Sub-marine palaeoenvironments during Emeishan flood basalt volcanism, SW China: implications for plume-lithosphere interaction during the Capitanian, Middle Permian ('end Guadalupian') extinction event.

Dougal A. Jerram[1,2], Mike Widdowson[3], Paul B. Wignall[4], Yadong Sun[4,5], Xulong Lai[5], David P.G. Bond[3], and Trond H. Torsvik[1,6,7].

[1] Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway. (email Dougal@dougalearth.com).

[2] DougalEARTH ltd., Solihull, UK (www.dougalearth.com)

[3] Department of Geography, Earth and Environmental Sciences (GEES), University of Hull, Hull HU6 7RX, UK

[4] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

[5] Key Laboratory of Geobiology and Environmental Geology, China University of Geosciences, Wuhan 430074, P. R. China

[6]NGU Geodynamics, Trondheim, Norway

[7]School of Geosciences, University of Witwatersrand, South Africa

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 >30 000 km^2 causing extensive radially-distributed erosion and alluvial fan formation. However, the recognition of submarine 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 centre 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 exacerbated any volcanically-induced cooling 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, whilst 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.

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 & 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 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, 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., 2010). 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 & Bryan 2008; Wignall et al. 2009a; Sun et al. 2010) reveal that Emeishan volcanism was initially characterised by a phreatomagmatic 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 phreatomagmatic deposits were described from sections around the periphery of the ‘inner zone’ of uplift as envisaged by He et al. (2006, 2010), the possibility of pre-eruption uplift remains (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. Palaeomagnetic 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 palaeomagnetic 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 extended area of pre-thinned lithosphere partially inundated by epeiric seas; this structurally complex, 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 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 a., 2009; Jones et al., 2012), than an homogeneous regional doming resulting from a simple LIP-uplift evolutionary model.

History of emplacement of the Emeishan LIP

The ELIP erupted c. 260 Myrs ago (Zi et al., 2010), and is temporally linked with a Capitanian (Middle Permian) extinction event (Wignall et al 2009; Bond et al. 2010). The “inner zone” is centred in north-west 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 south-west 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 southern-most 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 kilometres, 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 centre 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 generalised section through the sequence is presented in Figure 3 along with some key geological features, which are elaborated on below.

Upper Maokou Formation

Shuang Lang (25˚ 54.612’N 100˚ 11.679’E). A thick section (>100m) of bioclastic packstones with a diverse fauna including fusulinaceans (*Neoschwagerina*) is cross-cut by several dykes (e.g. figure 3f) (the largest being 15 m in width) that have well developed baked zones (c. 5 m thick) of coarsely re-crystallised limestones. 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 centres within the Emeishan Province.

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 of ~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 (Figure 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 Figure 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).

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 centre of the quarry section which is 10 m thick and >30 m wide (figure 3b). Conodont samples from this block yielded late forms of *Jinogondolella errata* indicating a basal Capitanian early *J. postserrata* zonal age (Wardlaw and Nestell, 2010).

Jiang Wei South (25˚ 56.607'N 100˚ 10.096'E). A 55 m thick road cut section showing, in ascending order, coarse basaltic agglomerate, meter-bedded coarse lapilli tuffs, silt grade tuffs and basaltic conglomerate containing sub-rounded to sub-angular clasts set in a fine grained glassy (now de-vitrified) hyaloclastic matrix (e.g. figure 3c-d). The attributes of the last bed suggest some sedimentary reworking but in the lower beds clasts are angular, some with 'jig-saw fit' textures revealing *in-situ* fracturing and/or cooling and lack of subsequent transport. These are interpreted to be mafic volcaniclastic deposits; a common feature in the Emeishan succession (Ukstins Peate and Bryan 2008). Within the volcaniclastic successions, marine fauna are found, such as the small lagenide foraminifer *Pachyphloia* that is seen encased in pyroclastic material (e.g. figure 4), which provide unequivocal evidence for eruption in a marine setting with the central part of the Emeishan province.

Upper Emeishan succession

Jiang Wei (25˚ 57.818'N 100˚ 08.518'E). Basaltic lava flows dominate exposures around Jiang Wei town; these are subaerial sheet flows with well-preserved flow fronts and inflated cores (e.g. figure 3a). Several isolated outcrops of limestone c. 50m thick are embedded in this basaltic landscape: one quarry face example reveals a massive *Tubiphytes*-calcisponge reef, the top surface of which shows a highly irregular topography that records either the original reef surface or localised karstification. Impressively, the overlying lava flow infills this topography and irregular masses of lava occur as "cave fills" up to 8 m below the top contact (figure 5).

