Crustal structure and rheology of the Longmenshan and Wenchuan Mw 7.9 earthquake epicentral area from magnetotelluric data

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ABSTRACT

The Longmenshan forms the eastern margin of the Tibetan Plateau adjacent to the Sichuan Basin. This range is anomalous because it formed despite low convergence and slip rates and without the development of a foreland basin. The devastating A.D. 2008 Wenchuan earthquake (Mw = 7.9) has renewed debate about the tectonics of the Longmenshan. A magnetotelluric (MT) study was undertaken subsequent to the earthquake to investigate the crustal structure of the Longmenshan, and inversion of the data reveals a low-resistivity (high-conductivity) layer at a depth of ~20 km beneath the eastern Tibetan Plateau that terminates ~25 km west of the Wenchuan-Maoxian fault. Its electrical properties are consistent with it being fluid-rich and mechanically weak. Beneath the Longmenshan and Sichuan Basin, a high-resistivity zone extends through the entire crust, but with a zone of low resistivity in the vicinity of the Wenchuan hypocenter. We show that the MT data, combined with other geological and geophysical observations, support geodynamic models for the uplift of eastern Tibet being caused by southeast-directed crustal flow that is blocked by stable lithosphere beneath the Sichuan Basin and Longmenshan, leading to inflation of the Songpan-Ganzi terrane. This rigid high-resistivity backstop not only provided a block to flow, but also may have accumulated stress prior to the earthquake. The MT observations provide new insights into the generation of the Wenchuan earthquake, which occurred in a region with low convergence rates prior to the earthquake.

INTRODUCTION

The disastrous A.D. 2008 Wenchuan earthquake (Mw = 7.9) in the Longmenshan region on the eastern margin of the Tibetan Plateau produced significant coseismic rupture and attendant significant loss of life (Xu et al., 2009; Zhang, P., et al., 2009). Prior to this earthquake, convergence rates and seismicity levels in the Longmenshan were significantly lower than in the surrounding area (Wang et al., 2008; Wen and Yi, 2003). Although some authors recognized the long-term hazard (Densmore et al., 2007), a major earthquake in this region was not expected. The Wenchuan earthquake renewed interest in the structure and tectonics of this region (Yin, 2010, and references therein), but without consensus to date.

Magnetotelluric (MT) exploration in 2009 and 2011 to investigate the crustal structure of this region, and resulting resistivity models, were used to constrain the crustal rheology and the tectonic setting of the Wenchuan earthquake.

BACKGROUND

The ongoing collision of the Indian and Asian plates dominates the tectonics of South and East Asia (Tapponnier et al., 1986) and causes high levels of seismicity on the margins of the Tibetan Plateau (Wen and Yi, 2003). Deformation in the eastern Tibetan Plateau is characterized by horizontal motion (Wang et al., 2008; Deng et al., 2003). Shortening was reported in the Songpan-Ganzi terrane by Roger et al. (2004), but this occurred in Mesozoic times, prior to the India-Asia collision. Geological observations that suggested widespread surface uplift with minimal internal deformation led to the suggestion that crustal flow occurs in this region (Clark and Royden, 2000). The crustal flow model can also explain variations in the topographic gradient of the eastern margin, because, where the Tibetan Plateau is juxtaposed against regions with rheologically strong lithosphere, flow can be blocked and/or diverted and produce steep topographic gradients (Clark and Royden, 2000). Other mechanisms have been proposed to account for the evolution of this region (Liu-Zeng et al., 2008).

The Longmenshan forms the eastern margin of the Tibetan Plateau adjacent to the Sichuan Basin, between latitudes of 30°N and 32°N, and was originally formed during the Triassic Indo-Sinian orogeny. The Cenozoic collision of India and Asia reactivated the Longmenshan to produce one of the steepest topographic gradients on the margins of the Tibetan Plateau. The Longmenshan is enigmatic because (1) it lacks a significant foreland basin, and (2) it is associated with low convergence rates, <2 mm/yr (Densmore et al., 2007; Zhang, P., et al., 2009). Low levels of seismicity were observed prior to the Wenchuan earthquake (Wen and Yi, 2003). Despite these indications of relative stability, the Longmenshan was identified as a zone of seismic hazard (Densmore et al., 2007).

