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Spatial distribution of seismic layer, crustal thickness, and Vp/Vs ratio in the Permian Emeishan Mantle Plume region

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ABSTRACT

Seismological studies of lithospheric structure and rheology can provide important information regarding the lithosphere's interaction with the mantle plume and its successive deformation characterization. The Emeishan Large Igneous Province (ELIP) in eastern Tibet was probably produced by a Late Permian Emeishan mantle plume and experienced tectonically driven modifications during Mesozoic–Cenozoic, such as the eastward subduction of the Indian Ocean plate and roughly north-southward tectonic escape or middle crustal flow. The crustal responses to the Emeishan mantle plume and its modification from successive tectonic activities are still unclear. Here, we present the lithosphere rheology structure derived from seismic activity and the spatial distribution of seismic energy release, which records the lithospheric deformation from the Late Permian mantle plume activity and the Mesozoic–Cenozoic modifications. In addition, we estimate the crustal thickness and the average crustal Vp/Vs ratio from wide-angle seismic profiling and receiver function imaging. Our results demonstrate that the seismogenic layer thins away from the proposed center of the Emeishan mantle plume. The layer is approximately 24 km in depth beneath the center of the Emeishan mantle plume and approximately 10 km in depth beneath the margin of the plume, with corresponding crustal thinning and spatial variations of the average crustal Vp/Vs ratio. Distinctive patterns among crustal thickness, seismogenic layer and the average crustal Vp/Vs ratio are observed both east and west of the Xiao Jiang Fault (XJF). These remarkable features are interpreted to result from the modification of the Late Permian mantle plume, probably by tectonic escape in the west of the XJF and by a north-southward middle crustal flow in the east of the XJF.

1. Introduction

The hypothesis of the mantle plume was proposed by geophysicist W. Jason Morgan in 1971 and has been evaluated by laboratory experiments (Whitehead and Luther, 1975), seismology (Zhao, 2004, 2007; Zhao, 2009), geochemistry (Roy et al., 2002; Xu et al., 2004, 2007; Ernst, 2006; Cheng and Kusky, 2007; Wang et al., 2009; Chen et al., 2011; Su et al., 2011; Yu et al., 2011) and dynamical modeling (Yuen et al., 1993). A mantle plume is an upwelling of abnormally hot rock within the Earth's mantle. As the tops/heads of mantle plumes can partially melt when they reach shallow depths and pressure is reduced, they are thought to be the cause of volcanic centers, known as hotspots, and are the probable cause of flood basalts, which have catastrophic effects once the magma spills out onto the crust.

In the last 20 years, increasingly more evidence for lower-mantle plumes has been found with seismic tomography studies (Goes et al., 1999; Li et al., 2000; Zhao, 2001; Rhodes and Davies, 2001; Romanowicz and Gung, 2002; Ritsema and Allen, 2003; Montelli et al., 2004, 2006; Lei and Zhao, 2006; Zhao, 2009). When the top of a mantle plume meets the base of the lithosphere, it is expected to flatten out against this barrier, uplift the lithosphere bottom and undergo widespread decompression melting to form large volumes of basalt magma. Thus, the activity of a mantle plume should be imprinted in the lithosphere structure. However, the crustal responses to the mantle plume and its modification from successive tectonic activities are still unclear. The Emeishan mantle plume (featured in the Emeishan Large Igneous Province — ELIP) is a unique place to study this phenomenon.

The ELIP is the only verified Large Igneous Province (LIP) in China. The Late Permian Emeishan continental flood basalts in southwestern China form a major part of the ELIP, which covers an area of 250,000 km^2 (Xu et al., 2001) from the eastern margin of the Tibetan Plateau to the western margin of the Yangtze block (Fig. 1). The Emeishan basalts in southwest China have attracted the attention of the scientific community in recent years because of their possible synchrony with the eruption of the Siberian traps and thus their possible relationship with the mass extinctions during the Late Permian (Chung and Jahn, 1995; Chung et al., 1998; Xu et al., 2001; Ali et al., 2002; Lo et al., 2002; Zhou et al., 2002; Courtillot and Renne, 2003; Wignall et al., 2009).