Discussion

Our field observations demonstrate that the exposed stratigraphy in the central part of the Emeishan is predominantly of marine origin. This marine palaeoenvironment existed temporally well beyond the onset of flood volcanism in the region, and highlights a complex story of the evolution of the ELIP with implication for both uplift and for the associated biological crisis discussed below.

(i) Implications for uplift

The Lake Er Hai sections reveal that much of the volcanic activity near the centre of the province began in submarine environments, and followed a deepening event in the latest phase of the Maokou Formation. The volcanic facies distributed along the Lake Er Hai section are depicted in Figure 6. In this regard, the region is geologically similar to those developed toward the periphery where platform collapse and deepening is also observed to have preceded eruption (e.g. Wignall et al. 2009; Sun et al. 2010). It also supports the recent observations of thick hydrovolcanic units within other newly reported 'inner zone' sections, in the Dali area (Zhu et al., 2014). The transition from pillow basalt volcanism through to predominantly hyaloclastites (described as palagonite-rimmed lapilli-tuffs by Zhu et al. 2014) in the mid-Emeishan succession could represent shallowing of the marine environment, possibly with volcaniclastic rocks prograding into the marine environment (e.g. Jerram et al 2009). Indeed the infilling of existing accommodation space within the marine palaeoenvironment of the 'inner zone' by the flood basalts would see a shallowing upwards in the cycle (Zhu et al., 2014). Prevalence of diverse pyroclastic activity in all but the latest stages of the eruption history reveals continuation of shallow marine emplacement and associated phreatomagmatic style eruptions (Ukstins Peate & Bryan, 2008: Zhu et al., 2014). Only in the later stages of the LIP eruptions do sub-aerial flood basalt flows become developed (Wignall et al., 2009; Sun et al., 2010), and even in this part of the lava stratigraphy interbedded *Tubiphytes* reefs demonstrate a close balance between emplacement and subsidence that kept the growing volcanic edifice at, or close to, sea-level. Such microbial reefs are common within the Emeishan lava pile and indicative of a post-extinction carbonate facies analogous to the widespread stromatolite reefs which follow the end-Permian extinction (Pruss et al. 2005). Since this base level did not change significantly during emplacement of a several kilometres thick volcanic pile rapid subsidence must have kept pace with aggradation throughout most of the brief eruption history (~1 myr, Ali et al. 2005, Wignall et al. 2009).

Our data indicates that the pattern of uplift and subsidence was complex, both within the peripheral areas and, crucially, across the central regions of the Emeishan LIP (Sun et al.; 2010. Maokou Formation limestone deposition spanned the Roadian-Capitanian stages, and the dating of the Haichaohe block shows it was sourced from the younger part of the Formation. Accordingly, erosion of Maokou limestone must have begun *after* the onset of Emeishan eruptions, with clasts incorporated into a depositional systems where both sediment-gravity flows and giant glide blocks (e.g. at Haichaohe) were depositing. The entrainment of small, angular fragments of mafic and carbonate material in these strata indicates either minimal sediment transport distances, or else that they were sourced during brecciation of the Maokou Formation by explosive volcanism.

It has been previously proposed that either 100s m of the Maokou Formation were removed down to lowermost Roadian levels, or else the Formation was removed entirely in this “inner zone” (e.g. He et al. 2003, 2010). However, discovery of large blocks from the upper Maokou Formation (Capitanian Stage) embedded within the middle of the Emeishan volcanics indicates that this was not the case. Similarly, the lack of erosion at the basal contact argues against pre-volcanic uplift, and that depositional base level only approached sea level late in the eruptive history as revealed by calcimicrobial reefs preserved between upper lava successions. One possible explanation for the records of a spectacular, high relief, pre-volcanic karst landscape may, in fact, derive from locations in the upper part of the

Emeishan volcanics where isolated outcrops of intra-trappean limestone (typically reefs) embedded in flood basalts could simulate an *apparent* ‘mega-karst landscape’. Previous arguments for uplift have hinged on the interpretation of volcaniclastic beds as alluvial deposits (He et al., 2003), an assertion that has have already been effectively countered with evidence that that they represent primary hydromagmatic volcanism (Ukstins Peate & Bryan, 2008; Wignall et al. 2009).