The topographic gradient may be partially due to denudation in the Sichuan Basin (Richardson et al., 2008), but ongoing deformation is needed to account for the elevation difference. Seismic receiver function data show an increase in crustal thickness of 20 km across the Longmenshan (Robert et al., 2010), and thermochronology shows that uplift has been most rapid in the past 8–13 m.y., west of the Longmenshan (Wang and Meng, 2009).

The mechanisms for both crustal thickening in the eastern Tibetan Plateau and the continued high relief in the Longmenshan remain unresolved. Structural studies in the western Sichuan Basin show a local correlation of shortening and uplift, which is evidence that uplift is locally caused by compression (Hubbard and Shaw, 2009). However, this model does not explain the uplift of the eastern Tibetan Plateau west of the Longmenshan. The high relief and absence of a foreland basin has been explained by the blocking of crustal flow by the rigid lithosphere of the Sichuan Basin (Clark and Royden, 2000), and seismic data give support for an anomalous mid-crustal layer that could be a flow channel (Zhang, Z., et al., 2009). Xu and Song (2010) reported a zone of low velocities and elevated Poisson's ratio at 15 km depth west of 104°E. Yu et al. (2010) reported a seismic reflection at the same depth that extended west of the Longmenshan. Robert et al. (2010) described a receiver function study that was close to profile L4. Those authors did not report a mid-crustal anomaly in the southern Longmenshan or adjacent eastern Tibetan Plateau (Robert et al., 2010). The discussion above illustrates that the extant seismic data are insufficient to determine crustal structure with the required precision for understanding the tectonic setting of the Wenchuan earthquake.

Understanding the style of deformation on the eastern margin of the Tibetan Plateau, and the generation of the Wenchuan earthquake, requires additional information about the crustal rheology structure. Geodynamic models proposed for this area suggest very different mechanisms for crustal thickening, and include crustal flow (Clark and Royden, 2000) and simple shear

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GEOLOGY, December 2012; v. 40; no. 12; p. 1139–1142; Data Repository item 2012326 | doi:10.1130/G33703.1 | Published online 18 September 2012

(Robert et al., 2010). It is expected that systematic geophysical studies would be able to determine which one is occurring.

To investigate the regional tectonics, a program of magnetotelluric (MT) studies was initiated. Previous studies of the India-Asia collision zone have shown that regional-scale MT studies can constrain crustal rheology (Unsworth et al., 2005; Zhao et al., 2008). Note that MT determines electrical resistivity, which in active regions is primarily controlled by the presence of interconnected fluids—either brines, partial melt, or both.

MAGNETOTELLURIC STUDY

Methods

Broadband MT data were acquired along the three profiles (L1, L2, L4) shown in Figure 1. High-quality MT responses were obtained in the frequency range of 300–0.001 Hz, which is appropriate for crustal-scale imaging. L1 and L2 pass directly through segments of the fault that experienced the largest coseismic rupture. Despite the fact that there are some along-strike changes in fault geometry, geoelectric strike direction analyses showed that a two-dimensional interpretation is appropriate for these MT data (see Fig. DR1 in the GSA Data Repository[1]). Thus, the standard two-dimensional MT inversion algorithm of Rodi and Mackie (2001) was used to generate the resistivity models in Figure 2. It was found that the main features in the resistivity models did not depend strongly on specific choices of starting models or inversion parameters (see Fig. DR4). Similar regional-scale resistivity structures are observed on all three profiles and are discussed below. There are profile-to-profile variations, but these are relatively minor, and our discussion will focus on the first-order features of the resistivity models. Further details of the MT data collection and analysis are described in Tables DR1–DR3 and Figures DR1–DR4 in the Data Repository.

