fragments in core and fine-grained ash rims (Daqiao). **d**, Mafic hydromagmatic deposit (thin section, plain light) with free microfossils (crinoid and foraminifer) in a basaltic lithic and glass-rich matrix. Basaltic ash partly infills foraminifer (centre right), indicating it was unbound at the time of deposition (basal Daqiao). **e**, Pillow lavas with glassy rinds (now altered) with syn-depositional limestone in the interstices and overlying the pillows (Binchuan).

Further styles of hydromagmatic volcanism occur in the inner zone where maximum domal uplift has been argued. The Binchuan locality of Xiao *et al.*[25] (near Dali, Fig. 1) contains a >10-m-thick sequence of pillow lavas with well-developed chill rinds (Fig. 3e and Supplementary Information), conformably overlain by an approximately 4-m-thick, banded limestone deposit. Limestone also partly fills the interstices of the underlying pillow lava mounds (Fig. 3e), indicating that this is a primary depositional contact and the units have not been tectonically juxtaposed.

RE-INTERPRETATION AS MAFIC HYDROMAGMATIC DEPOSITS

The presence of pyroclastic textures such as accretionary lapilli, volcanic bombs with bomb sags and ductile deformation of basaltic clasts throughout the section unequivocally identifies the 'alluvial fan conglomerate wedge' at Daqiao as the products of hydromagmatic volcanic eruptions[23,26,27]. A range of depositional processes are indicated: thick massive beds were deposited by high-concentration pyroclastic density currents; thinner intervals exhibiting normal grading, erosive to sharp planar bases and low-angle stratified cross-bedding were emplaced by more dilute pyroclastic density currents or base surges, and blocks and bomb sags reflect lateral ejection and ballistic fall. A similar range of volcanic textures is observed in other sections of this 'clastic facies' at Xiluo (Fig. 1 and Supplementary Information), demonstrating that hydromagmatic volcanism was widespread and dominated the initial eruptions of the Emeishan LIP. This is seen in several other LIPs such as the Siberian Traps (see, for example, Ross *et al.*[16]), the East Greenland flood basalts[28] and Ferrar flood basalts[29–32].

Regionally, pre-, syn- and post-volcanic sedimentation in southwest China was dominated by shallow marine carbonate platform deposition such that marine limestones are intercalated with distal and proximal Emeishan lavas (Fig. 1 and Supplementary Information). The shallow marine setting of southwest China in the Permian, the ubiquitous presence of fossiliferous limestone, coupled with free fossils within the mafic volcaniclastic deposits themselves (Fig. 3), suggests that the source of the water fuelling hydromagmatic eruptions was marine (see also Bryan *et al.*[33,34]), precluding kilometre-scale pre-volcanic uplift. Furthermore, the occurrence of free fossils within the mafic volcaniclastic deposits demonstrates that unbound and probably living reefal material was being incorporated into these hydromagmatic deposits, precluding uplift and karstification of the Maokou limestone before the onset of volcanism.

Vertical facies changes in the mafic volcaniclastic deposit sequence indicate a progressive decrease in the volume of water fuelling hydromagmatism, which was probably due to both decreasing water interaction as well as increasing magma volume leading to subsequent burial by effusive, subaerial lava flows. The decrease in the content of accidental lithic fragments of limestone country rock with time may represent an initial diatreme-excavating stage of volcanism, followed by continuing eruptions through the newly deposited lavas and mafic volcaniclastic deposits.

RE-EVALUATION OF PLUME-INDUCED UPLIFT

The re-interpretation of the Daqiao and along strike 'conglomerate' sections as mafic volcaniclastic deposits, and the presence of thick basaltic pillow lavas interbedded with limestone in the basal to lower parts of the Emeishan LIP stratigraphy have significant implications for the accuracy of numerical and fluid-dynamic models that predict pre-volcanic kilometre-scale plume uplift[4,5,9]. The initial stage of volcanism in the Emeishan, and within the inner zone of predicted maximum uplift, was strongly dominated by voluminous and widespread hydromagmatic eruptions, most likely the result of basalt magma injection and eruption through an active shallow marine carbonate platform. The wedge-shaped geometry of the mafic volcaniclastic deposits (Fig. 1) is strongly controlled by the Xichang–Qiaojia fault, suggesting syn-depositional normal faulting. The estimated volume of this clastic wedge is about 1,200–5,000 km^3 (ref. 12) (Fig. 1), indicating that the Emeishan LIP contains volumetrically significant mafic volcaniclastic deposits generated at the initiation of flood volcanism. These clastic deposits, when interpreted as alluvial fan conglomerates, were one of the lines of evidence used to support a phase of domal uplift and erosion of the Maokou Formation[12,13]. Because they are hydromagmatic deposits, erupted and emplaced at or near sea level, not only do they not reflect uplift on the edge of the inner zone, they also do not provide any evidence for uplift and erosion of inner zone Maokou Formation limestones. Pillow basalt lavas intercalated with marine limestone and clastic sedimentary rocks in the lower to middle parts of the volcanic succession, from the core to the distal edges of the flood basalt province[13,35] (Fig. 1), corroborate evidence from the mafic volcaniclastic deposits and further support the widespread extent and persistence of shallow marine palaeodepositional environments during initial emplacement of the Emeishan LIP.