The original mantle plume updoming models predict that locations in the centre of the province, such as those studied here, should have experienced deep erosion. However, a simple plume head model is inadequate at explaining all of the observed sedimentary and palaeontological evidence of the ELIP, and also other LIP examples. LIPs can often contain volcaniclastic deposits at the onset of flood volcanism dependent on the palaeoenvironment at eruption (e.g. Ross et al; 2003), their existence and importance is often underestimated due to poor exposure or overlooked. It is known from examples elsewhere, (e.g. North Atlantic Igneous Province; Wrangellia, Canada), that rapid, transient elevation changes result in complex patterns of erosion and sedimentation both prior to, and during flood volcanism, (e.g., Saunders et al., 2007; Greene et al., 2008; Jones et al., 2010). This is especially the case in regions of heterogeneous lithosphere because plume – lithosphere interactions are conditioned not only by the dynamics of the rising plume head (Sleep 1997), but also by the interaction of the plume with rheology and structure of the overlying lithosphere, and the far-field stresses affecting that lithosphere (e.g. Burov and Guillou-Frottier, 2005). In effect, plume—generated surface uplift can become significantly modified resulting in affected regions experiencing crustal dilation and/or contraction (Burov and Gerya, 2014). In such cases, pulses of uplift and subsidence of several hundred metres can produce a series of narrow basins (Burov et al., 2007, 2014), with this system of highs and lows evolving into an intra-basin topography with 10s – 100s km wavelengths and attendant patterns of erosion and deposition. The complex tectonic environment at the time of the Emeishan flood basalts, similarly seems to have resulted in a complex surface response to mantle plume impact, and a significant amount of the volcanic material erupted into the sea. This pattern of lithospheric response in ELIP is consistent with that predicted in recent models (Burov et al., 2014), and thus provides an important link between predictive theory and observation.

(ii) Possible effects of sub-marine eruption on end-Guadalupian environment

As has been demonstrated elsewhere, the onset of volcanism in a submarine setting and the consequent violent phreatomagmatic-style eruptions forming volcaniclastics (Fig. 6) can exacerbate the cooling effects of LIP volcanism through the input of volatiles into the stratosphere (e.g., Jolley and Widdowson, 2005; Self et al., 2006). Additionally, the input of volcanic material directly into the marine environment would have had significantly different consequences than subaerial eruptions alone. The Capitanian extinction losses are noteworthy for the effect they have on warm-water, photosynthetic groups such as fusulinacean foraminifera, calcareous algae and alatoconchid bivalves (e.g. Isozaki & Aljinovic 2009; Wignall et al. 2009) which supports a cooling-driven crisis; though recent studies in the Arctic have discovered an equally severe marine extinction in Boreal latitudes (Bond et al. 2015), coincident with an elevation of mercury concentrations implying an elevation of global volcanism (Grasby et al. in press). Therefore the effects of volcanogenic ocean anoxia and acidification may also be applicable to the Capitanian crisis (Bond et al. 2015). Further, greenhouse gas emissions are also possible sinceGanino and Arndt (2009) argue that thermogenic carbon dioxide release due to magma emplacement through carbon-rich sedimentary succession significantlyamplified primary volcanogenic greenhouse gas releases of the Emeishan Province: Arguably such a scenario (is supported by our observations of major feeder dykes with exceptionally wide contact metamorphic aureoles at Shuang Lang. However, evaluating the varying temperature trends during the Capitanian crisis/Emeishan volcanism remains polemical, and awaits detailed study.

Conclusions

The model for the evolution of the Emeishan LIP in the Lake Er Hai region, based on detailed observations of the lithologies and their key relationships is as follows (see figure 4):

1) The Maokou Formation records a persistent period of shallow-water platform carbonate deposition terminated by a brief emergence (eustatic regression?) and subsequent rapid deepening.

