1 **Sub-marine palaeoenvironments during Emeishan flood basalt volcanism,**

2 **SW China: implications for plume-lithosphere interaction during the**

3 **Capitanian ('end Guadalupian') extinction event.**

4 **Dougal A. Jerram[1,2], Mike Widdowson[3], Paul B. Wignall[4], Yadong Sun[4,5], Xulong Lai[5], David**

5 **P.G. Bond[4], and Trond H. Torsvik[1,6,7].**

6 [1] Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Norway. (email

7   Dougal@dougalearth.com).

8 [2] DougalEARTH ltd., Solihull, UK (www.dougalearth.com)

9 [3] Department of Earth Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

10 [4] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

11 [5] Key Laboratory of Geobiology and Environmental Geology, China University of Geosciences,

12   Wuhan 430074, P. R. China

13 [6]NGU Geodynamics, Trondheim, Norway

14 [7]School of Geosciences, University of Witwatersrand, South Africa

15

16 **Abstract**

17 Plume-induced lithospheric uplift and erosion are widely regarded as key features of large igneous

18 province (LIP) emplacement, as is the coincidence of LIP eruption with major extinction and oceanic

19 anoxic events (OAE). The Emeishan LIP, which erupted during the Capitanian (formally 'end

20 Guadalupian') extinction event, has provided the most celebrated example where advocates argue that

21 in excess of 500 m of axisymmetric uplift occurred over >30 000 km^2 causing extensive radially-

22 distributed erosion and alluvial fan formation. However, the recognition of submarine and

23   phreatomagmatic-style volcanism, as well as syn-volcanic marine sediments interbedded in the

24   eruptive succession, now requires further examination to this simple plume – uplift model. Here we

25   present data from newly-discovered sections from the center of the putative uplifted area (around

26   Lake Er Hai, SW Yunnan Province,) that provide a more complete history of the Emeishan

27   volcanism. These reveal that platform carbonate deposition was terminated by rapid subsidence,

28   followed quickly by the onset of volcanism. For at least the lower two thirds of the 4-5 km thick lava

29   pile, eruptions continued at or below sea level, as testified by the presence of voluminous mafic

30   volcaniclastic deposits, pillow lavas and development of syn-volcanic reefal limestones in the

31   Emeishan inner zone. Only in the later stages of eruption did terrestrial lava flows become widely

32   developed. This onset of volcanism in a submarine setting and the consequent violent,

33   phreatomagmatic-style eruptions may have exacerbated the cooling effects of volcanism during the

34   Capitanian. The late Permian of SW China at the time of the Emeishan was an extended area of

35   thinned lithosphere with epeiric seas, which appear to have been sustained through the onset of LIP

36   emplacement. Therefore, whilst there remains substantial geochemical support of a plume origin for

37   Emeishan volcanism, LIP emplacement cannot be ubiquitously associated with regional pre-eruption

38   uplift particularly where complex lithospheric structure exists above a plume.

39

40   **Introduction and rationale**

41   Large igneous provinces (LIPs) in the form of continental flood basalts, represent the largest lavas

42   outpourings recorded on the planet (Bryan and Ernst, 2008), and are commonly linked with the ascent

43   of mantle plumes (e.g. Richards et al., 1989) from the lowermost mantle (Burke et al. 2008, Torsvik et

44   al. 2008), and with mass extinction events (Wignall, 2001; Courtillot & Renne 2003). Plume-

45   generated continental uplift is predicted to precede LIP volcanism (Campbell and Griffiths, 1990; He

46   et al., 2003; Saunders et al., 2007) although evidence for this phenomenon is difficult to obtain either

47   because it is buried beneath the lava piles themselves, or because preferential weathering and erosion

48   of ancient examples removes less resistant clastic materials which might otherwise provide evidence

49   for pre-eruptive uplift and erosion (White and Lovell, 1997; Jerram and Widdowson, 2005). However,

50   the Middle Permian Emeishan LIP of SW China preserves the basal contact of the volcanics in many

51   locations, and interpretation of these have provided the quintessential, but highly debated, example of

52   axisymmetric pre-eruption mantle plume doming (He et al. 2003, 2006, 2010; Saunders et al. 2007;

53   Ali et al. 2010). The province is also linked to mass extinction late in the Guadalupian (e.g. Zhou et

54   al., 2002) with the extinctions in South China shown to precisely coincide with the eruption onset

55   (Wignall et al. 2009) and carbon isotope perturbations (Bond et al., 2010). Any major uplift events

56   and the resultant volcanic styles will clearly help our understanding of the environmental impact of

57   the province, and its role in the extinction.

58   Initial uplift estimates indicated > 1 km of elevation over an area greater than 400 km radius

59   (He et al. 2006) although the uplift figure has recently been reduced to < 500 m (He et al. 2010).

60   Recent investigation of the basal part of the lava pile reveals that Emeishan volcanism was initially

61   characterised by a phreatomagmatic phase indicating eruptions at, or below, sea level and not, as

62   argued by He et al. (2010), upon uplands elevated to c.500 m (Ukstins Peate & Bryan 2008; Wignall

63   et al. 2009a; Sun et al. 2010). However, because these phreatomagmatic deposits were described from

64   sections around the periphery of the 'inner zone' of uplift as envisaged by He et al. (2006, 2010), the

65   possibility of pre-eruption uplift remains (Ali et al. 2010).

66   Pangea formed in the Late Carboniferous (about 320 million years ago) but South China only

67   became part of the supercontinent in the Late Triassic (see Fig. 1a). In the Late Permian, South China

68   was a separate continent with passive margins toward North China and Annamia (Indochina) and an

69   active eastern margin facing the Panthalassa Ocean. Palaeomagnetic data position South China

70   confidently on equatorial latitudes in the Late Permian (Fig. 1b). The Emeishan LIP (ELIP) erupted

71   from in equatorial latitudes, with contemporaneous tropical humid conditions evinced by widespread

72   coal-measures (Wang et al. 2011; Boucot et al. 2013) and shallow marine carbonates. Coal-bearing

73   and carbonate successions are very common, and the coal-forming materials are interpreted to be

74   derived from marine mangrove-like plants (e.g. Shao et al. 1998). Ancient longitude cannot be

75   determined from palaeomagnetic data, but South China is located in longitude (Torsvik et al. 2008,

76 2014) in such a way that ELIP was sourced by a deep plume from the eastern margin (red line in Fig.

