Lithos 204 (2014) 4–13

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

# Mantle origin of the Emeishan large igneous province (South China) from the analysis of residual gravity anomalies

Yangfan Deng [a,b,*], Zhongjie Zhang [b], Walter Mooney [c], José Badal [d], Weiming Fan [a], Qiu Zhong [e]

[a] Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[c] U.S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025, USA
[d] Physics of the Earth, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain
[e] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

*Article history:*
Received 5 June 2013
Accepted 10 February 2014
Available online 20 February 2014

*Keywords:*
Stripping
Residual gravity anomaly
Density anomaly model
Mantle plume
Emeishan igneous province
South China

ABSTRACT

Despite numerous geologic and geochemical studies conducted on the Emeishan Large Igneous Province (LIP) in SW China, the deep origin of this LIP is still poorly constrained. Here we investigate the residual gravity anomaly in South China, and its relationship to the Emeishan LIP, in conjunction with deep seismic sounding profiles, deep seismic reflection surveys and a variety of broadband seismic observations performed in South China during the past few decades. Our analysis includes the removal of related gravitational effects due to: (1) the sediments, (2) the crystalline basement, undulations of (3) the upper crust, (4) the Moho and (5) the mantle lid. The resultant residual gravity anomaly in the Emeishan LIP and surrounding region reaches a maximum value of +150 mGal and decreases gradually with distance from this inner zone. With the conjugate gradient method, we develop a lithospheric model consisting of a cylindrical-shaped positive density anomaly that provides a good fit to the observed residual gravity anomaly. The inverted density anomaly of the Emeishan LIP is +0.06 g/cm$^3$ in the inner zone and decreases to about +0.03 g/cm$^3$ in the outer zone. The observed positive residual gravity and the corresponding high density can be attributed to mafic/ultramafic rocks and cooled surrounding rocks generated by large scale magmatic intrusion. Hence, taking account of the Permian Emeishan LIP, our residual gravity and density model provide evidence for the formation by an upwelling of a mantle plume.



## 1. Introduction

A mantle plume is the ascent of hot buoyant material toward the Earth's surface or the base of the lithosphere (Griffiths and Campbell, 1991; Larson, 1991; Leng and Zhong, 2010). As the top/head of a mantle plume can partially melt when it reaches shallow depths and pressure is reduced, they are thought to be the cause of volcanic centers and flood basalts (Campbell and Griffiths, 1990; Coffin and Eldholm, 1994; Morgan, 1971; White and McKenzie, 1989; Zhao, 2001). The plume hypothesis has been widely adopted to explain the formation of age-progressive volcanic chain hotspots such as Hawaii and Large Igneous Provinces (LIPs) in both oceanic and continental settings (Campbell and Griffiths, 1990; Coffin and Eldholm, 1994; Morgan, 1971; White and McKenzie, 1989; Xu et al., 2004, 2007; Zhao, 2001, 2007; Zhong and Watts, 2002).

The Late Permian basalts of the Emeishan LIP are erosional remnants of mafic rock from a series of voluminous volcanic eruptions that occurred in the western margin of the Yangtze Craton (Xu et al., 2004, 2007). Previous studies have documented that the main phase of the flood basalt volcanism occurred at the Middle-to-Late Permian boundary that is estimated at 260 Ma (Gradstein et al., 2012). The total age span of the Emeishan basalts has been estimated to be in the range of 251–263 Ma (Xu et al., 2007), but more recent chronological studies suggest that the Emeishan volcanics were emplaced during a very short period (<2 m.y.) at ~259 Ma (Shellnutt et al., 2012; Zhong et al., submitted for publication).

The Emeishan LIP lies within a rhombus-shaped area of 250,000 km$^2$ bounded by the Longmenshan fault to the northwest and the Red River fault to the southwest (Xu et al., 2001). In recent years, the Emeishan LIP has attracted the attention of the scientific community because of its possible synchrony with the eruption of the end-Permian mass extinction (Ali et al., 2002; Chung and Jahn, 1995; Chung et al., 1998; Lo et al., 2002; Shellnutt, 2013; Wignall et al., 2009; Wu and Zhang, 2012).