Chung and Jahn (1995) used the mantle plume model to explain the eruption of the Emeishan flood basalts in China. More research on a rigorous evaluation of the role of mantle plumes in the

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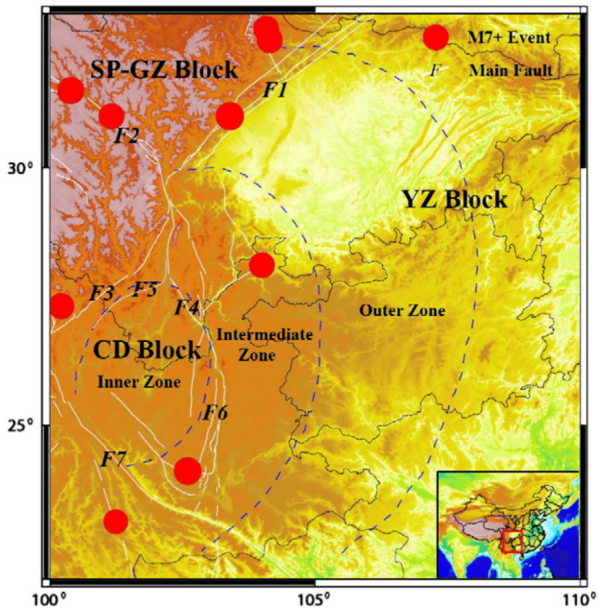

Fig. 1. ELIP distribution with geology, topography, earthquakes, and faults: *F1* Longmenshan Fault; *F2* Xianshui River Fault; *F3* Lijiang Fault; *F4* Zemuhe Fault; *F5* Jinhe Fault; *F6* Xiao Jiang Fault; *F7* Ailao Shan–Red River Fault. SP–GZ Block: Songpan–Ganzi Block; CD Block: Chuan Dian Block; YZ Block: Yangtze Block. Inner Zone, Intermediate Zone, and Outer Zone: the spatial distribution of the ELIP, separated by the blue curve. Inset: the red square is the location of the ELIP in China.

generation of this large igneous province has become available in the last 10 years (He et al., 2003; Xu et al., 2004; Zhang et al., 2006). A recent review of the Late Permian ELIP shows that 7 out of the 9 most convincing arguments in support of mantle plumes are found in the ELIP (Xu et al., 2007). In particular, sedimentology data show unequivocal evidence for a lithospheric doming event prior to the Emeishan volcanism. In addition, the presence of high-temperature magmas, the emplacement of an immense volume of magmas over a short time span, and spatial variation in the basalt geochemistry are all consistent with predictions of plume modeling. These observations strongly support the validity of the Late-Permian mantle plume hypothesis (Xu et al., 2007).

Seismic investigations can trace mantle plumes in modern, active hotspots, but are of limited benefit in identifying ancient plumes, mainly because geophysics provides us with a present snapshot of the structure of the Earth superposed on a long evolutionary history. The present structure of the Earth, as described by geophysics, can provide hints on whether the ancient plumes experienced any kind of tectonically driven modifications.