77 1b; the so-called plume generation zone) of the Pacific Large Low Shear-wave Velocity Province in

78 the lowermost mantle (Burke et al., 2008). The Permian of SW China was an extended area of pre-

79 thinned lithosphere partially inundated by epeiric seas; this structurally complex, attenuated

80 lithosphere would have promoted surfaceward advection and emplacement of magma from the plume

81 feeding the ELIP (e.g., Sobolev et al., 2011).

82 Here we present new data from sections within this "inner zone" of the ELIP that reveal accelerated

83 subsidence immediately prior to, and during, the eruption of the main volcanic succession. These

84 indicate that crustal response to plume impingement during ELIP emplacement was complex,

85 producing a collage of uplifted blocks and basinal areas, with extensive marine environments existing

86 well within the volcanic succession. These conditions were more analogous to the volcano-tectonic

87 development of the Palaeogene North Atlantic margin, which developed mixed subaerial and

88 submarine environments (e.g. Jerram et a., 2009; Jones et al., 2012), than an homogeneous regional

89 doming resulting from a simple LIP-uplift evolutionary model.

90

91 **History of emplacement of the Emeishan LIP**

92 The ELIP erupted c. 260 Myrs ago (Zi et al., 2010), and is temporally linked with a Capitanian

93 (Middle Permian) extinction event (Wignall et al 2009; Bond et al. 2010). The "inner zone" is centred

94 on the north-western Panzhihua City, Sichuan Province (Fig. 2). The newly-discovered outcrops

95 studied here occur on the eastern border of Lake Er Hai, approximately 100 km to the south-west of

96 Dali city. Regional dip is to the north, and the contact between the volcanics and underlying Maokou

97 Formation limestones is seen at Wa Se village in the southern-most section, and is repeated by

98 faulting at Shuang Lang town. Due to faulting, the total thickness of the lava pile is difficult to

99 estimate accurately, but it is likely to be 4-5 kilometres, making it one of the thickest known

100 successions (Ali et al. 2005), and is consistent with its location within the central portion of the main

101 Emeishan outcrops. This area has been placed at the centre of the Province (e.g. He et al. 2006, 2010),

102 however the extensive faulting and possible missing/eroded portions of the ELIP make this somewhat

103 difficult to exactly constrain. A generalized section up through the sequence is presented in figure 3

104 along with some key geological features, which are elaborated on below.

105

Upper Maokou Formation

107 Shuang Lang (25˚ 54.612'N 100˚ 11.679'E). A thick section (>100m) of bioclastic packstones with a

108 diverse fauna including fusulinaceans (Neoschwagerina) is cross-cut by several dykes (e.g. figure 3f)

109 (the largest being 15 m in width) that have well developed baked zones (c. 5 m thick) of coarsely re-

110 crystallised limestones. The thickness of both dykes and aureoles indicates these to have been major,

111 and long-lived magmatic feeders, and provide clear evidence that the overlying volcanic succession is,

112 in part,locally sourced. Normally the volcanic sources (volcanoes/fissures etc.) for the ELIP are not

113 well known but with the dykes discovered here it helps highlight that the Lake Er Hai region was near

114 to lava feeder centres within the Emeishan Province.

Maokou Fm/Emeishan volcanic succession contact

116 Wa Se (25˚ 49.2912'N 100˚ 13.773'E). Thick section of Maokou Formation with foraminifera-peloid

117 packstones capped by a karstic surface displaying kamnitzas (dissolution hollows) with 30 cm of

118 relief. This surface is overlain by 10-40 cm of dark radiolarian-spiculitic wackestones indicative of

119 deeper water conditions than seen in the underlying Maokou Formation (Sun et al. 2010). The ensuing

120 beds consist of ~20 m of red clays with devitrified angular volcanic clasts and a succession of

121 alternating ~10m thick pillow basalt layers separated by further red clays (Figure 3e). The clays are

122 likely derived from submarine plumes or clouds of hyaloclastite. The location of these pillows and of

123 other sections containing pillows throughout the Emeishan (see figure 1), indicate that a substantial

124 area was under water at the onset of the volcanism. This sedimentary – volcanic contact can be traced

125 along strike for several hundred meters up a hillside and does not display any evidence of a 10 – 200

126 m-scale karstic topography invoked in domal uplift models (He et al. 2003, 2010; Ali et al. 2010).

127 <u>Mid Emeishan succession</u>

128 Haichaohe (25˚ 56.265'N 100˚ 10.524'E). Quarry showing 20 m thick succession of breccia

129 composed of Maokou limestone clasts, occasionally showing weak alignment, set in a matrix of

130 siliceous, spiculitic mudstone and interbedded with thin beds of lapilli tuff. Clasts show intense

131 recrystallization and are < 1 m in size, except for a large block of limestone in the centre of the quarry

132 section which is 10 m thick and >30 m wide (figure 3b). Conodont samples from this block yielded

133 late forms of Jinogondolella errata indicating a basal Capitanian early J. postserrata zonal age

134 (Wardlaw and Nestell, 2010).

135 Jiang Wei South (25˚ 56.607'N 100˚ 10.096'E). A 55 m thick road cut section showing, in ascending

136 order, coarse basaltic agglomerate, meter-bedded coarse lapilli tuffs, silt grade tuffs and basaltic

137 conglomerate containing sub-rounded to sub-angular clasts set in a fine grained glassy (now de-

138 vitrified) hyaloclastic matrix (e.g. figure 3c-d). The attributes of the last bed suggest some

139 sedimentary reworking but in the lower beds clasts are angular, some with 'jig-saw fit' textures

140 revealing in-situ fracturing and/or cooling and lack of subsequent transport. These are interpreted to

141 be mafic volcaniclastic deposits; a common feature in the Emeishan succession (Ukstins Peate and

142 Bryan 2008). Within the volcaniclastic successions, marine fauna are found (e.g. figure 4), which

143 provide unequivocal evidence for eruption in a marine setting with the central part of the Emeishan

144 province.