2) The onset of flood volcanism occurred during this rapid deepening phase and the extrusion of thick sequences of pillow basalts and associated marine sediments. Rapid subsidence persisted until late into the eruption history of the province because only high in the succession are subaerial lavas encountered.
3) Volcanism continued with the eruption of hyaloclastites in shallow marine environments. The presence of large glide blocks and much smaller clasts of Maokou carbonates indicates either local uplift and erosion of the uppermost parts of this Formation or spectacularly violent eruptions capable of moving blocks tens of metres in dimensions.
4) The final stages of volcanism are characterised by emergence of the province and development of subaerial lava flows and shallow-water *Tubiphytes* reefs. This emergence probably resulted from the continuous build-up of the lava pile.
5) Contrary to most model predictions, the record of uplift, rifting and sedimentation in the ELIP does not conform to the accepted simple, axisymmetric model; this suggests that each LIP may reveal its own pattern of lithospheric response as a response to regional lithospheric structure and attendant far-field stresses.
6) Models looking at the causes of the Capitanian extinction event need to take into account that unlike many predominantly subaerial flood basalt provinces, a significant component of the Emishan erupted in a marine setting.
7) Clearly, the volcano-tectonic evolution of the Emeishan LIP is complex, and better understood as a plume-lithosphere interaction that was controlled not only by the thermal dynamic of the plume head, but also by the heterogeneous nature of the Late Permian extended lithosphere of the South China (Fig 1).
8) Advection and emplacement of the ELIP magma and lava resulted in various eruption styles. These would have exerted profound effects upon local and regional environments; especially vulnerable would have been reef-dominated marine fauna since extensive hyaloclastite development into restricted, fault-bounded basins would certainly have led to local anoxia. Further, the near-equatorial position of the the ELIP volcanism provided a geographical postion

that allowed delivery of both aerosol and gases, and marine anoxia to both hemispheres through the natural thermally-driven (equator to pole) convection operating in both the atmosphere and oceans. Clearly the ELIP eruptions are large enough to had a global environmental effect. However, the relative roles and timing of ELIP volcanogenic greenhouse gas release (i.e., CO_2) versus elevated atmospheric optical density from aerosols (i.e., SO_2) still remain to demonstrated, as is the case for well-known LIP eruptions elsewhere.

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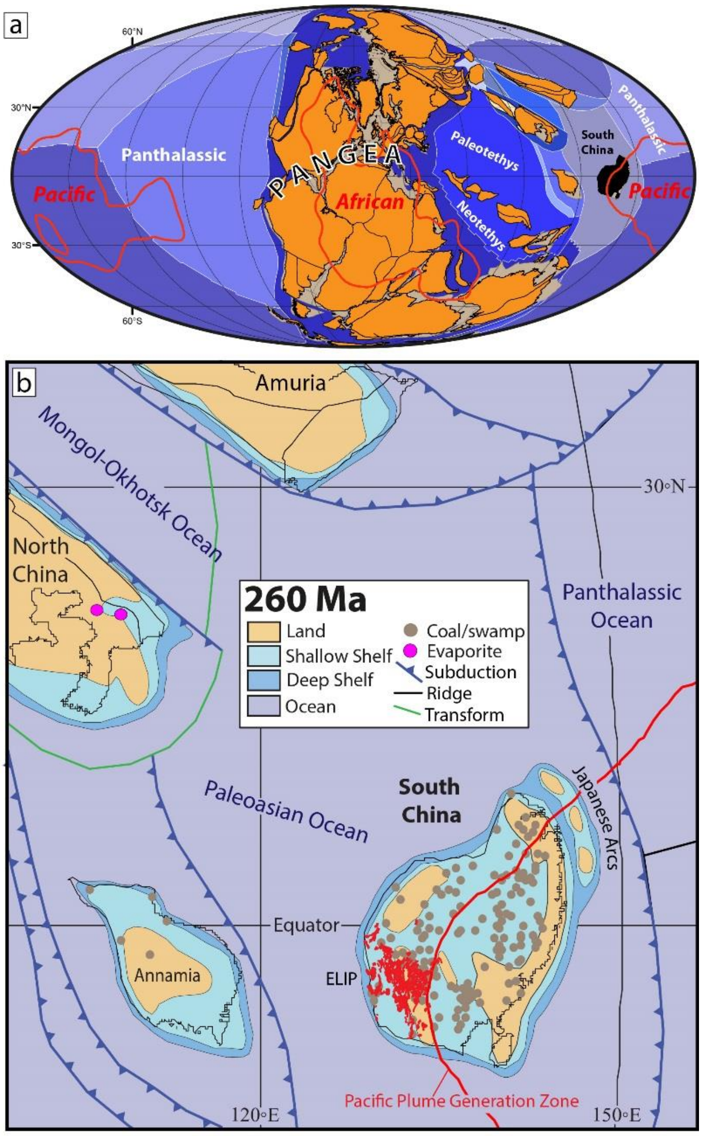