Results

A low-resistivity layer is observed at the surface on all profiles in the Sichuan Basin, and is consistent with the presence of several kilometers of Cenozoic–Mesozoic sedimentary rocks (Bureau of Geology and Mineral Resources of Sichuan Province, 1982). This layer is underlain by higher resistivity values, typical of basement rocks. Coincident seismic exploration was used to interpret the upper 30 km of the resistivity model along profile L1, as shown in Figure 3 and adapted from Hubbard and Shaw

[1]GSA Data Repository item 201326x, Figures DR1–DR4, Tables DR1–DR3, data collection, details of inversion, and interpretation, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

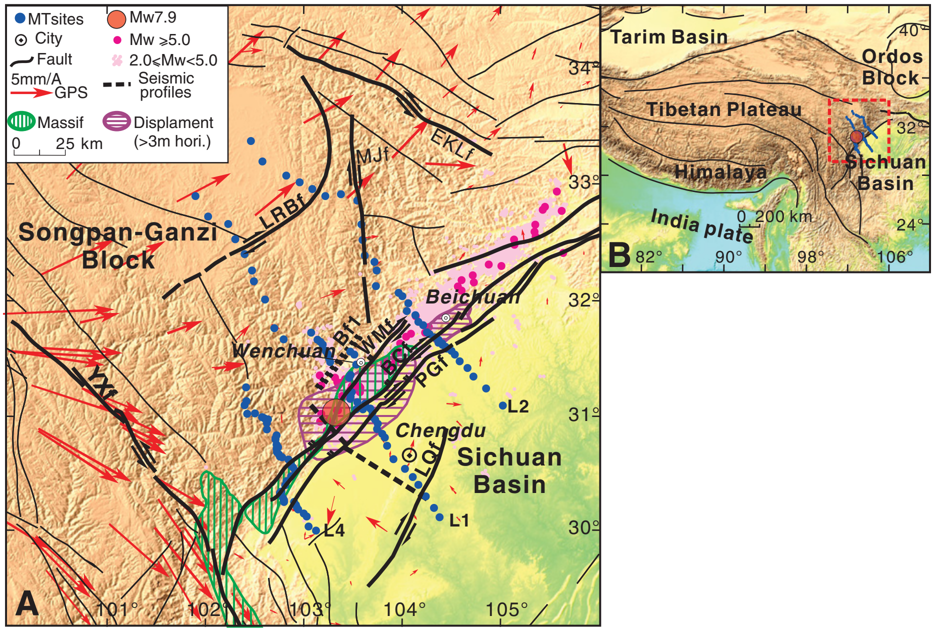

Figure 1. A: Map of the eastern Tibetan Plateau and Longmenshan, with faults taken from Deng et al. (2003). Thick lines show boundary faults of Songpan-Ganzi Block (WMf, BCf, PGf, YXf, and EKLf) and major faults discussed in this paper (LQf, LRBf, and MJf). Thin lines show other faults. WMf—Wenchuan-Maowen fault; BCf—Beichuan fault; PGf—Pengguan fault; YXf—Yushu-Xianshuihe fault; EKLf—East Kunlun fault; LQf—Longquan fault; LRBf—Longriba fault; MJf—Minjiang fault; Bf1—blind fault 1. Large red circle denotes epicenter of the Wenchuan earthquake; magenta dots show aftershocks with M ≥ 5, and pink dots show aftershocks with 2 ≤ M < 5 (Zhu et al., 2008). Blue circles are magnetotelluric stations. The WMf, BCf, and PGf define the Longmenshan fault belt. GPS velocity vectors (Wang et al., 2008) are plotted relative to the South China Block. Black dashed line shows location of seismic profile (Hubbard and Shaw, 2009). Hatched violet area shows region where the coseismic horizontal displacement was greater than 3 m (Zhang, Y., et al., 2009). Vertical green hatching shows the Longmenshan Massif region (Xu et al., 2008), including the Baoxing Massif crossed by L4 and Pengguan Massif crossed by L1. B: Regional map of Tibetan Plateau and surrounding area.