145 <u>Upper Emeishan succession</u>

146 Jiang Wei (25˚ 57.818'N 100˚ 08.518'E). Basaltic lava flows dominate exposures around Jiang Wei

147 town; these are subaerial sheet flows with well-preserved flow fronts and inflated cores (e.g. figure

148 3a). Several isolated outcrops of limestone c. 50m thick are embedded in this basaltic landscape: one

149 quarry face example reveals a massive Tubiphytes-calcisponge reef, the top surface of which shows a

150 highly irregular topography that records either the original reef surface or localised karstification.

151 Impressively, the overlying lava flow infills this topography and irregular masses of lava occur as

152 "cave fills" up to 8 m below the top contact (figure 5).

153

154

Discussion

Our field observations demonstrate that the exposed stratigraphy in the central part of the Emeishan is clearly predominantly of marine origin. This marine palaeoenvironment clearly existed 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 Erhai 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 Erhai 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 swallowing 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, 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

179   are common within the Emeishan lava pile and indicative of a post-extinction carbonate facies

180   analogous to the widespread stromatolite reefs which follow the end-Permian extinction (Pruss et al.

181   2005). Since this base level did not change significantly during emplacement of a several kilometres

182   thick volcanic pile rapid subsidence must have kept pace with aggradation throughout most of the

183   brief eruption history (~1 myr, Ali et al. 2005, Wignall et al. 2009).

184   The current work, makes clear that the pattern of uplift and subsidence is complex within both the

185   peripheral and central regions of the Emeishan LIP, and is in agreement with Sun et al. (2010).

186   Maokou limestone deposition spanned the Roadian-Capitanian stages, and the dating of the

187   Haichaohe block shows it was sourced from the younger part of the Formation. Accordingly, erosion

188   of Maokou limestone must have begun after onset of Emeishan eruptions, with clasts incorporated

189   into a depositional systems where both sediment-gravity flows and giant glide blocks (e.g. at

190   Haichaohe) were depositing. The entrainment of small, angular fragments of mafic and carbonate

191   material in these strata indicates either minimal sediment transport distances, or else that they were

192   sourced during brecciation of the Maokou Formation by explosive volcanism.

193   It has been proposed previously either that 100s m of the Maokou Formation were removed, either

194   down to lowermost Roadian levels, or the Formation was removed entirely in this "inner zone" (e.g.

195   He et al. 2003, 2010). However, discovery of large blocks from the upper Maokou Formation

196   (Capitanian Stage) embedded within the middle of the Emeishan volcanics indicates that this is not

197   the case. Similarly, the lack of erosion at the basal contact argues against pre-volcanic uplift, and that

198   depositional base level only approached sea level late in the eruptive history as revealed by

199   calcimicrobial reefs preserved between upper lava successions. One possible explanation for the

200   records of a spectacular, high relief, prevolcanic karst landscape may in fact derive from locations in

201   the upper part of the Emeishan volcanics where isolated outcrops of intra-trappean limestone

202   (typically reefs) embedded in flood basalts could simulate an apparent mega-karst landscape. Previous

203   arguments for uplift have hinged on the interpretation of volcaniclastic beds as alluvial deposits (He et

204   al., 2003) and have already been countered with the suggestion that they represent primary

205   hydromagmatic volcanism (Ukstins Peate & Bryan, 2008; Wignall et al. 2009).

206   Mantle plume updoming models predict that locations in the centre of the province, such as those

207   studied here, should have experienced deep erosion. However, a simple plume head model is

208   inadequate at explaining all of the observed sedimentary and palaeontological evidence. LIPs can

209   often contain volcaniclastic deposits at the onset of flood volcanism dependent on the

210   palaeoenvironments at eruption (e.g. Ross et al; 2003), their existence and importance is often

211   underestimated due to poor exposure or overlooked. It is known from examples elsewhere, (e.g. North

212   Atlantic Igneous Province; Wrangellia, Canada), that rapid, transient elevation changes result in

213   complex patterns of erosion and sedimentation both prior to, and during flood volcanism, (e.g.,

214   Saunders et al., 2007; Greene et al., 2008; Jones et al., 2010). This is especially the case in regions of

215   heterogeneous lithosphere because plume – lithosphere interactions are conditioned not only by the

216   dynamics of the rising plume head (Sleep 1997), but also by the interaction of the plume with

217   rheology and structure of the overlying lithosphere, and the far-field stresses affecting that lithosphere

218   (e.g. Burov and Guillou-Frottier, 2005). In effect, plume—generated surface uplift can become

219   significantly modified resulting in affected regions experiencing crustal dilation and/or contraction

220   (Burov and Gerya, 2014). In such cases, pulses of uplift and subsidence of several hundred metres can

221   produce a series of narrow basins (Burov et al., 2007, 2014), with this system of highs and lows

222   evolving into an intra-basin topography with 10s – 100s km wavelengths and attendant patterns of

223   erosion and deposition. The complex tectonic environment at the time of the Emeishan flood basalts,

224   seems to have resulted in a complex surface response to mantle plume impact, and a significant

225   amount of the volcanic material erupted into the sea. This pattern of lithospheric response in ELIP is

226   consistent with that predicted in recent models (Burov et al., 2014), and thus provides an important

227   link between predictive theory and observation.

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

229   The onset of volcanism in a submarine setting and the consequent violent phreatomagmatic-style

230   eruptions forming volcaniclastics (Fig. 6) may have exacerbated the cooling effects of volcanism due

231   to the input of volatiles into the stratosphere. Additionally, the input of volcanic material directly into

232   the marine environment would have had significantly different consequences than subaerial eruptions

233 alone. The Capitanian extinction losses are noteworthy for the effect they have on warm-water,

234 photosynthetic groups such as fusulinids foraminifers, calcareous algae and alatoconchid bivalves

235 (e.g. Isozaki & Aljinovic 2009; Wignall et al. 2009) which supports a cooling-driven crisis, although

236 recent studies in the Arctic have discovered an equally severe marine extinction in Boreal latitudes

237 (Bond et al. 2015), coincident with an elevation of mercury concentrations implying an elevation of

238 global volcanism (Grasby et al. in press). The effects of warming, anoxia and acidification may

239 therefore be more applicable to the Capitanian crisis (Bond et al. 2015) suggesting greenhouse gas

240 emissions are also likely to have been substantial. Suggestions that thermogenic carbon dioxide

241 release also amplified the volcanogenic greenhouse gas releases of the Emeishan Province (Ganino &

242 Arndt 2009) is supported by our observations of major feeder dykes with thick contact metamorphic

243 aureoles. However, evaluating the different temperature trends during the Capitanian crisis/Emeishan

244 volcanism awaits a detailed study.

