Discussion of

Thick and high velocity crust in the Emeishan large igneous province, SW China: Evidence for crustal growth by magmatic underplating/intraplating

by

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21st December, 2006, Hetu C. Sheth

Xu et al. write: "After having studied drainage patterns of three continental LIPs, Cox (1989) suggested topographic doming associated with plume activity can be preserved after ~200 Ma, and crustal thickening by magmatic underplating is the most likely cause for the persistence of such features. Although the work by Cox (1989) on the Deccan traps receives some criticism (Sheth, this volume), the link between underplating and persistant uplift remains valid."

One of the objectives of my paper (Sheth, this volume) was to show that major uplift in many flood basalts is significantly younger (tens of millions of years) than the flood volcanism and associated underplating. It is important to get the facts right. We are simply not seeing uplift *commencing* at or just prior to flood basalt volcanism and *persisting* for tens of hundreds of millions of years, as Cox (1989) imagined and which Xu et al. have quoted. Rather, we are seeing uplift *commencing* tens of millions of years after the flood volcanism and all underplating are over. See my paper in this volume for studies that have argued for major Neogene uplift of the Indian peninsula and western Indian rifted margin.

In this connection, Xu et al. may be interested in reading three papers (Bonow et al., 2006a,b; Japsen et al., 2006) published on West Greenland this year. These nicely complement my paper. The authors' main argument is that major *Neogene* uplift events (>2 km) raising flat planation surfaces have shaped the present topography of West Greenland, and the youngest is as young as 7-2 Ma. The flood volcanism occurred in the Palaeogene, of course. Is it really Palaeogene underplating, then, that has caused such major uplift?

It is well to acknowledge that we do not know. But keeping the facts right and looking for a solution is better practice, to my mind, than lumping every uplift event of any age whatsoever with magmatic underplating and hypothetical plume heads that simply won't die.

See also the Discussion of Sheth (this volume).

5th January 2007, Warren B. Hamilton

Many papers on the Emeishan igneous province have appeared in the Western literature in the past decade, but mostly they present only local trace elements or other details or, like this paper by Xu and He (this volume) and many others of which one or both of them are co-authors, are internally and externally inconsistent plumological conjectures. The papers have been uncritically cited by many proponents of hypothetical plumes elsewhere. Supporting data for the syntheses are cited as in the Chinese literature, where they cannot be evaluated by Western readers—but the data base obviously is weak.

My comments here express some of the frustration of a reader trying to comprehend the Emeishan. I have been in the area briefly (but have not looked at the Emeishan), and appreciate the difficulties of working in a region of deep weathering and mostly poor exposures.

The schematic regional geologic map by Xu and He (this volume, Figure 1; essentially the same as He et al., 2003, Figure 1) shows quite different distribution of basalt, and altogether different regional structure, than does the map by Lo et al. (2002, Figure 1), even though the two papers share as an author Chung, who has been senior author on a number of Emeishan papers and must have access to the published data.

[Note added 16th February 2007: after receiving this Discussion, Xu and He (see their following response) substituted a new geologic map for their initial Figure 1. My comment applies to the initial Figure 1. The new map uses the strikingly different Emeishan-basalt distribution of Lo et al. (2002, Figure. 1-B) while retaining the fault pattern of the initial Figure 1 of Xu and He (this volume). On the new figure, great regional post-Emeishan faults cross small to huge outcrops of Emeishan without offsetting them; and the purported isopachs of the Maokou Formation cross through younger major faults without being offset. Adding these new conflicts to the numerous weaknesses and inconsistencies in this and other Emeishan reports reinforces my prejudice that the geology and geophysics are too poorly known to provide support for the unique and elaborate geodynamic and crustal-evolution speculations of Xu and He (this volume) and other plumologists.]

Does a "large igneous province" of "flood basalts" exist? Correlative A- and I-type granites occur in the heart of the area (Zhong et al., 2007). The areal extent of rocks of a likely unified province is small, ~0.3 x 106 km2 (Alt et al., 2005). Preserved sections apparently are mostly thin, and the 5-km local section schematized by Lo et al. (2002, Figure 1) is of rocks (including abundant pyroclastics) suggestive to me of a volcano rather than flood basalts. (Or perhaps much of the section was shallow-submarine, and the purported great dome never existed, which I infer from other data.) What are the igneous rock types (not just their Ti/Y ratios), and do they have subregional stratigraphy? The assignment to a single age and petrographic province of basalts on all sides of the major faults (Xu and He, this volume, Figure 1) in this complex region is implausible.

