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Submarine palaeoenvironments during Emeishan flood basalt volcanism, SW China: Implications for plume–lithosphere interaction during the Capitanian, Middle Permian ('end Guadalupian') extinction event

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ABSTRACT

Plume-induced lithospheric uplift and erosion are widely regarded as key features of large igneous province (LIP) emplacement, as is the coincidence of LIP eruption with major extinction and oceanic anoxic events (OAE). The Emeishan LIP, which erupted during the Capitanian (previously termed 'end Guadalupian') extinction event, has provided the most widely discussed example of axisymmetric doming above a rising mantle 'plume'; advocates have argued that in excess of 500 m of uplift occurred over >30000 km^2 causing extensive radially distributed erosion and alluvial fan formation. However, the recognition of submarine hydromagmatic and phreatomagmatic-style volcanism, as well as syn-volcanic marine sediments interbedded in the eruptive succession, now requires further examination to this simple plume–uplift model.

Here we present data from newly discovered sections from the center of the putative uplifted area (around Lake Er Hai, SW Yunnan Province,) that provide a more complete history of the Emeishan volcanism. These reveal that platform carbonate deposition was terminated by rapid subsidence, followed quickly by the onset of volcanism. Importantly, these eruptions also coincide with widespread losses amongst fusulinacean foraminifera and calcareous algae. For at least the lower two thirds of the 4–5 km thick lava pile, eruptions continued at or below sea level, as testified by the presence of voluminous mafic volcaniclastic deposits, pillow lavas, and development of syn-volcanic reefal limestones in the Emeishan inner zone. Only in the later stages of eruption did terrestrial lava flows become widely developed. This onset of volcanism in a submarine setting and the consequent violent, phreatomagmatic-style eruptions would have had a profound effect on marine fauna and exacerbated any volcanically induced climate effects during the Capitanian. The late Permian of SW China at the time of the Emeishan was an extended area of thinned lithosphere with epeiric seas, which appear to have been sustained through the onset of LIP emplacement. Therefore, while there remains substantial geochemical support of a plume origin for Emeishan volcanism, LIP emplacement cannot be ubiquitously associated with regional pre-eruption uplift, particularly where complex lithospheric structure exists above a plume.

1. Introduction and rationale

Large igneous provinces (LIPs) represent the largest lava outpourings recorded on the planet (Bryan and Ernst, 2008) and are commonly linked with the ascent of mantle plumes (e.g. Richards et al., 1989) from the lowermost mantle (Burke et al., 2008; Torsvik et al., 2008), and with mass extinction events (Wignall, 2001; Courtillot and Renne, 2003). In continental flood basalt settings (CFBPs), plume-generated continental uplift is predicted to precede volcanism (Campbell and Griffiths, 1990; He et al., 2003; Saunders et al., 2007). However, evidence for this phenomenon is often difficult to obtain either because it is buried beneath the lava piles themselves or because preferential weathering and

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erosion of ancient examples removes less-resistant clastic materials which might otherwise provide evidence for pre-eruptive uplift and erosion (White and Lovell, 1997; Jerram and Widdowson, 2005). However, the Middle Permian Emeishan LIP of SW China preserves the basal contact of the volcanics in many locations, and interpretation of these have provided the quintessential, but highly debated, example of axisymmetric pre-eruption mantle plume doming (He et al., 2003, 2006, 2009, 2010; Saunders et al., 2007; Ali et al., 2010). The province is also linked to mass extinction late in the Guadalupian (e.g. Zhou et al., 2002), with the extinctions in South China shown to precisely coincide with eruption onset (Wignall et al., 2009) and carbon isotope perturbations (Bond et al., 2010a, 2010b). Understanding the nature of any uplift events and the resultant volcanic styles will permit evaluation of the environmental impact of the province, and its role in the extinction.

Initial uplift estimates indicated > 1 km of elevation over an area greater than 400 km radius (He et al., 2006) although the uplift figure has recently been reduced to < 500 m (He et al., 2010). Recent investigations of the basal part of the lava pile (e.g., Ukstins Peate and Bryan, 2008; Wignall et al., 2009; Sun et al., 2010) reveal that Emeishan volcanism was initially characterized by a hydromagmatic phase indicating eruptions at, or below, sea level and not, as argued by He et al. (2010), upon uplands elevated to c.500 m. However, because these hydromagmatic deposits were described from sections around the periphery of the 'inner zone' of uplift as envisaged by He et al. (2006, 2009, 2010), the possibility of pre-eruption uplift in the central Emeishan remained (Ali et al., 2010).