245 **Conclusions**

246 The model for the evolution of the Emeishan in the Lake Erhai section, based on detailed observations

247 of the lithologies and their key relationships is as follows (see figure 4):

248 1) The Maokou limestones record a persistent period of shallow-water platform carbonate

249 deposition terminated by a brief emergence (eustatic regression?) and subsequent rapid

250 deepening.

251 2) The onset of flood volcanism occurred during this rapid deepening phase and the extrusion of

252 thick sequences of pillow basalts and associated marine sediments. Rapid subsidence

253 persisted until late into the eruption history of the province because only high in the

254 succession are subaerial lavas encountered.

255 3) Volcanism continued with the eruption of hyaloclastites in shallow marine environments. The

256 presence of large glide blocks and much smaller clasts of Maokou carbonates indicates either

257 local uplift and erosion of the uppermost parts of this Formation or spectacularly violent

258 eruptions capable of moving blocks tens of meters in dimensions.

259   4) The final stages of volcanism are characterised by emergence of the province and

260   development of subaerial lava flows and shallow-water Tubiphytes reefs. This emergence

261   probably resulted from the continuous build-up of the lava pile.

262   5) Contrary to most model predictions, the record of uplift, rifting and sedimentation in the ELIP

263   does not conform to the accepted simple, axisymmetric model; this suggests that, each LIP

264   may reveal its own pattern of lithospheric response as a response to regional lithospheric

265   structure and attendant far-field stresses.

266   6) Models looking at the causes of the Capitanian extinction event, need to take into account that

267   unlike many predominantly subaerial flood basalt provinces, a significant component of the

268   Emishan erupted into marine conditions.

269   7) Clearly, the volcano-tectonic evolution of the Emeishan LIP is complex, and better

270   understood as a plume-lithosphere interaction that was controlled not only by the thermal

271   dynamic of the plume head, but also by the heterogeneous nature of the Late Permian

272   extended lithosphere of the South China (Fig 1).

273

283

284   References

285   Ali, J. R., Thompson, G. M., Zhou M., Song X., 2005. Emeishan large igneous province, SW China.

286   Lithos 79, 475-489.

287   Ali, J.R., Fitton, J.G., Herzberg, C., 2010. Emeishan large igneous province (SW China) and the

288   mantle-plume up-doming hypothesis. J. Geol. Soc. Lond. 167, 953-959.

289   Bond, D.P.G., Hilton, J., Wignall, P.B., Ali, J.R., Stevens, L.G., Sun, Y-D., Lai X-L., 2010. The

290   Middle Permian (Capitanian) mass extinction on land and in the oceans. Earth-Sci. Rev. 109,

291   100-116.

292   Bond, D. P. G.; Wignall, P. B., Joachimski, M.M., Sun, Y.-D., Savov, I., Grasby, S.E., Beauchamp,

293   B., Blomeier, D.P.G., 2015. An abrupt extinction in the Middle Permian (Capitanian) of the

294   Boreal Realm (Spitsbergen) and its link to anoxia and acidification. Bull. Geol. Soc. Amer. doi:

295   10.1130/B31216.1

296   Bond, D. P. G.; Wignall, P. B. Wang, W. Izon, G. Jiang, H.-S. Lai, X.-L. Sun, Y.-D. Newton, R. J.

297   Shao, L.-Y. Védrine, S., Cope, H., 2010. The mid-Capitanian (Middle Permian) mass extinction

298   and carbon isotope record of South China. Palaeogeogr., Palaeoclimatol., Palaeoecol., 292, 282–

299   294.

300   Boucot, A.J., Xu, C., Scotese, R., 2013. Phanerozoic paleoclimate: An atlas of lithologic indicators of

301   climate. SEMP Concepts in Sedimentology and Paleontology No. 11, Tulsa, Oklahoma, 478 pp.

302   Bryan, S.E., Ernst, R.E., 2008, Revised definition of large igneous provinces (LIPs): Earth- Sci. Rev.

303   v. 86, p. 175–202.

304   Burke, K., Steinberger, B., Torsvik, T. H., Smethurst, M. A., 2008. Plume generation zones at the

305   margins of large low shear velocity provinces on the core–mantle boundary. Earth Planet. Sci.

306   Lett. 265, 49–60.

307   Burov, E., Guillou-Frottier, L., 2005. The plume head-continental lithosphere interaction using a

308   tectonically realistic formulation for the lithosphere. Geophys. J. Int. 161, 469-490.

309   Burov, E., Guillou-Frottier, L., d'Acremont, E., Le Pourhiet, L., Cloetingh, S., 2007. Plume head-

310   continental lithosphere interactions near continental plate boundaries. Tectonophysics 434, 15-

311   38.

312   Burov, E., Gurya, T., 2014. Asymmetric three-dimensional topography over mantle plumes. Nature
313   513, 85-89.

314   Cocks, L.R.M., Torsvik, T.H., 2013. The dynamic evolution of the Palaeozoic geography of eastern
315   Asia. Earth-Sci, Rev. 117, 40-79.

316   Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events: Comp. Rend. Geosci. 335,
317   113–140.

318   Domeier, M., Torsvik, T.H., 2014. Plate kinematics of the Late Paleozoic. Geosci. Frontiers 5, 303-
319   350.

320   Ganino, C., Arndt, N.T. 2009. Climate change caused by degassing of sediments during emplacement
321   of large igneous provinces. Geology 37, 323-326.

322   Grasby, S.E., Beauchamp, B., Bond, D.P.G., Wignall, P.B., Sanei, H., in press. Mercury deposition in
323   association with three Permian extinction events in NW Pangea. Geol. Mag.

324   Greene, A.R., Soates, J.S., Weis, D., 2008. Wrangellia flood basalts in Alaska: A record of plume-
325   lithosphere interaction in a Late Triassic oceanic plateau. Geochem. Geophy. Geosyst. 9(12).
326   DOI:10.1029/2008GC002092

327   He B., Xu Y., Chung S.L., Xiao L., Wang Y., 2003. Sedimentary evidence for a rapid, kilometer-scale
328   crustal doming prior to the eruption of the Emeishan flood basalts. Earth Planet. Sci. Lett. 213,
329   391-405.