Figure 1. (a) Global palaeomagnetic plate reconstruction (Molweide projection) at 260 Ma (Domeier & Torsvik 2014). Pangea formed in the Late Carboniferous but early breakup is witnessed already in the Early Permian by opening of the Neotethys. Cimmerian terranes leaving Pangea included parts of Iran, Turkey, Afghanistan, Tibet, Burma, Thailand and Malaysia (Sibumasu). Since Pangea formed, plumes that sourced the majority of Large Igneous Provinces and kimberlites have been derived from the edges of two stable and antipodal thermochemical reservoirs at the core-mantle boundary beneath Africa and the Pacific (Torsvik et al. 2008, 2010, 2014; Burke et al. 2008). South China cannot be related to Pangea by plate circuits but using (assuming) this remarkable surface to deep Earth correlation we can position South China in longitude in a such a way that ELIP erupted directly above the Pacific plume generation zone (thick red line). Latitude is derived from palaeomagnetic data and net true polar wander at 260 Ma is zero (Torsvik et al. 2014).

(b) Detailed 260 Ma reconstruction of South China, Annamia (Indo-China), North China (including Sulinheev) and Amuria (Central Mongolia, Hutag Uul-Songliao, Hinggan-Nuhetdavaa and Khanka-Jiamusu Bureya). The reconstruction with detailed plate boundaries follows Domeier & Torsvik (2014) and draped with Guadalupian (272-260 Ma) and Lopingian (260-252 Ma) coal/swamp and evaporate occurrences (Boucot et al. 2013). Indicated areas of Late Permian land, shallow and deep shelf modified from Cocks & Torsvik (2013) but both facies patterns and plate boundary configurations are rather dynamic in the Late Permian.