Volcano-stratigraphic evidence thus strongly indicates that the initial stages of Emeishan LIP volcanism did not involve kilometre-scale rapid pre-volcanic uplift, because of the requirement to maintain: (1) an active carbonate reef system and (2) both widespread explosive (producing mafic volcaniclastic deposits) and non-explosive (pillow lavas) seawater–magma interaction during the early stages of flood basalt volcanism. The geographic location and positioning of the voluminous mafic volcaniclastic deposits, pillow lavas and marine sedimentation in the Emeishan LIP stratigraphy consequently do not support the zonal definition of a broad uplifted dome, as suggested by previous studies.

The limited uplift (<500 m) observed in continental LIPs such as the Emeishan, Afro-Arabia (a few tens of metres[36]), the North Atlantic (~300–400 m) (ref. 28) and Deccan[11] indicates that significant plume-head-induced uplift, as predicted by many numerical and fluid dynamic models[4,5,9], is not a commonly observable feature of LIP events. Previous modelling of plume–lithosphere interaction requiring kilometre-scale uplift may be an artefact of the model assumptions about lithospheric rheology generating inaccurate predictions of surface evolution[37]. Alternative models of continental volcanism do not require uplift with LIP emplacement, and instead suggest that magmatism can be simultaneous with topographic subsidence due to lithospheric gravitational instabilities[29,38–40].

In summary, correct lithological identification, detailed field analysis and an understanding of volcanic processes and environments are critical elements in studies of large igneous provinces that can provide geologic evidence to test the predictions of mantle plume theory[8,9]. The Emeishan 'conglomerate wedge' is a sequence of mafic volcaniclastic deposits and the product of hydromagmatism; the requirements for formation are incompatible with interpretations of kilometre-scale pre-volcanic dynamic uplift as predicted by numerical and fluid-dynamic modelling of mantle-plume-induced volcanism. We find that the initial erupted products of the Emeishan LIP event were emplaced at or around sea level, and that modest positive relief then developed in response to the rapid accumulation of the volcanic pile. Importantly, these types of deposit provide some uniquely powerful constraints on the palaeoenvironmental conditions immediately preceding and during the early stages of an extinction-linked LIP event.

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Author contributions

I.U.P. and S.E.B. both contributed to carrying out field studies, as well as writing and editing this manuscript.