A recent review shows that there are seven convincing arguments in support of a Permian mantle plume origin for the Emeishan LIP, namely: (1) pre-volcanic crustal uplift, (2) high-temperature magmas, (3) thermal zoning structure, (4) geochemistry, (5) duration of volcanism, (6) extent and volume of volcanism, (7) physical volcanology (Xu et al., 2007). From the sedimentological and paleogeographic data, the

* Corresponding author at: State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.
*E-mail address:* dengyangfan@mail.iggcas.ac.cn (Y. Deng).

http://dx.doi.org/10.1016/j.lithos.2014.02.008
0024-4937/

dome-shaped structure associated with the Emeishan LIP can be divided into three zones, the inner, middle and outer zones, according to the extent of erosion of the Maokou Formation composed of Mid–Late Permian carbonates (He et al., 2003; Xu et al., 2004) (Fig. 1). The boundary between the inner and middle zones is the Xiaojiang fault to the east (labeled F7 in Fig. 1). The extent of erosion is the most apparent in the inner zone that is proposed to be the site of a rising plume head (He et al., 2003).

Many geological and geochemical studies have been conducted on the Emeishan LIP, but the deep origin is still poorly constrained. Globally, there has been an increasing body of evidence for the existence of deep mantle plumes, particularly on the basis of the results supplied by seismic tomography (Goes et al., 1999; Lei and Zhao, 2006; Lü et al., 2013; Montelli et al., 2004, 2006; Rhodes and Davies, 2001; Ritsema and Allen, 2003; Romanowicz and Gung, 2002; Zhao, 2001). In this paper we assess the mantle plume model for the Emeishan LIP based on a detailed modeling of gravity data, because neither the seismic P-wave nor S-wave velocities by themselves provide sufficient information about the density structure of the lithosphere (Mooney and Kaban, 2010). The cratonic roots, which show positive S-wave velocities, offer a clear example of the ambiguity of the seismic models for determining lithospheric density. These cratonic roots present near-zero density anomalies because their low temperatures (which increase density) are compensated by the low Fe composition of the root. Thus, gravity data provide valuable constraints on the physical state of the lithosphere that are complementary to the seismic data, and may shed more light on geodynamic processes in the region. For example, density variations in the lithosphere and sublithospheric mantle play an important role in controlling the surface elevation.

Measured Bouguer gravity is a summation of all density anomalies within the lithosphere including the density difference to the reference model within the layers and the undulation of intra-crustal and sub-crustal layers (Fig. 2) (Q.S. Wang et al., 2003; Zeng, 2005). In this paper we investigate the residual gravity of the Emeishan LIP through a process of gravity-stripping that consists of the systematic calculation of 3D corrections to the observed Bouguer gravity. We obtain the residual gravity by removing the effects caused by the sediments, crystalline basement and the undulation of the lithospheric layers as inferred from deep seismic sounding profiles, deep seismic reflection surveys, and a variety of broadband seismic observations (Bai et al., 2011; Deng et al., 2011; Hu et al., 2003; Li et al., 2006; C.Y. Wang et al., 2003; Xiong et al., 2009; Zhang et al., 2009, 2010). The consequent residual gravity mainly reflects the compositional density anomaly (the circles in Fig. 2) of the lithosphere beneath the study area, which in turn is correlated with the geological evolution of the Emeishan LIP.

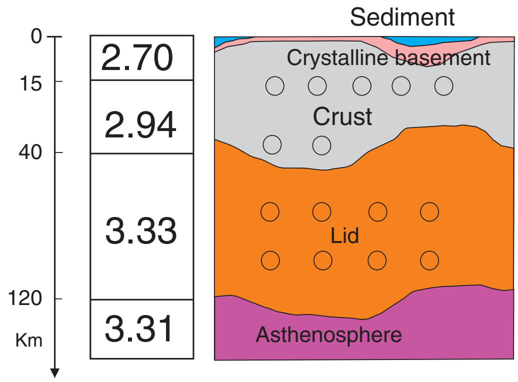


**Fig. 2.** Left: the reference lithospheric/asthenospheric structure described in terms of the respective depths and densities (in g/cm$^3$) of the major layers. Right: sketch illustrating the laterally varying lithosphere in South China. The circles indicate the compositional density anomaly of the lithosphere to the reference model within the layers.