The primary basis for the assertion of Xu and He (this volume) that the Emeishan basalt "is unambiguously related to a mantle plume" [i.e., it can be forced into a speculative plume model] appears to be the pre-basalt doming deduced by He et al. (2003). The latter work, alone and in comparison with Xu and He (this volume), contains so many inconsistencies that it is not at all clear that a dome exists. Thus, He et al. (2003) show the Permian limestones to be syndepositionally faulted along a regional pre-basalt fault, with a great change in thickness across the fault (their Figure 4), yet their isopachs (Figure 1) all pass undisturbed across this purported fault. They (Figure 3) define doming by zones of fusulinids (all rocks were deposited in the photic zone) in unscaled stratigraphic columns of Middle Permian limestone that show basalt as lying upon progressively older zones in the center of the dome; but their geologic map (Figure 1) shows the truncated limestone sections as mostly 20 to 50 km from the nearest outcrops of basalt. Further, most of the fusulinid identifications in the domal region are to a few genera only, not to the preferable species.

In Xu and He (this volume, Figure 5), the fault noted above has been replaced by a concordant section of, in order upward, Middle Permian limestone, Emeishan basalt, Upper Permian terrestrial and marine clastic rocks, and Lower Triassic limestone. The limestone varies little in thickness: the stratigraphic basis for the flank of the dome has disappeared. The great doming, the basis for the plume, nevertheless is still postulated; it produced no unconformity, but rose high from just below sea level immediately before the basalt was deposited, then was promptly flattened and back slightly below sea level again.

Xu and He (this volume, Figure 5) present sketches of interpretations of velocity boundaries in reconnaissance "seismic sounding" lines. However, their description of the seismic experimental details is too cursory (the details are again in a Chinese publication) for the reader to judge the quality and reliability of the results. The individual lines were interpreted quite differently, and Xu and He (this volume) rely on the differences. One line shows steep faults continuous to depths of 80 km(!), one shows a mid-crustal low-velocity zone continuous for 200 km laterally, and one shows only monotonic velocity increases. I infer the lines to have been seriously over-interpreted. The basal-crustal layer of $Vp > 7$ km/s, to which Xu and He (this volume) attribute great local plumological significance, is common in many regions. Xu and He (this volume) give the reader no basis for judging the viability of the tomography (Figure 3) which also is important to their model.

I do not share the authors' faith in chemical calculations, particularly in the absence of mineralogical data, to determine the precise sources and complex fractionation histories of the rising melts that produced the evolved rocks erupted at the surface.

I may be wrongly maligning a superb data base. If so, I urge the authors to make more of that base accessible to non-Chinese readers, and to clarify the inconsistencies between their various papers.

February 4, 2007, Yi-Gang Xu and Bin He

In our chapter we refer to the relationship between permanent uplift and underplating in LIPs. This is mentioned by Cox (1989) and other groups using numerical modeling and field geology (e.g., McKenzie, 1984, White et al., 1987; MacLennan and Lovell, 2002). The link between underplating and persistent uplift is valid.

Sheth argues (his comment of 21st December, 2006) that uplift at Deccan commencing at or just prior to flood basalt volcanism and persisting for 10s or 100s of Ma is absent. Without field experience on the Deccan traps we cannot comment, except to say that we were inspired by the approach of Cox (1989) to investigate the Emeishan LIP by relating geomorphology and deep mantle processes. Widdowson arrived at different conclusions from Sheth (Saunders et al., in press), and proposes three episodes of crustal uplift at the Deccan. Pre-volcanism uplift is most likely in the Kutch – Cambay – western Narmada region, though sedimentary evidence is equivocal. This may be due to the short-lived thermal and dynamic uplift in the north, because the northward movement of India decoupled the initial plume-head-impact site from the plume center. The pattern of uplift preserved in the sedimentary sequences surrounding the Deccan, and the distribution of lavas, are consistent with northward movement of the continent over a stationary hotspot (Saunders et al., in press). Permanent uplift occurs along the western Ghats as a result of magmatic underplating, isostatic adjustment caused by scarp recession and erosion, and deposition across the thinned continental margin (Widdowson and Cox 1996; Widdowson, 1997). It seems clear that transient and permanent uplift occured, features shared with the Emeishan case (He et al., 2003; 2006; Xu and He, this volume).