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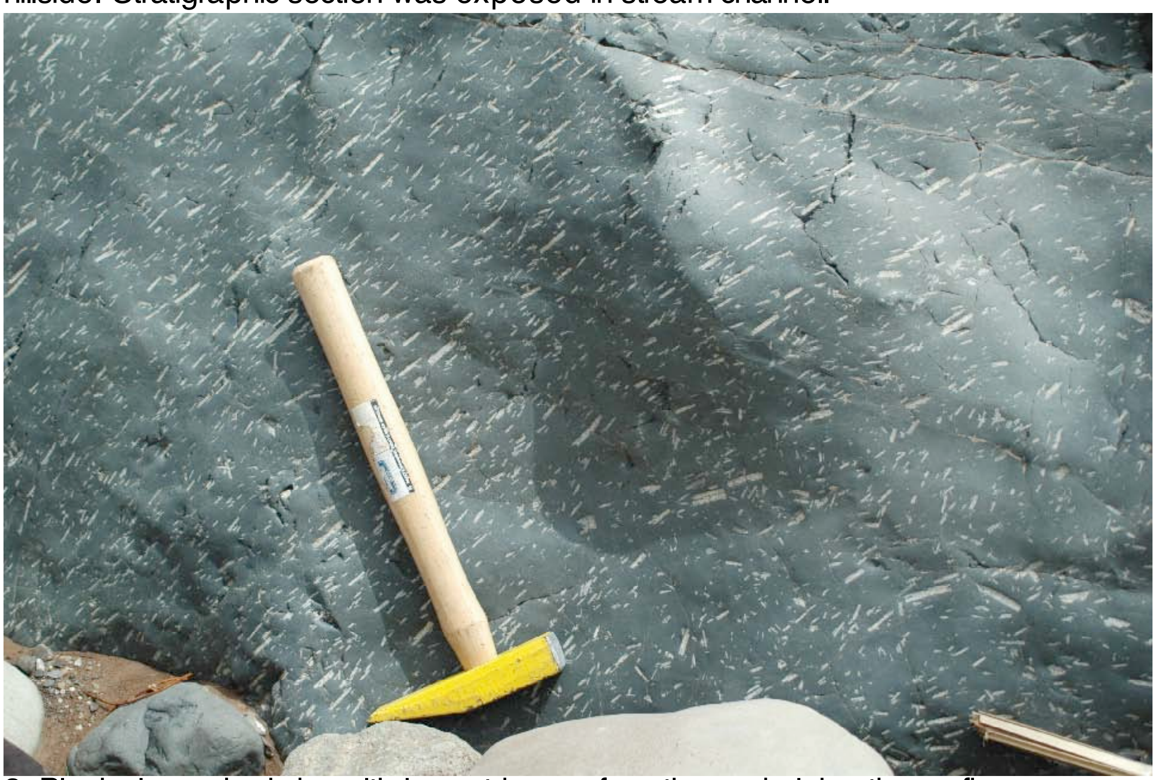
Ukstins Peate & Bryan: Re-evaluating plume-induced uplift in the Emeishan large Igneous Province, SW China.

1. Daqiao locality, showing dipping mafic volcaniclastic unit as resistant ridge on hillside. Stratigraphic section was exposed in stream channel.