Pangea formed in the Late Carboniferous (c. 320 million years ago), but South China only became part of the supercontinent in the Late Triassic (see Fig. 1a). In the Late Permian, South China was a separate continent with passive margins toward North China and Annamia (Indochina), and an active eastern margin facing the Panthalassa Ocean. Paleomagnetic data position South China confidently in equatorial latitudes in the Late Permian (Fig. 1b), and accordingly, the Emeishan LIP (ELIP) erupted in tropical humid conditions as evidenced by widespread contemporaneous coal-measures (Wang et al., 2011; Boucot et al., 2013) and shallow marine carbonates. Both types of succession are very common; the coal-forming materials being derived from marine mangrove-like plants (e.g. Shao et al., 1998) growing along the coastal zones. Ancient longitude cannot be determined from paleomagnetic data, but South China was positioned such that the ELIP was sourced by a deep plume at the eastern margin (red line in Fig. 1b; the so-called plume generation zone) of the Pacific Large Low Shear-wave Velocity Province in the lowermost mantle (Burke et al., 2008; Torsvik et al., 2008, 2014). Therefore, immediately prior to the onset of ELIP eruptions, the Permian of SW China existed as an area partially inundated by epeiric seas (Fig. 1b). It is also possible that the region represented an extended area of structurally complex prethinned lithosphere. This attenuated lithosphere would have promoted surfaceward advection and emplacement of magma from the plume feeding the ELIP (e.g., Sobolev et al., 2011).

Here we present new data from sections within this 'inner zone' of the ELIP that reveal accelerated subsidence, and extensive hydromagmatic activity immediately prior to, and during, the eruption of the main volcanic succession. These indicate that crustal response to plume impingement during ELIP emplacement was complex, producing a collage of uplifted blocks and basinal areas, with extensive marine environments existing well within the volcanic succession. These conditions were more analogous to the volcano-tectonic development of the Palaeogene North Atlantic margin, which developed mixed subaerial and submarine environments (e.g. Jerram et al., 2009; Jones et al., 2012), than an homogeneous regional doming resulting from a simple LIP–uplift evolutionary model. As a result the onset of Emeishan volcanism in predominantly marine conditions would have had a profound effect on upon marine fauna, and its near-equatorial position provided a geographical situation that allowed delivery of both aerosol and gases, and marine anoxia to both hemispheres.

2. History of emplacement of the Emeishan LIP

The ELIP erupted c. 260 Ma ago (Zi et al., 2010) and is temporally linked with a Capitanian (Middle Permian) extinction event (Wignall et al, 2009; Bond et al., 2010a,2010b). The 'inner zone' is centered in northwest Panzhihua City, Sichuan Province (Fig. 2). The newly discovered outcrops studied here are exposed along the eastern margins of Lake Er Hai, approximately 100 km to the southwest of Dali city. Regional dip is to the north. The contact between Emeishan volcanics and underlying Maokou Formation limestones is seen at Wa Se village in our southernmost section and is repeated by faulting at Shuang Lang town. Due to faulting, the total thickness of the lava pile is difficult to estimate accurately, but it is likely to be 4–5 kilometers, making it one of the thickest known successions (Ali et al., 2005), consistent with its location within the central portion of the main Emeishan outcrops. This area has been placed at the center of the province (e.g. He et al., 2006, 2010); however, the extensive faulting and possible missing/eroded portions of the ELIP make this somewhat difficult to constrain. A generalized section through the sequence is presented in Fig. 3 along with some key geological features, which are elaborated on below.

2.1. Upper Maokou Formation

Shuang Lang (25° 54.612′N 100° 11.679′E). A thick section (>100 m) of bioclastic packstones with a diverse fauna including fusulinaceans (*Neoschwagerina*) is cross-cut by several dykes (e.g. Fig. 3f) (the largest being 15 m in width) that have well-developed baked zones (c. 5 m thick) of coarsely recrystallized limestones. The thin sections of these reveal a recrystallized texture of coarse calcite crystals, resultant from a very pure initial carbonate. The thickness of both dykes and aureoles indicates these to have been major, and long-lived magmatic feeders, and provide clear evidence that the overlying volcanic succession is, in part, locally sourced. The volcanic sources (volcanoes/fissures etc.) for the ELIP are not well known but the dykes discovered here suggest that the Lake Er Hai region was near to lava feeder centers within the Emeishan Province.

2.2. Maokou Fm/Emeishan volcanic succession contact

Wa Se (25° 49.2912'N 100° 13.773'E). Thick section of Maokou Formation with foraminifera-peloid packstones capped by a karstic surface displaying kamnitzas (dissolution hollows) with 30 cm of relief. This surface is overlain by 10–40 cm of dark radiolarian-spiculitic wackestones indicative of deeper water conditions than those recorded by the underlying Maokou Formation (Sun et al., 2010). The ensuing beds consist ~20 m of red clays with devitrified angular volcanic clasts and a succession of alternating ~10 m thick pillow basalt layers separated by further red clays (Fig. 3e). The clays are likely derived from submarine plumes or clouds of hyaloclastite. The location of these pillows and of other sections containing pillows throughout the Emeishan (see Fig. 1) indicate that a substantial area was under water at the onset of the volcanism. This sedimentary–volcanic contact can be traced along strike for several hundred meters up a hillside and does not display any evidence of a 10–200 m-scale karstic topography invoked in domal uplift models (He et al., 2003, 2010; Ali et al., 2010).

2.3. Mid Emeishan succession

Haichaohe (25° 56.265′N 100° 10.524′E). Quarry showing 20 m thick succession of breccia composed of Maokou limestone clasts, occasionally showing weak alignment, set in a matrix of siliceous, spiculitic mudstone and interbedded with thin beds of lapilli tuff. Clasts show intense recrystallization and are < 1 m in size, except for a large block of limestone in the center of the quarry section which is 10 m thick and >30 m wide (Fig. 3b). Conodont samples from this block yielded late