We regret that the schematic geologic map by Xu and He (this volume, Figure 1) shows a different basalt distribution of basalt from that by Lo et al. (2002). We took the distribution from a Memoir of the Chinese Geological Survey (Regional Geology of Sichuan, Yunnan and Guizhou Provinces, Geological Publishing House, Beijing). Lo et al. (2002) based their map on the PhD thesis of Huang (1986). Discrepancies might reflect mapping difficulties where erosion is intensive and volcanic sequences are tilted.

We see no problem with the occurrence of correlative A- and I-type granites in the area (Zhong et al., 2007, i.e., in the inner zone in terms of our subdivision scheme). When plume–derived basalts pond in the crust, they melt roof rocks, provided their melting temperature is sufficiently low (Campbell 2001). The resultant products vary widely in composition. Thus, the co-existence of A- and I-type granites is a consequence of plume-related melting events and has been documented at many LIPs. The exposure of granites in the inner zone is the result of intensive erosion, as demonstrated by He et al. (2003).

Basalt is not abundant on the western Yangtze craton (~0.3 x 106 km2; Xu et al., 2001), but this does not argue against “the Emeishan LIP”. The Emeishan province is remnant of deep erosion, also disrupted tectonically (Courtillot et al., 1999; Xu et al., 2004; He et al., 2006). Tectonic disruption accounts for the late Permian mafic-ultramafic bodies in SE Yunnan (Xiao et al., 2003) and northern Vietnam (Hanski et al., 2004). Coeval late Permian mafic magmatism also occurs in Guangxi province and Songpan-Ganze region (see also Zhou et al., 2006; Xiao et al., 2005), suggesting a much larger exposure of the original basalts.

The absence of basalts in the uplifted area (i.e., the inner zone) is due to enhanced erosion in the uplifted area. Nevertheless, lava section thicknesses in the inner zone are 1 - 5 km (Xu et al., 2004), with most sections > 2 km thick. The volcanic succession comprises predominantly basaltic flows and subordinate pyroclastics (Ross et al., 2005), a feature most evident in the Yongsheng section.

A wide range of rocks occur in the province, including picrite, basalts (tholeiitic and alkali), basaltic andesites, hawaiites, mugearite to benmoreite, phonolite and rhyolite. Because Ti/Y is an effective petrogenetic indicator (Peate et al., 1992; Xu et al., 2001) and helps decipher the thermal structure of the postulated mantle plume (Xu et al., 2004), a chemical classification of rock type is adopted. Although low-Ti and high-Ti lavas do not necessarily correspond to specific rock types, most low-Ti lavas are tholeiitic and basaltic andesite, while most high-Ti lavas are transitional. The temporal and spatial relation between low- and high-Ti basalts (see Xu et al., 2001; 2004; Xiao et al., 2004b) reveals the stratigraphy. Over 350 analyses throughout 10 entire sections provide an excellent geochemical dataset.

Our age assessment does not rely on one age, but from stratigraphic correlation, Ar-Ar dating on basalts, and zircon U-Pb dating on mafic intrusions, alkaline rocks, and silic ignimbrite (Zhou et al., 2002, 2005; Zhong et al., 2006, 2007; He et al. (2007).

Isopachs (Figure 1) are from interpolating the thicknesses of 67 sections of the Maokou Formation. The possible influence of long-term faulting (active from Late Permian to present) was not included. Indeed, it is difficult to determine the exact location of the faults of a zone tens of kilometres wide, because a limited number of stratigraphic columns were investigated and the basalts and underlying strata are strongly tilted. Thus the isopachs are shown undisturbed across the purported fault, though they do reflect a syn-doming fault, across which the Maokou Formation thickens from ~50 m to >300 m. Stratigraphic columns (except section A) of Middle Permian limestone are scaled in Figure 3, with the thickness of the Maokou Formation marked at lower left in every section. The Maokou limestone in the Inner zone is incomplete due to erosion and thermally-drived metamorphism, and as a result only a few fusilinids have been found in the domal region.