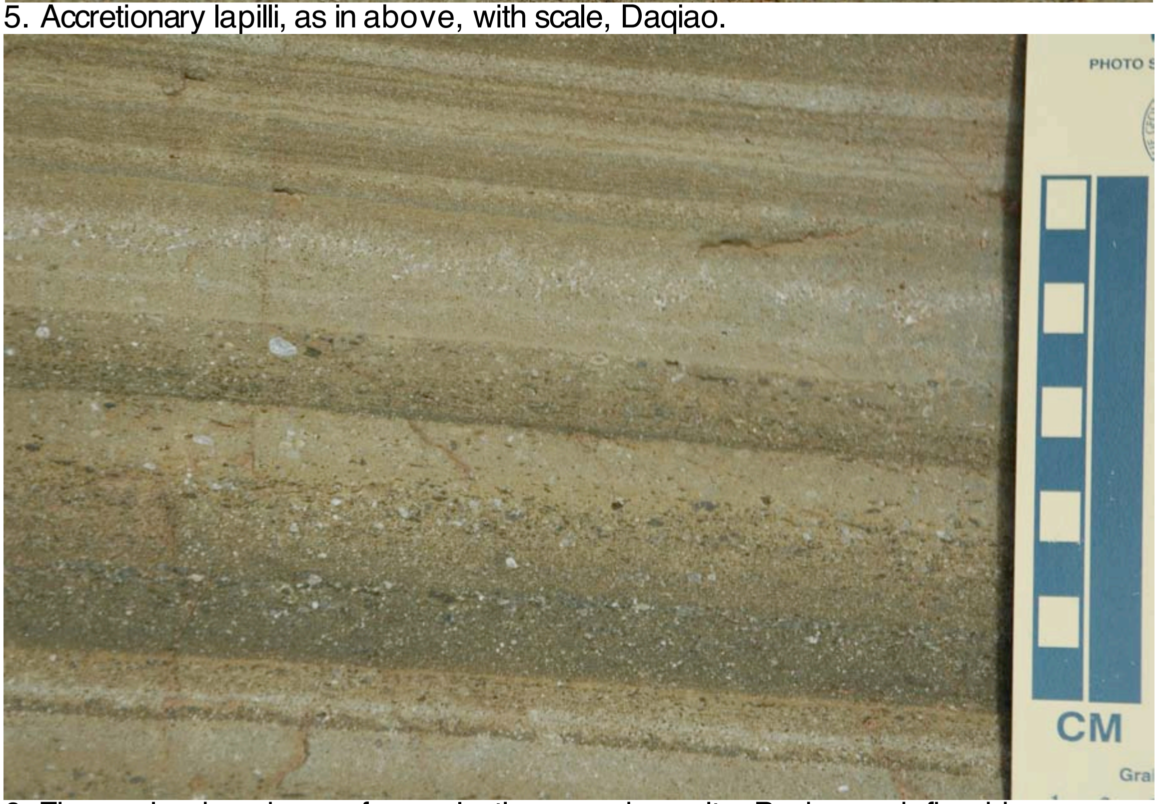


2. Plagioclase-phyric basaltic lava at base of section underlying the mafic volcaniclastic deposits, with plagioclase megacrysts up to 3 cm in length and sub-parallel flow aligned, Daqiao.

3. Outcrop of basal contact of mafic volcaniclastic wedge with high-relief lava flow top, Daqiao.

4. Accretionary lapilli deposited in hollows of underlying lava flow top, Daqiao.

5. Accretionary lapilli, as in above, with scale, Daqiao.



6. Fine-grained package of pyroclastic surge deposits. Beds are defined by normally-graded (?density sorted), fining upwards lithic fragments of basalt and limestone (note dark and light stripes). The thickest bed (bottom of photo) is dominated by basaltic lithics (>90 %), whereas upper beds are variably dominated by basalt or limestone fragments

7. Basaltic bomb with aphyric basaltic lithic core, mantled by plagioclase-phyric basalt with plagioclase laths wrapping around core. Lithic fragments are dominated by angular limestone (>90 %) and plagioclase-phyric basalt, set within a basaltic ash matrix.

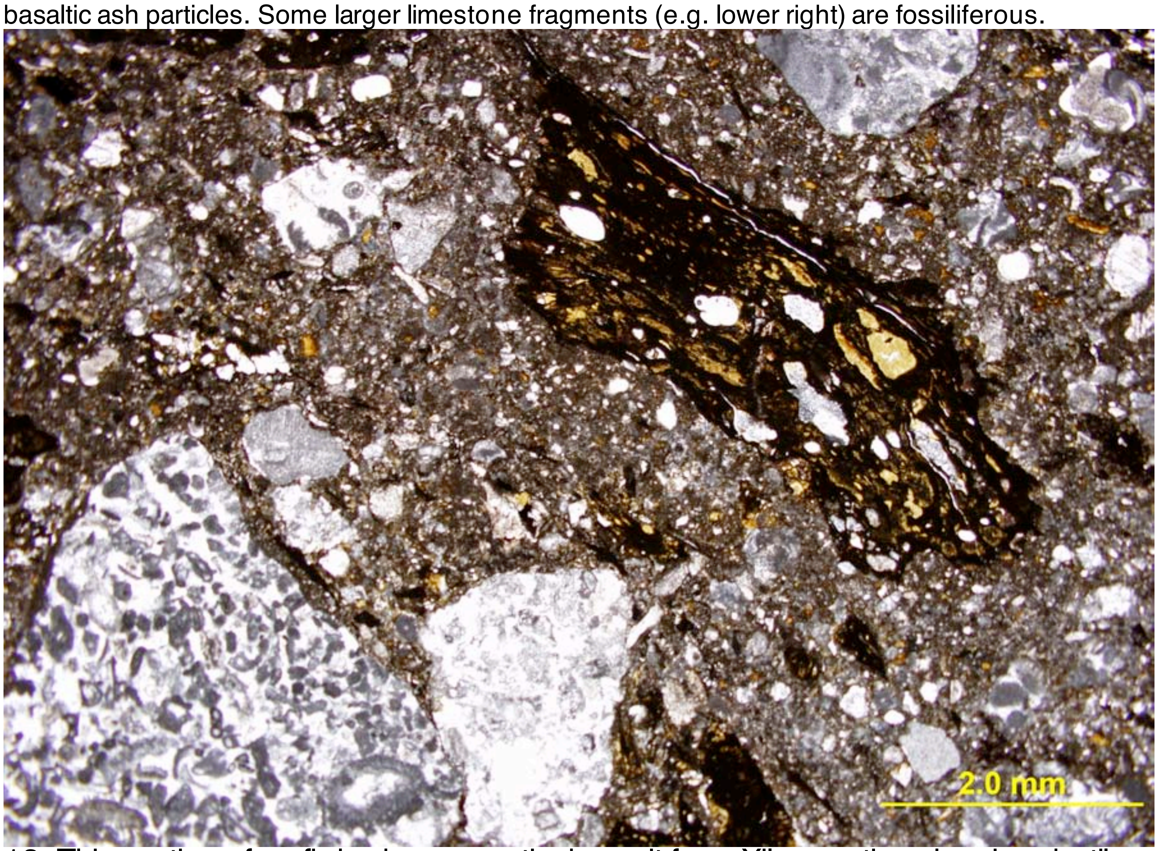
8. Uppermost mafic volcaniclastic unit (left, grey) in contact with overlying lava of the Emeishan main phase of flood volcanism (right, dark brown), Daqiao.