The Late-Permian mantle plume beneath ELIP experienced multi-phased large-scale deformation from tectonic activities, such as the Indian oceanic plate eastward subduction (Wang and Gang, 2004; Lei et al., 2009) and/or tectonic escape (Molnar and Tapponnier, 1975; Yin and Harrison, 2000) or crustal flow (Clark and Royden, 2000; Zhang et al., 2009b; Bai et al., 2010a). These events would be expected to be recorded in elevated heat flow and the consequent attenuated brittle behavior of the lithosphere, i.e., the lower level of seismic energy release and the shallower focal depth of seismic events (Panza and Raykova, 2008; Zhang et al., submitted for publication). Tremendously deep geophysical experiments in last 30 years in the research area (mainly initiated with earthquake monitoring, Deng et al., 2011) have provided an excellent opportunity to understand the lithospheric response to mantle plume activity and its subsequent deformation. In this paper, we combine the lithospheric structure derived from deep seismic sounding (Cui et al., 1987; Xiong et al., 1993; Zhang et al., 2007; Deng et al., 2011) and receiver function imaging (Hu et al., 2003; Zhang et al., 2009a) with the distribution versus depth of earthquakes to assess the brittle properties of the highly sensitive Earth. A synoptic representation of the mechanical properties of the uppermost 60 km is provided, along with the seismicity, averaged over cells 1° by 1° in size. According to the rheology and structure of the lithosphere under southwest China, we investigate whether the lithosphere's structure with ancient plume activity was maintained under the ELIP. If the structure was maintained, it would mean that the lithosphere's structure was not superposed with prominent tectonically driven modification occurring since the formation of the ELIP, whereas if it was not maintained, then we need to determine what occurred with the ancient plume after the formation of the ELIP in the Late Permian. Our results show a systematic lateral variation of the seismic layer (brittle layer) from the inner to outer zones of the proposed Late Permian mantle plume (He et al., 2003; Xu et al., 2004). Our observed lateral/azimuthal variations of crustal thickness, the average crustal Vp/Vs ratio and the seismic layer thickness contradict the expected characteristics from a classic mantle plume. We attribute the discrepancy between the observed and the expected to the lithosphere enduring successive tectonic activities: the eastward Indian Ocean plate subduction and the nearly north-southward middle crustal flow or tectonic escape. The paper is structured as follows: first, a brief description of the tectonic setting is provided; then, the seismic rheology and lithosphere structure is presented; and finally, the lateral/azimuthal variations of crustal thickness, the average crustal Vp/Vs ratio, seismic layer thickness, and the corresponding tectonic implications are discussed.

2. Tectonic setting

The ELIP is located at the southwest of the Chinese continent. Fig. 1 shows the tectonic framework and spatial distribution of the topography and earthquake epicenters with magnitudes of $Ms \geq 7.0$ since 1970 in the ELIP region. The ELIP is displayed as three subzones (named the inner, intermediate and outer zones by Xu et al., 2004) that are circular or semi-circular in shape corresponding to the convergence belt of the three main sub-blocks, which are the SP–GZ (Songpan–Ganzi) block, the Yangtze block, and the CD (Chuan Dian) block. The Late Permian Emeishan basalts are erosional remnants of the voluminous mafic volcanic successions that occurred in the western margin of the Yangtze Craton, SW China. These successions are exposed in a rhombic area of 250 000 km^2 (Xu et al., 2001) bounded by the Longmenshan thrust fault in the northeast and the Ailao Shan Red River (ASRR) slip fault in the southwest (Fig. 1). The tectonic setting of the study area is highly complex, with the distribution of seven main faults concentrated in the west of the ELIP. The ELIP is one of the most active areas of earthquake activity in China, and nine strong earthquakes ($Ms \geq 7.0$) have occurred since 1970, including the disastrous Mw 7.9 Wenchuan Earthquake (May 12, 2008) on the Longmenshan Fault, which result in an enormous loss of life and property.

The Late Permian Emeishan mantle plume model is proposed initially from unambiguous evidence for a rapid crustal doming prior to the Emeishan flood volcanism (258–254 Ma) in southwest China (He et al., 2003). From the middle Permian–late Permian sedimentology and geochemistry of the volcanic successions (Xu et al., 2004), He et al. (2003) claimed a lithospheric uplift prior to the Emeishan volcanism, which was responsible for (1) the rapid sea-level fall recorded by a regression at the boundary between the middle Permian and upper Permian rocks in the western Yangtze craton and (2) the generation of clastic deposits surrounding the apex of the domal structure during the Permian. They divided the domal structure associated with the Emeishan Large igneous province into inner, intermediate and outer zones regarding the extent of erosion of the Maokou Formation. The boundary between the inner and the intermediate zones is the XJF (*F6* in Fig. 1) to the east, the Zemuhe Fault (*F4*) to the northeast, and the Jinhe Fault (*F5*) to the northwest. These faults controlled the rapid deposition of clastic deposits in canyons and on alluvial fans. The extent of erosion is most apparent (at