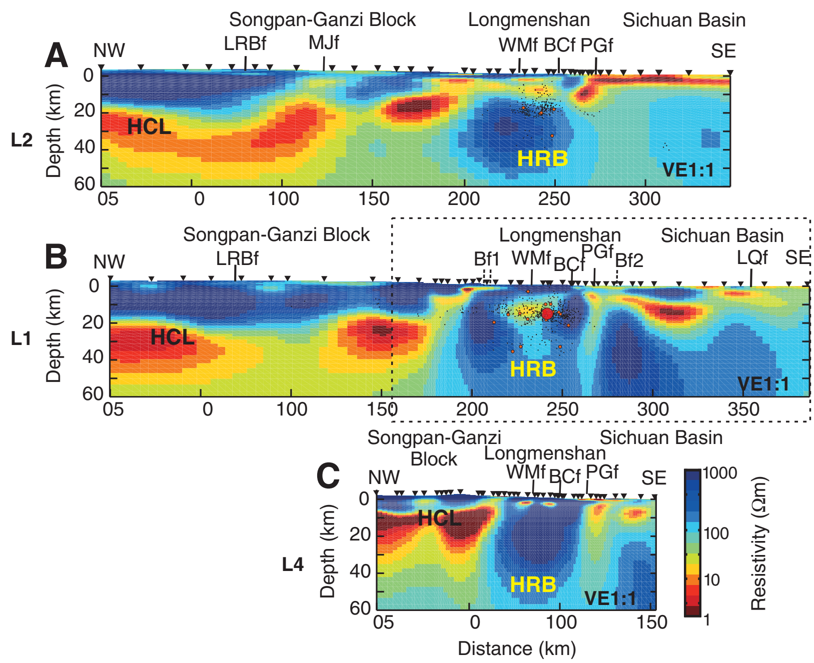

Figure 2. Electrical resistivity models derived by two-dimensional inversion of the magnetotelluric data. A: L2. B: L1. C: L4. HCL—high-conductivity layer; HRB—high-resistivity body; Bf2—blind fault 2; VE—vertical exaggeration. Abbreviation of faults as in Figure 1. Inverted triangles show magnetotelluric stations. Dotted rectangle shows extent of the resistivity model plotted in Figure 3.

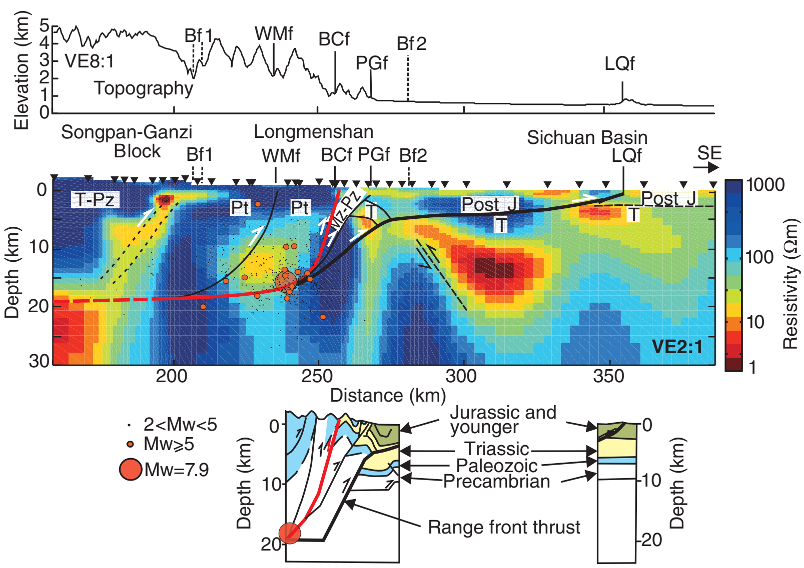

Figure 3. Detail of the resistivity model for L1, showing comparison with seismic reflection data of Hubbard and Shaw (2009). J—Jurassic; T—Triassic; Mz—Mesozoic; Pz—Paleozoic; Pt—Proterozoic. Abbreviation of faults as in Figure 1. Note the 2:1 vertical exaggeration (VE). Hypocenters taken from Zhu et al. (2008) and include events within 20 km of the profile. Depths are ±1 km. Topography is from the Shuttle Radar Topography Mission (SRTM) data set, and is plotted along the magnetotelluric profile.