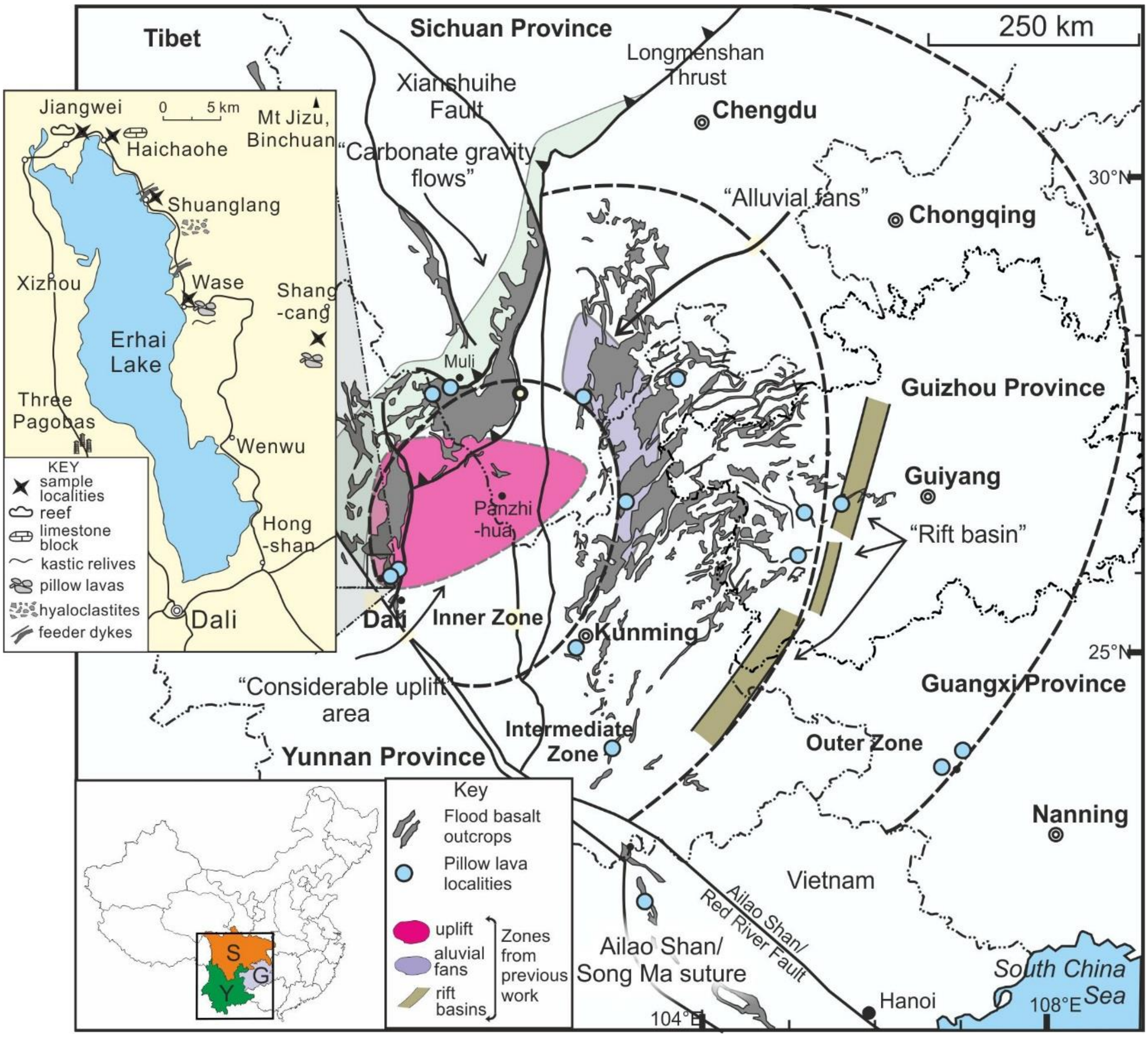

Figure 2. Distribution of Emeishan volcanic and location map of the study section found within the originally mapped 'inner zone'. On the main map, locations of pillow lavas sections are indicated as well as the original zones labelled from previous studies (adapted from He et al., 2010). Inset map shows Lake ErHai and the locations that make up the section in figure 3.