We emphasize that all the basalts overlie the Maokou Formation (Fig. 3 in He et al., 2003). Hamilton’s comment that limestone sections in Fig. 1 (He et al. 2003) are separated from the nearest basalt outcrops by 20-50 km is incorrect. Some outcrops of basalts are simply too small to be clear on the map.

Figure 5 shows changes in sedimentation and paleogeography before and after volcanism, so faults were not included. It is clear that the fault lies between the Chuandian old land (i.e., the center of the LIP) and the east of the LIP. Only in the east does a concordant section occur, of (in upward order) Middle Permian limestone, Emeishan basalt, Upper Permian terrestrial and marine clastic rocks, and Lower Triassic limestone. Two unconformities occur between the Maokou limestone and Emeishan basalts, and between basalts and Upper clastic rocks (He et al., 2003). The unconformities are distinct in the inner zone, where the Maokou limestone is variably thinned and capped by Triassic sediments. Figure 5 shows clearly that the center of the Emeishan LIP was domally uplifted during the Late Permian to Triassic (He et al., 2006).

Hamilton is correct that that the basal-crustal layer of Vp > 7 km/s is common and widespread. Such a high-velocity structure can be explained by different mechanisms. Hamilton ignores the reasoning we used to develop the plume-related model. We reiterate: The seismically anomalous bodies at different levels are all distributed within the inner zone of the Emeishan LIP, e.g., high-velocity upper crust is absent in the intermediate and outer zones. The western and eastern margins of this seismically anomalous body correspond to longitudes 100.8°E and 102.8°E, agreeing well with the location of the inner zone (Xu et al., 2004). These observations indicate a common factor governing the formation of these seismically anomalous bodies and crustal doming.

As petrologist/geologists we cannot assess the quality of the tomography (Figure 3) and the experimental results. Figure 5 compiles velocity data from different groups, and over-interpretation might have occurred. In our chapter, we focused on the DDP results and velocity structure, not the fault penetration depths. We were encouraged by the first-order features of these geophysical data, since different approaches showed similar crust-mantle structure (e.g., thick and high velocity in the inner zone). Also, the crust-mantle structure inferred from velocity profiles correlates with domal structure inferred from sedimentary records. We believe this correlation is not just a coincidence.

Two independent data types constrain the genesis of the HVLC; the crust-mantle structure in the Emeishan LIP varies systematically with the domal structure, and the petrologic calculations. We accord equal importance to these two arguments. The latter approach has been widely employed and thermodynamic modeling of magmatic fractionation at variable P-T conditions is well-established (Ghioso and Sack, 1995). This approach has been justified by Farnetani et al. (1996), MacLennan et al. (2001) and Trumbull et al. (2002).

References

Ali, J.R., Thompson, G.M., Zhou, M.F. and Song, X.Y., 2004. Emeishan Basalts Ar-Ar overprint ages define several tectonic events that affected the western Yangtze Platform in the Meso- and Cenozoic. Journal of Asian Earth Sciences, v. 23, pp. 163-178.

Alt, J.R., Thompson, G.M., Zhou, M.-F., and Song, X., 2005, Emeishan large igneous province, SW China: Lithos, v. 79, p. 475-489.

Bonow, J. M., Japsen, P., and Lidmar-Bergstrom, K., 2006a, Palaeosurfaces in central West Greenland as reference for identification of tectonic movements and estimation of erosion: Global and Planetary Change, v. 50, p. 161-183.

Bonow, J. M., Japsen, P., Lidmar-Bergstrom, K., Chalmers, J. A., and Pedersen, A. K., 2006b, Cenozoic uplift of Nuusuuaq and Disko, West Greenland – elevated erosion surfaces as uplift markers of a passive margin: Geomorphology, v. 80, p. 325-337.

Boven, A., Pasteels, P., Punzalan, L.E., Liu, J., Luo, X., Zhang, W., Guo, Z. and Hertogen, J., 2002. 40Ar/39Ar geochronological constraints on the age and evolution of Permo-Triassic Emeishan volcanic province, Southwest China, Journal of Asian Earth sciences, v. 20, pp. 157–175.