9. Binchuan pillow lava locality, located near Dali in the core of inferred domal uplift. Pillow lavas have well-developed glassy (now altered) rinds and basal pinch structures where pillows have stacked on top of underlying pillows. Some pillows also display radial fractures (top right)

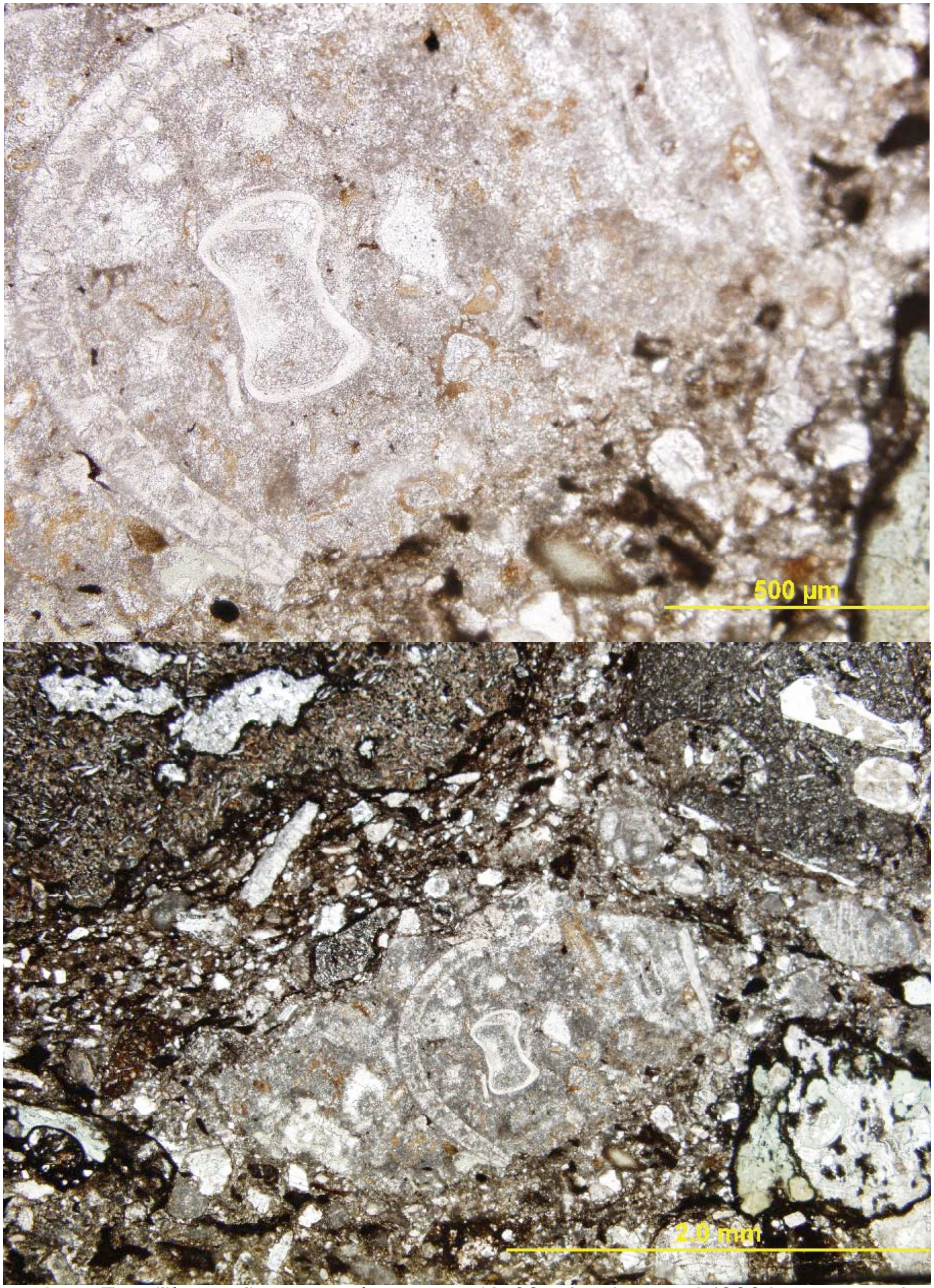
10. Pillow lavas (bottom half of outcrop) with overlying planar-bedded limestone. Limestone fills interstices of pillow structures, indicating that it is syn-depositional and not a tectonic contact.