330   He B., Xu Y., Wang Y., Luo Z., 2006. Sedimentation and lithofacies paleogeography in SW China
331   before and after the Emeishan flood volcanism: New insights into surface response to mantle
332   plume activity. J. Geol. 114, 117-132.

333   He B., Xu Y., Campbell, I., 2009. Pre-eruptive uplift in the Emeishan? Nature Geoscience 2, 530-531.

334   He B., Xu Y., Guan J.-P., Tong, Y-T., 2010. Paleokarst on top of the Maokou Formation: further
335   evidence for domal crustal uplift prior to the Emeishan flood volcanism. Lithos 119, 1-9

336   Isozaki, Y., Aljinovic, D., 2009. End-Guadalupian extinction of the Permian gigantic bivalve
337   Alatoconchidae: end of gigantism in tropical seas by cooling. Palaeogeogr. Palaeoclimatol.
338   Palaeoecol. 284, 11-21.

339 Jerram, D. A., Widdowson, M., 2005. The anatomy of Continental Flood Basalt Provinces: geological

340   constraints on the processes and products of flood volcanism. Lithos 79, 385-405.

341 Jerram, D. A., Single, R.T, Hobbs, R.W., Nelson, C.E., 2009.Understanding the offshore flood basalt

342   sequence using onshore volcanic facies analogues: an example from the Faroe–Shetland basin

343   Geol. Mag. 146,. 353–367.

344 Jones, S.M., Lovell, B., Crosby, A.G., 2012. Comparison of modern and geological observations of

345   dynamic support from mantle convection. J. Geol. Soc. Lond. 169, 745-758.

346 Pruss, S.B., Corsetti, F.A., Bottjer, D.J., 2005. The unusual sedimentary rock record of the Early

347   Triassic: A case study from the southwestern United States. Palaeogeogr. Palaeoclimatol.

348   Palaeoecol. 222, 33-52.

349 Richards, M.A., Duncan, R.A., Courtillot, V.E., 1989. Flood Basalts and Hot-Spot Tracks: Plume

350   Heads and Tails. Science, 246, 103-107.

351 Ross, P.-S., Ukstins Peate, I., Mcclintock, M.K., Xu, Y.G., Skilling, I.P., White, J.D.L., Houghton,

352   B.F., 2003. Mafic volcaniclastic deposits in flood basalt provinces: a review. J. Volcan.

353   Geotherm. Res. 145, 281-314.

354 Saunders, A. D., Jones, S. M., Morgan, L. A., Pierce, K. L., Widdowson, M., Xu Y.-G., 2007.

355   Regional uplift associated with continental large igneous provinces: The roles of mantle plumes

356   and the lithosphere. Chem. Geol. 241, 282–318, doi:10.1016/j.chemgeo.2007.01.017

357 Shao, L., Zhang, P., Ren, D., Lei, J., 1998. Late Permian coal-bearing carbonate successions in

358   southern China: coal accumulation on carbonate platforms. Intern. J. Coal Geol. 37, 235-256.

359 Sleep, N.H., 1997. Lateral flow and ponding of starting plume material. J. Geophys. Res. 102, 10001-

360   10012.

361 Sobolev, S.V., Sobolev, A.V., Kuzmin, D.V., Krivolutskaya, N.A., Petrunin, A.G., Arndt, N.T.,

362   Radko, V.A., Vasiliev, Y.R., 2011. Linking mantle plumes, large igneous provinces and

363   environmental catastrophes. Nature 477, 312-316.

364 Sun Y-D., Lai X-L., Wignall, P.B., Widdowson, M., Ali, J.R., Jiang H-S., Wang W., Yan C-B., Bond,

365   D.P.G., Védrine, S., 2010. Dating the onset and nature of the Middle Permian Emeishan large

366   igneous province eruptions in SW China using conodont biostratigraphy and its bearing on

367   mantle plume uplift models: Lithos, 119, 20-33.

368 Torsvik, T.H., Steinberger, B., Cocks, L.R.M. Burke, K., 2008. Longitude: Linking Earth's ancient

369   surface to its deep interior. Earth Planet. Sci. Lett. 276, 273-283.

370 Torsvik, T.H. Burke, K., Steinberger, B., Webb, S.C. Ashwal, L.D., 2010. Diamonds sourced by

371   plumes from the core mantle boundary. Nature 466, 352-355

372 Torsvik, T.H., Van der Voo, R., Doubrovine, P.V., Burke, K., Steinberger, B., Ashwal, L.D., Trønnes,

373   R., Webb, S.J., Bull, A.L., 2014. Deep mantle structure as a reference frame for movements in

374   and on the Earth. Proc. Nat. Acad. Sci. 111, 24, 8735–8740.

375 Wang, H., Shao, L., Hao, L., Zhang, P., Glasspool, I.J., Wheeley, J.R., Wignall, P.B., Yi, T., Zhang,

376   M., Hilton, J., 2011. Sedimentology and sequence stratigraphy of the Lopingian (Late Permian)

377   coal measures in southwestern China. Int. J. Coal Geol. 85, 168-183.

378 Wardlaw, B.R., Nestell, M.K., 2010. Three Jinogondolella apparatuses from a single bed of the Bell

379   Canyon Formation in the Apache Mountains,West Texas: Micropaleo. 56, 195-212.

380 White, N. & Lovell, J.P.B., 1997. Measuring the pulse of a plume with the sedimentary record. Nature

381   387, 888-891.

382 Wignall, P.B., 2001. Large igneous provinces and mass extinctions. Earth-Sci. Rev. 53, 1–33.

383 Wignall, P.B., Sun Y-D., Bond, D.P.G., Izon, G., Newton, R.J., Védrine, S., Widdowson, M., Ali,

384   J.R., Lai X-L., Jiang H-S., Cope, H, Bottrell, S.H., 2009. Volcanism, mass extinction and

385   carbon isotope fluctuations in the Middle Permian of China. Science 324, 1179-1182.