(2009). At the eastern end of the profile, Triassic units exposed at the surface have low resistivity (10–30 Ω·m). These units are underthrust at the Longquanshan fault (LQf), and are observed again at the surface close to the Pengguan fault (PGf), showing good agreement between the MT model and seismic sections.

Beneath the Longmenshan, the models from all three profiles exhibit a high-resistivity body (HRB) that extends from the surface to the uppermost mantle, with resistivity on the order of 1000 Ω·m. The HRB feature extends east from a location ~20 km west of the Wenchuan-Maowen fault (WMf). The western part of the HRB is coincident with the Pengguan Massif (Xu et al., 2008), a region of Proterozoic crystalline rocks exposed in the Longmenshan (Fig. 1). The high resistivity is as expected for crystalline rocks (Bureau of Geology and Mineral Resources of Sichuan Province, 1982; Wang and Meng, 2009). The HRB extends farther east, where it can be associated with basement rocks beneath the Sichuan Basin.

A zone of elevated conductivity is observed locally within the HRB, coincident with the 2008 earthquake hypocenter (Fig. 3). This feature probably indicates the presence of a zone with an elevated quantity of interconnected (saline) fluids. However, it could also be due to a conducting solid phase, such as sulfides, iron oxides, or graphite films (Duba et al., 1994). This observation of a conducting zone is significant, as it has been suggested that fault behavior is strongly influenced by the presence of fluids, and this feature could explain the location of the hypocenter of the main shock (Zhu et al., 2008). However, the lack of pre-earthquake MT data does not allow temporal variations in resistivity to be inferred.

A resistive upper crust is observed to the west of the Longmenshan, within the Songpan-Ganzi Block, and is indicative of dry crystalline rocks. A high-conductivity layer (HCL) is observed below a depth of 20 km beneath the eastern Tibetan Plateau. This type of HCL is observed in many parts of the Tibetan Plateau, and the resistivity is best interpreted as a zone of elevated fluid content (Unsworth et al., 2005; Zhao et al., 2008). These layers have been interpreted as zones of mechanical weakness that are likely to deform (Unsworth et al., 2005; Zhao et al., 2008). The lowest frequency used in the MT survey was 0.001 Hz, which is insufficient to constrain the lower boundary of the layer.

DISCUSSION

Despite significant geological and geophysical research, the crustal structure of the Longmenshan and eastern Tibetan Plateau is not well resolved. A range of geodynamic models are consistent with the extant seismic, geological, and geodetic data (Yin, 2010). The resistivity models, combined with prior seismic studies, reduce the uncertainty in crustal structure. The presence of the HCL to the west of the Longmenshan is significant in this context, because such a feature is indicative of the probable presence of either aqueous fluids or partial melt or both, which weakens the crust (Unsworth et al., 2005; Wannamaker et al., 2002). The HCL is coincident with a layer of elevated Poisson's ratio at a depth of 15 km, extending west of 104°E (Xu and Song, 2010). The top of the HCL is coincident with a prominent seismic reflector (Yu et al., 2010), as is the case with other HCLs observed in southern Tibet (Unsworth et al., 2005). Both of these seismic observations are consistent with the presence of the HCL caused by elevated fluid content. The conductance of the HCL appears to increase in a southwest direction, consistent with an increase in Poisson's ratio (Xu and Song, 2010).

The receiver function study of Robert et al. (2010) does not appear to agree with the MT results or the seismic tomography of Xu and Song (2010), because the authors do not report a mid-crustal low-velocity zone. These seismic studies can be reconciled by noting that the P-wave anomaly map of Xu and Song (2010) shows significant horizontal variations under the eastern Tibetan Plateau, with a zone of relatively high velocities in the mid-crust at 31°N where the Robert et al. (2010) profile is located. There are lateral spatial variations in the properties of the HCL on the MT profiles in the range 3–30 Ω·m, but overall, the resistivity of the layer is anomalously low for continental crust.