11. Closer views of limestone deposited in pillow lava upper surface relief, Binchuan.

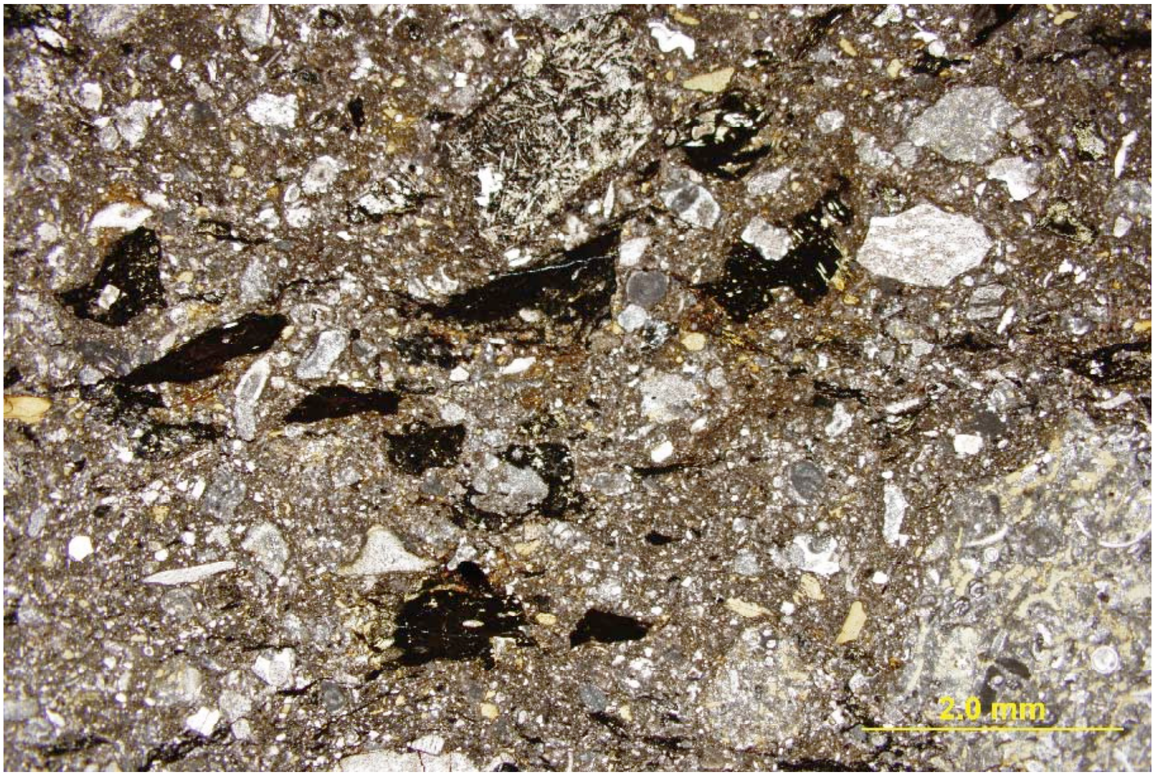
12. MVD near top of Daqiao section, with large, well-preserved accretionary lapilli and fragmental rinds. Lapilli have coarse-grained cores of mafic and limestone clasts and fine-grained rims of basaltic ash particles. Some larger limestone fragments (e.g. lower right) are fossiliferous.



13. Thin section of mafic hydromagmatic deposit from Xiluo section showing ductile volcanic fragments and fossiliferous limestone clasts.



14 & 15 Fossiliferous limestone fragment with ??volcanic material??? incorporated into the bound structure.



16 & 17. Thin sections of mafic hydromagmatic deposits from Xiluo, showing fossiliferous shelly material, ragged, fluidal mafic spatter (dark), mafic glass (transparent brown, now altered) and plagioclase-phyric lava fragments. Upper photo, bottom right limestone has ??volcanic material??? incorporated into the bound structure.