386 Zhou M-F., Malpas, J., Song, X-Y., Robinson, P.T., Sun, M., Kennedy, A.K. Lesher, C.M., Keays,

387   R.R., 2002. A temporal link between the Emeishan large igneous province (SW China) and the

388   end-Guadalupian mass extinction. Earth Planet. Sci. Lett. 196, 113-122.

389 Zhu, B. Guo, Z., Liu, R., Liu, D., Du, W., 2014. No pre-eruptive uplift in the Emeishan large igneous

390   province: New evidences from its 'inner zone', Dali area, Southwest China. J. Volcanol.

391   Geotherm. Res. 269, 57–67.

392   Zi J.-W., Fan, W.-M., Wang, Y-J., Cawood, P.A.,Peng, T.-P. Sun, L.-H., Xu, Z.-Q., 2010. U-Pb

393   geochronology and geochemistry of the Dashibao Basalts in the Songpan-Ganzi Terrane, SW

394   China, with implications for the age of Emeishan volcanism. Amer. J. Sci. 310, 1054-1080.

395

396

397

398

399

400

401
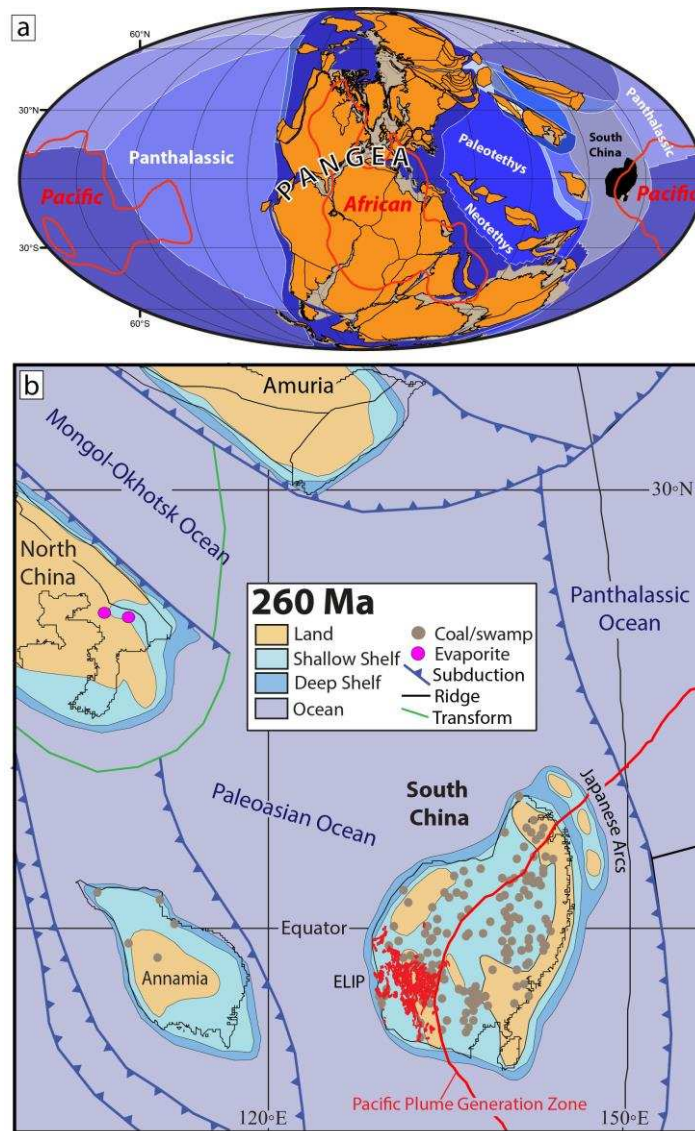