Campbell, I.H., 2001. Identification of ancient mantle plumes. In: Ernst R.E. and Buchan, ed., Mantle plumes: their identification through time. Geological Society of America Special Papers, v. 352, pp. 5-22.

Courtillot, V.E., Jaupart, C., Manighetti, I., Tapponnier, P., and Besse, J., 1999. On causal links between flood basalts and continental breakup, Earth Planet. Sci. Lett. 166: 177-195.

Farnetani, C.G., Richards, M.A., Ghiorso, M.S., 1996. Petrological models of magma evolution and deep crustal structure beneath hotspots and flood basalts. Earth Planet. Sci. Lett., 143: 81-94.

Ghioso, M.S., and Sack, R.O., 1995. Chemical mass transfer in magmatic processes, IV. A revised and internally consistent thermodynamic model for the interpretation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressure. Contrib. Mineral. Petrol., 119: 197-212

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W. and Lourens, L.J., 2004. A new geologic time scale, with special reference to Precambrian and Neogene. Episodes 27, 83-100.

Hanski, E., Walker, R.J., Huhma, H., Polyakov, G.V., Balykin, Hoa T.T., and Phuong, N.T., 2004. Origin of the Permian-Triassic komatiites, northwestern Vietnam. Contrib. Mineral. Petrol. 147: 453-469

He B., YG Xu, Ya-Mei Wang, Zhen Yu Luo, 2006, Sedimentation and lithofacies paleogeography in SW China before and after the Emeishan flood volcanism: New insights into surface response to mantle plume activity. Journal of Geology 114: 117-132.

He, B., Xu, Y.-G., Chung, S.-L., Xiao, L., and Wang, Y., 2003, Sedimentary evidence for a rapid, kilometer-scale crustal doming prior to the eruption of the Emeishan flood basalts: Earth and Planetary Science Letters, v. 213, p. 391-405.

He B., Yi-Gang Xu, Xiao-Long Huang, et al., 2007, Age and duration of the Emeishan flood volcanism, SW China: Geochemistry and SHRIMP zircon U-Pb dating of silicic ignimbrites, post-volcanic Xuanwei Formation and clay tuff at the Chaotian section. Earth Planet. Sci. Lett. (in press)

Huang, K.N., 1986, The petrological and geochemical characteristics of the Emeishan basalts from SW China and the tectonic setting of their formation (Ph.D. thesis). Institute of Geology, Academy Sinica (in Chinese).

Isozaki, Y., Yao, J.X., Matsuda, T., Sakai, H., Ji, Z.S., Shimizu, N., Kobayashi, N., Kawahata, H., Nishi, H., Takano, M., Kubo, T., 2004. Stratigraphy of the Middle-Upper Permian and Lower Triassic at Chaotian, Sichuan, China. Proceeding of Japan Academy, v. 80, ser. B, pp. 10-16.

Japsen, P., Bonow, J. M., Green, P. F., Chalmers, J. A., and Lidmar-Bergstrom, K., 2006, Elevated, passive continental margins: Long-term highs or Neogene uplifts? New evidence from West Greenland: Earth and Planetary Science Letters, v. 248, p. 330-339.

Lo, C.-H., Chung, S.-L., Lee, T.-Yi, and Wu, G., 2002, Age of the Emeishan flood magmatism and relations to Permian-Triassic boundary events: Earth and Planetary Science Letters, v. 198, p. 449-458.

MacLennan, J., McKenzie, D., Gronvold, K. and Slater, L., 2001. Crustal accretion under northern Iceland. Earth Planet Sci Lett., 191: 295-310

MacLennan, J., Lovell, B. 2002. Control of regional sea level by surface uplift and subsidence caused by magmatic underplating of Earth's crust. Geology. 30_675-678.

McKenzie, D. 1984. A possible mechanism for epeirogenic uplift. Nature. 307(16) 616-618

Peate, D.W., Hawkesworth, C.J. and Mantovani, M.S.M., 1992. Chemical stratigraphy of the Parana lavas (south America): classification of magma-types and their spatial distribution. Bull. Volcanol., 55: 119-139.