## 2. Data processing and gravitational effects

In order to better understand the gravity anomaly of the Emeishan LIP, we first analyze the data on a larger scale. Pavlis et al. (2008, 2012), who presented the Earth Gravitational Model (EGM2008), computed the original Bouguer gravity over South China and surrounding region. This model has a grid spacing of 2.5 × 2.5 arc-minute in both land and ocean. The standard deviation of the Bouguer gravity data in this area is less than 5 mGal (Pavlis et al., 2008). As shown in Fig. 3, in South China, small positive gravity anomalies (< + 100 mGal) are confined to regions near the ocean and offshore. Considering a larger geographic area, negative gravity anomalies (about −200 mGal) can be

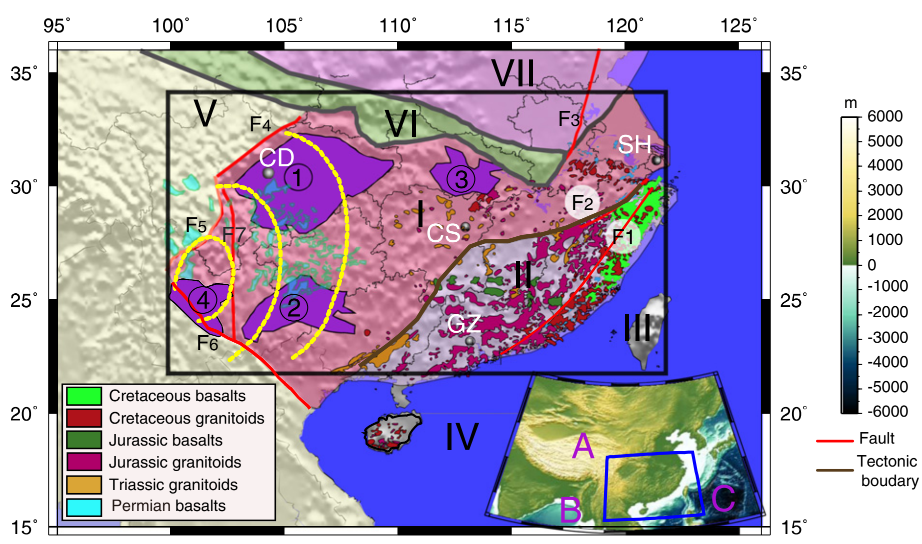


**Fig. 1.** Topographic relief and tectonic units in South China (location map is in the bottom right corner). The central rectangle drawn by black lines depicts the study area. The yellow dashed lines indicate the inner, middle and outer zones of the Emeishan Large Igneous Province (LIP). The spatial distribution of the Mesozoic magmatic rocks is based on Chen et al. (2008) and Liu et al. (2012); the distribution of the Permian basalts is based on Xu et al. (2004, 2007). A: Asian plate; B: Indian plate; C: Philippine Sea plate; I: Yangtze Block; II: Cathaysia Block; III: Taiwan orogen; IV: South China Sea basin; V: East of Songpan–Ganzi Block; VI: Qinling–Dabie orogen; VII: North China Block; F1: Zhenghe–Dapu fault belt; F2: Jiangshan–Shaoxing fault belt; F3: Tanlu fault belt; F4: Longmenshan fault belt; F5: Anninghe fault belt; F6: Red River fault belt; F7: Xiaojiang fault belt; CD: Chengdu city; CS: Changsha city; SH: Shanghai city; GZ: Guangzhou city. There are four main basins in South China, namely: ① Sichuan basin; ② Jianghan basin; ③ Nanpanjiang basin; ④ Chuxiong basin.