Figure 1. (a) Global palaeomagnetic plate reconstruction (Molweide projection) at 260 Ma (Domeier & Torsvik 2014). Pangea formed in the Late Carboniferous but early breakup is witnessed already in the Early Permian by opening of the Neotethys. Cimmerian terranes leaving Pangea included parts of Iran, 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.
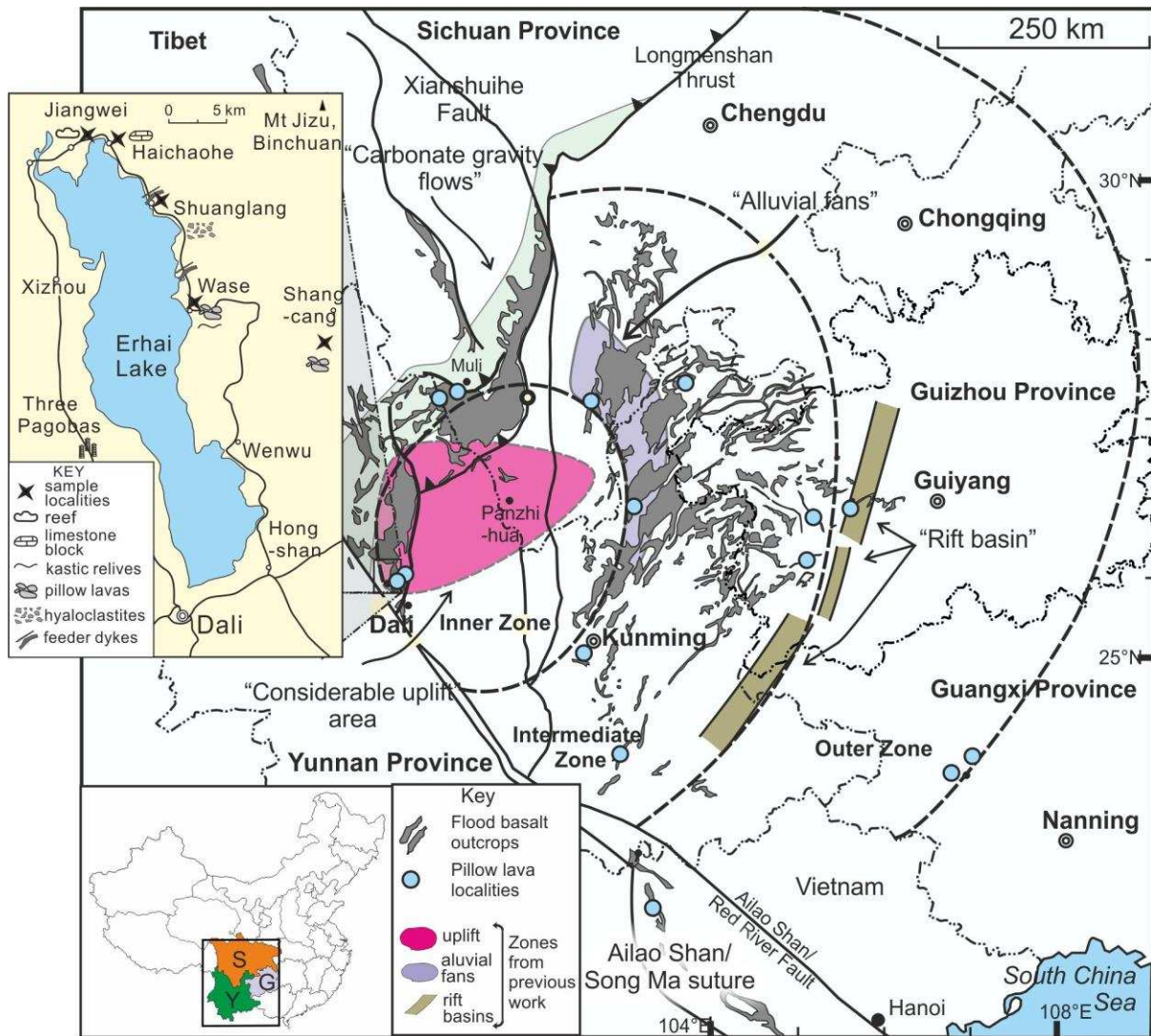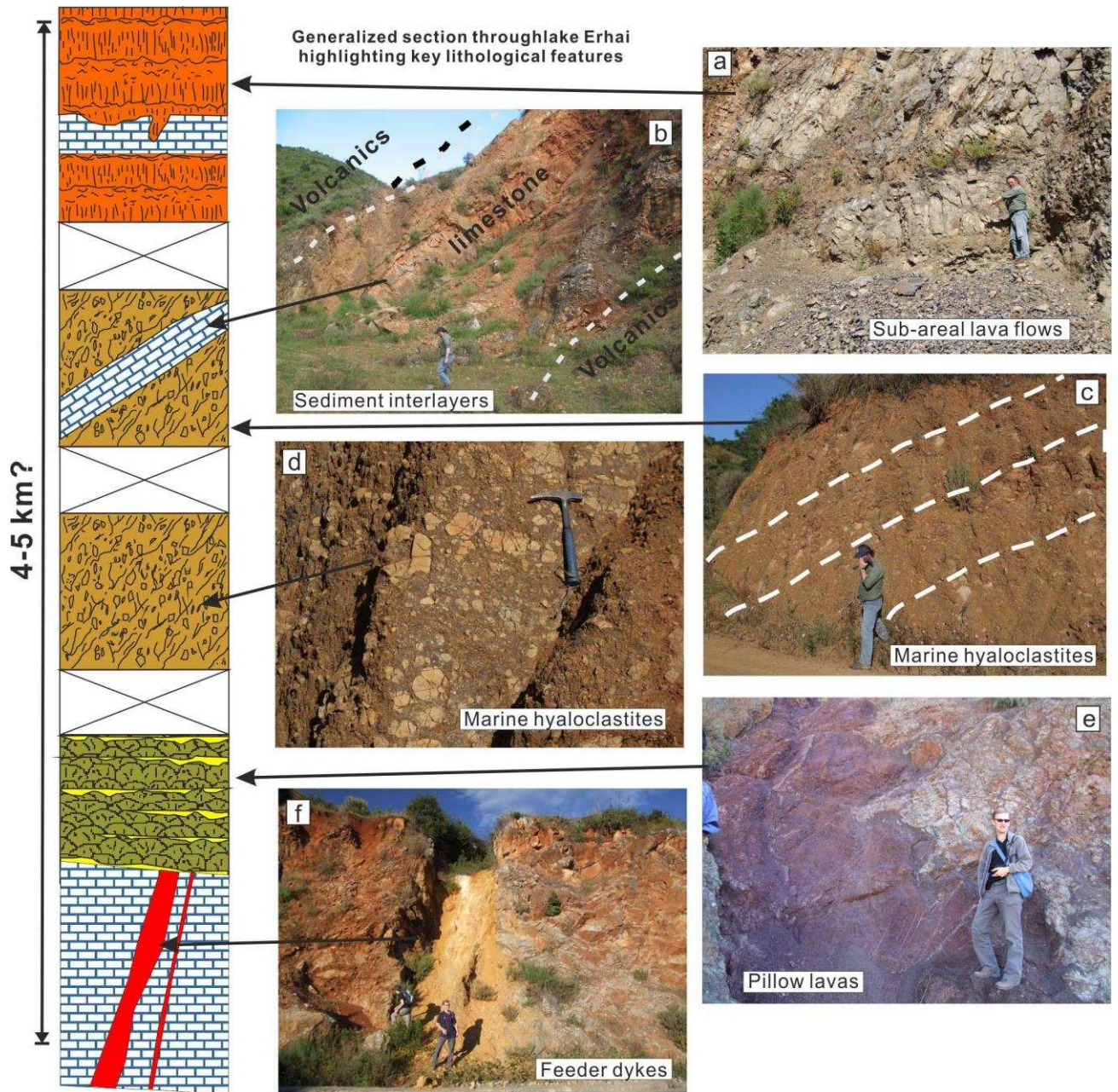
Figure 2. Distribution of Emeishan volcanic and location map of the study section found within the originally mapped 'inner zone'. On the main map, locations of pillow lavas sections are indicated as well as the original zones labelled from previous studies (adapted from He et al., 2010). Inset map shows 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.
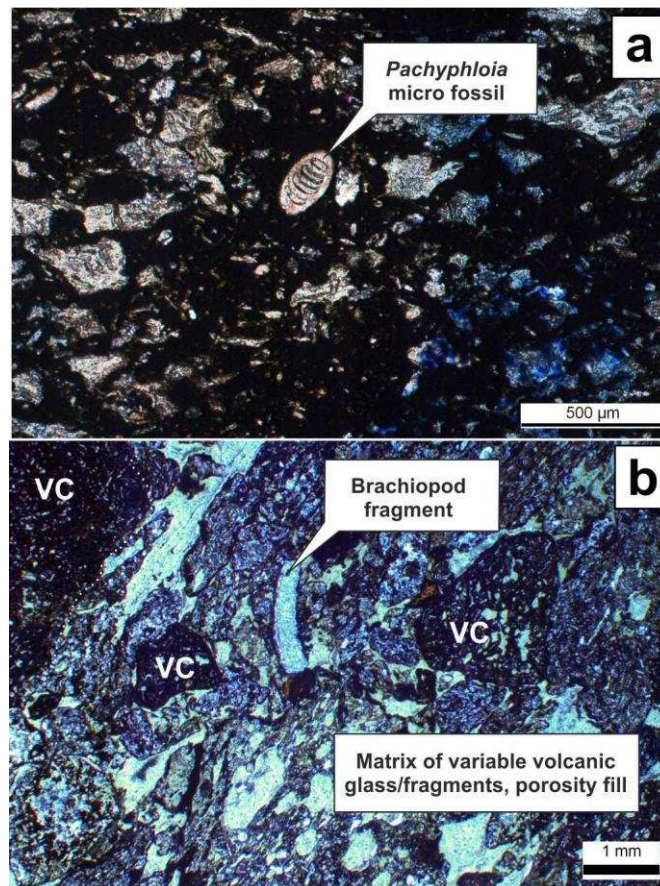