Ross P.-S., I. Ukstins Peate, M.K. McClintock, Y.G. Xu, I.P. Skilling, J.D.L. White and B.F. Houghton, 2005, Mafic volcaniclastic deposits in flood basalt provinces: A review. J Vol. Geotherm Res. 145: 281-314.

Saunders A.D., S.M. Jones, L.A. Morgan, K.L. Pierce, M. Widdowson, Y.G. Xu, 2006. The role of mantle plumes in the formation of continental LIPs: field evidence used to constrain the effects of regional uplift. Chemical Geology, in press

Tan, T.K., 1987. Geodynamics and tectonic evolution of the Panxi rift. Tectonophysics, 133: 287-304.

Trumbull, R.B., Sobolev, S.V., and Bauer, K. 2002. Petrophysical modeling of high seismic velocity crust at the Namibian volcanic margin. In "Volcanic Rifted Margins", M.A. Menzies, S.L., Klemperer, C.J. Ebinger, J. Baker, eds., Geological Society of America Special Paper, 362, 225-234.

White, R.S., Spence G.D., Fowler S.R., McKenzie D.P., Westbrook G.K., Bowen A.N. 1987. Magmatism at rifted continental margins. Nature. 330, 439-444.

Widdowson, M., 1997. Tertiary palaeosurfaces of the SW Deccan, Western India: implications for passive margin uplift. In: Widdowson, M. (Ed.), Palaeosurfaces: Recognition, Reconstruction and Palaeoenvironmental Interpretation. Geological Society of London Special Publication 120, 221-248.

Widdowson, M. and Cox, K. G., 1996. Uplift and erosional history of the Deccan Traps, India: Evidence from laterites and drainage patterns of the Western Ghats and Konkan Coast. Earth and Planetary Science Letters 137, 57-69.

Xiao, L., Xu, Y.-G., Chung, S.-L., B. He, and Mei, H.J., Chemostratigraphic Correlation of Upper Permian Lava Succession from Yunnan Provinc, China: Extent of the Emeishan LIP. International Geologic Review, 45: 753-766

Xiao L., Xu Y-G, Xu J-F, Bin He, Pirajno F. 2004a Chemostratigraphy of flood basalts in the Garze-Litang Region and Zangza Block: implications for western extersion of the Emeishan LIP, SW China. Acta Geologica Sinica, 78: 61-67

Xiao L., Y.G. Xu, H.J. Mei, Y.F. Zheng, B. He and Franco Pirajno, 2004b. Distinct mantle sources of low-Ti and high-Ti basalts from the western Emeishan LIP, SW China: implications for plume–lithosphere interaction. Earth and Planetary Science Letters 228: 525-546

Xu, Y.G., Chung, S.L., Jahn, B.M., Wu, G.Y., 2001. Petrologic and geochemical constraints on the petrogenesis of Permian–Triassic Emeishan flood basalts in SW China. Lithos 58, 145–168.

Xu, Y.-G., He, B., Chung, S.L., Menzies, M.A. and Frey, F.A., 2004. The geologic, geochemical and geophysical consequences of plume involvement in the Emeishan flood basalt province. Geology, v. 30, pp. 917-920.

Zhong H., Zhu W-G., 2006, Geochronology of layered mafic intrusions from the Pan–Xi area in the Emeishan LIP, SW China, Miner Deposita 41, 599–606

Zhong H., Zhu W-G., et al., 2007, Shrimp U–Pb zircon geochronology, geochemistry, and Nd-Sr isotopic study of contrasting granites in the Emeishan LIP, SW China, Chem. Geol. 236, 112-133.

Zhou M.F., Malpas J., et al., 2002, A temporal link between the Emeishan LIP (SW China) and the end-Guadalupian mass extinction. Earth Planet. Sci. Lett. 196, 113-122.

Zhou M.F., Robinson P.T., et al., 2005, Geochemistry, petrogenesis, and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe-Ti-V-oxide deposits, Sichuan Province, SW China, Journal of Petrology 46, 2253-2280.

Zhou M.-F., Zhao J.-H., et al., 2006, Zircon U-Pb geochronology and elemental and Sr -Nd isotopic geochemistry of Permian mafic rocks in the Funing area, SW China, Contributions to Mineralogy and Petrology 151 1-19.