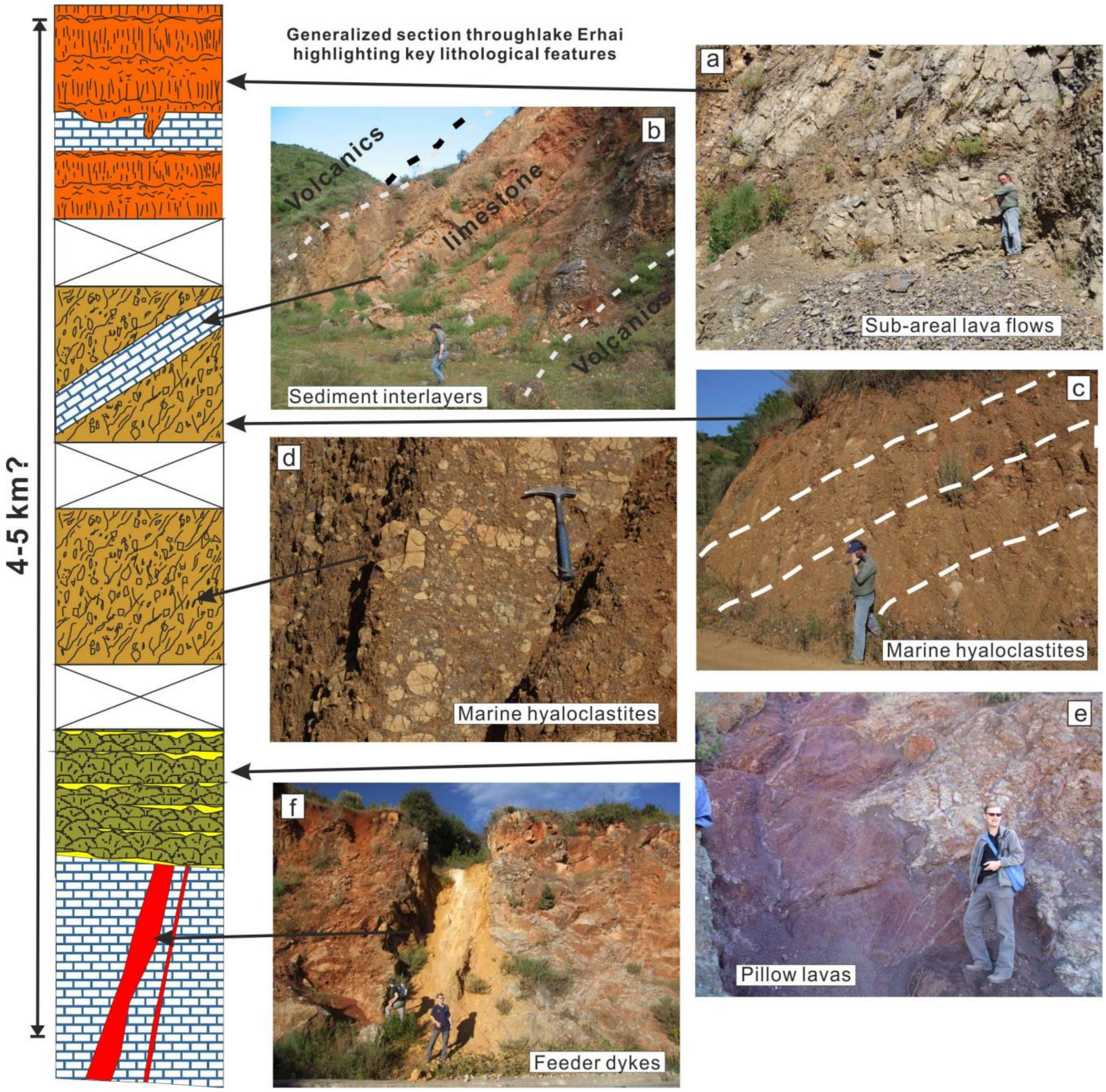

Figure 3. Generlised section through the Lake ErHai region. Showing key lithostratigraphic features including: Feeder dykes (f), Pillow lavas (e), Hyaloclastites (d-c), Sediment interlayers (b), and Sub-areal lava flows (a). Overall section covers some 4-5 km.

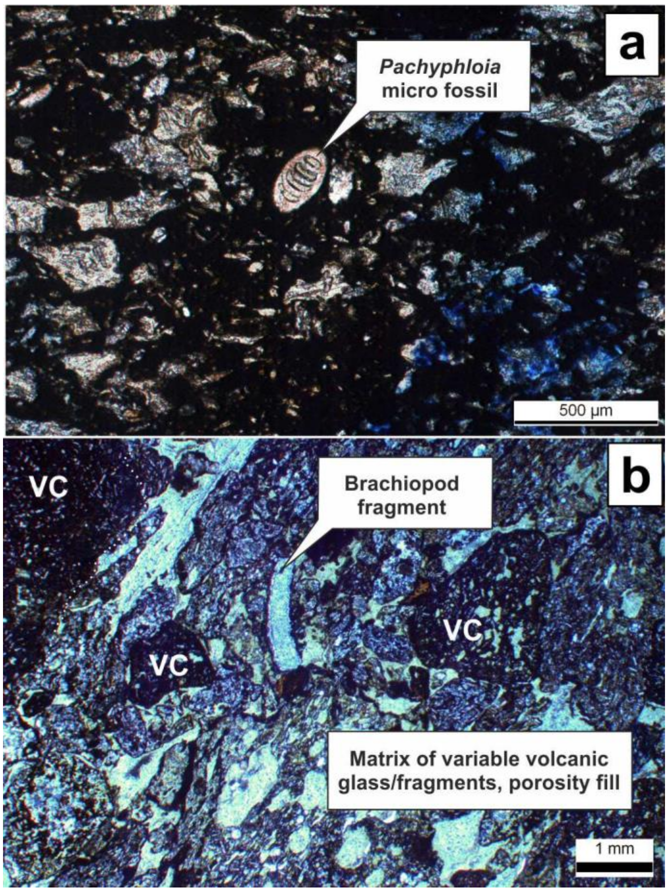

Figure 4. Evidence of marine fauna in volcaniclastics. A) Complete Pachyploia within volcanic glass and fragments. B) Brachipod shells within volcanic fragments (examples of microcrystalline volcanic clasts marked VC on photomicrograph).