When considered in combination with the seismic data, the geometry and properties of the HCL reported in this paper support models that propose crustal flow and inflation as the cause of crustal thickening in the eastern Tibetan Plateau (Clark and Royden, 2000). The depth and eastward limit of the HCL are in good agreement with both geodynamic models (Clark and Royden, 2000) and seismic tomography evidence for a low-velocity zone (Xu and Song, 2010). Note that the MT measurements determine the electrical properties of the layer, which in active regions are indicative of the rheological properties of the layer, but the conductivity value does not determine whether the layer is flowing. In the study area, the HCL has a vertically averaged conductance in excess of 5000 S, which can be shown to be sufficient for flow to occur if a sufficient horizontal pressure gradient exists (Rippe and Unsworth, 2010). If the HCL represents a southeastward-directed zone of crustal flow, then it is clear that it terminates significantly to the northwest of the Longmenshan, and is blocked by the HRB and forced to flow around the Sichuan Basin.

The discovery of the HCL west of the Longmenshan is also significant because this layer, if due to fluids as we propose, must be mechanically weak. Under sufficient shear stress it will decouple the upper and lower crust and allow differential horizontal motion. Evidence for a décollement west of the Longmenshan comes from seismic reflection data (Yu et al., 2010) and structural studies. Together these data suggest that thrust faults in the Longmenshan join to form a décollement at mid-crustal depths beneath the eastern Tibetan Plateau (Yu et al., 2010). The low-resistivity layer beneath the eastern Tibetan Plateau provides a mechanically weak layer to localize this type of deformation.

Finally, it is significant that the earthquake appears to have nucleated in a region of low resistivity within the HRB. It is possible that this feature was produced by the earthquake, but without pre-earthquake data it is impossible to address this question.

CONCLUSIONS

The resistivity models presented in this paper have provided a clearer image of crustal structure in the Longmenshan and its bordering regions. The resistivity models show clearly that the Longmenshan is characterized by a laterally and vertically extensive block of high resistivity. Enigmatically, the hypocentral location of the Wenchuan earthquake exhibits anomalously low resistivity—whether this was an existing feature that focused nucleation of slip or whether it is a new feature caused by the fault is impossible to verify.

When combined with seismological studies and GPS data, the resistivity models suggest the presence of a fluid-rich mid-crustal layer that terminates west of the Longmenshan. There is no doubt that the crust has thickened west of the Longmenshan—the question is what mechanism caused this thickening. This fluid-rich layer would be weak, and under sufficient applied stress would be able to flow. Thus our models support the idea of crustal flow as proposed by Clark and Royden (2000), who predict that crustal thickening occurs at least partially by inflation. It would also provide a weak layer to decouple the upper and lower crust, providing a source of stress for the observed thrusting in the Longmenshan that led to the 2008 Wenchuan earthquake. The blocking of this southeastward flow by the rigid lithosphere beneath the northeastward-striking Longmenshan and Sichuan Basin leads to surface deformation that has a significant strike-slip component along the Longmenshan, and limited convergence.

ACKNOWLEDGMENTS

This study was supported by the Wenchuan Earthquake Project of the China Earthquake Administration, the National Basic Research Program of China (grant 2008CB425702-2), the Natural Science Foundation of China (grants 40841008, 41074047, 41074046, and 40534023), the Special Fund for Basic Scientific Research of the Chinese National Nonprofit Institutes (IGCEA1013), the China Institute at the University of Alberta (Canada), and the Natural Sciences and Engineering Research Council of Canada. Discussions with Xu Xiwei, Zhang Peizhen, and John Booker, and reviews by Ian Ferguson and an anonymous reviewer, are gratefully acknowledged.

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Manuscript received 4 June 2012
Revised manuscript received 1 July 2012
Manuscript accepted 4 July 2012

Printed in USA