Figure 4. Evidence of marine fauna in volcaniclastics. A) Complete Pachyploia within volcanic glass and fragments. B) Brachipod shells within volcanic fragments (examples of microcrystalline volcanic clasts marked VC on photomicrograph).
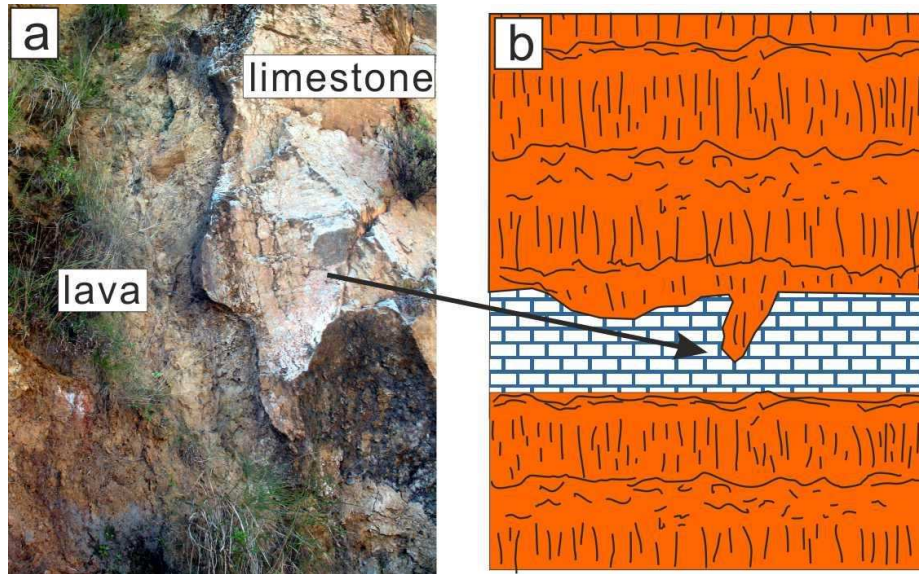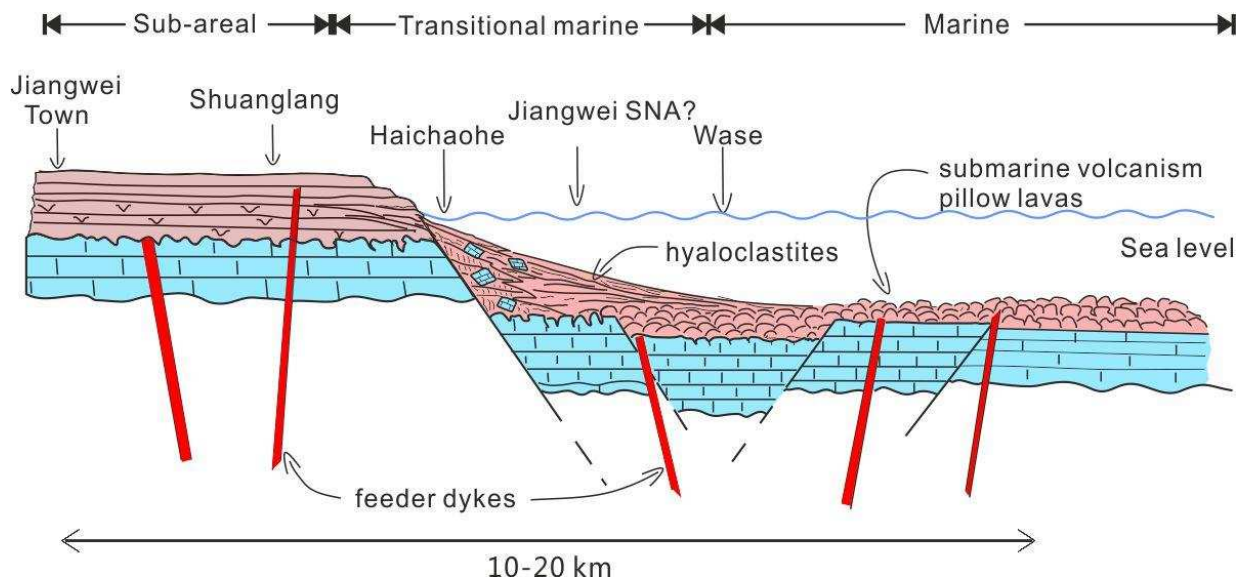
443
444
445 Figure 5. The upper volcanic section highlighting spectacular examples of lava flows into a karst topography
446   within the limestone. This indicates that the upper parts of the volcanic sequence have been erupted
447   into a subareial environment.
448

Volcanic facies distribution along Lake Erhai section

449
450
451 Figure 6. Idealized cross section through the volcanic succession along the Lake Erhai section. The onset of
452 flood volcanism in the majority of the section is characterized by submarine volcanism with pillow
453 lavas and hyaloclastites.