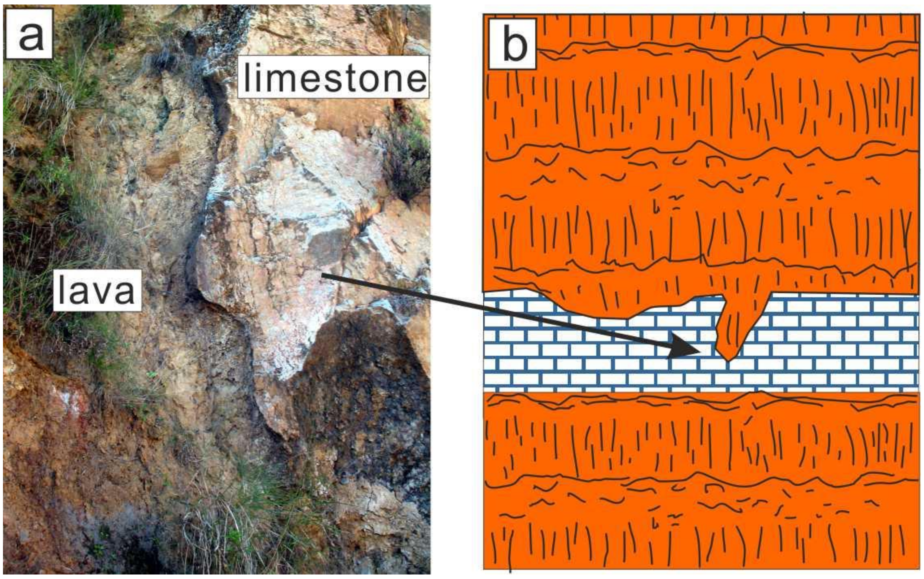

Figure 5. The upper volcanic section highlighting spectacular examples of lava flows into a karst topography within the limestone. This indicates that the upper parts of the volcanic sequence have been erupted into a subareial environment.

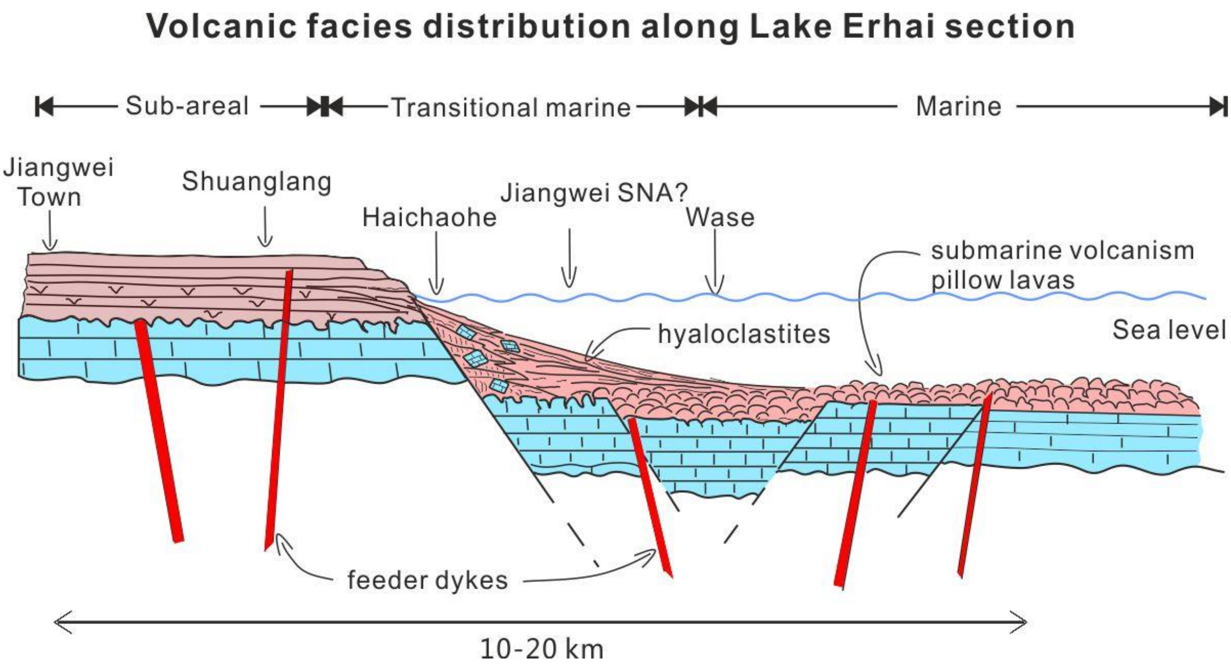

Figure 6. Idealized cross section through the volcanic succession along the Lake Erhai section. The onset of flood volcanism in the majority of the section is characterized by submarine volcanism with pillow lavas and hyaloclastites.