International Geology Review
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tigr20

Irregular western margin of the Yangtze block as a cause of variation in tectonic activity along the Longmen Shan fault zone, eastern Tibet

Xiaoyu Guo[ab], G. Randy Keller[b], Rui Gao[a], Xiao Xu[b], Haiyan Wang[a] & Wenhui Li[a]
[a] Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China
[b] School of Geology and Geophysics, The University of Oklahoma, Norman, OK, USA
Published online: 30 Jan 2014.

International Geology Review, 2014
Vol. 56, No. 4, 473–480, http://dx.doi.org/10.1080/00206814.2013.873358

Irregular western margin of the Yangtze block as a cause of variation in tectonic activity along the Longmen Shan fault zone, eastern Tibet

Xiaoyu Guo[a,b]*, G. Randy Keller[b], Rui Gao[a], Xiao Xu[b], Haiyan Wang[a] and Wenhui Li[a]

[a]*Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China;* [b]*School of Geology and Geophysics, The University of Oklahoma, Norman, OK, USA*

(*Received 21 November 2013; accepted 21 November 2013*)

On 12 May 2008 and 20 April 2013, respectively, the devastating magnitude 7.9 (Wenchuan) and magnitude 7.0 (Ya'an) earthquakes struck the southwestern Longmen Shan fault zone (LMSFZ), the eastern margin of the Tibetan Plateau. These events were notable because they occurred in a heavily populated area and resulted in severe damage and loss of life. Here we present an integrated analysis of potential field anomalies and a crustal-scale seismic reflection image to investigate the crustal structure and some tectonic relationships associated with these devastating events. Our results show that the western margin of the Yangtze crustal block possesses an irregular margin that extends westward beyond the LMSFZ to the northeast and merges gradually with the LMSFZ to the southwest. We interpret this variation in deep structure to create a lateral heterogeneity in the local stress regime that explains the observed variations in fault geometry and slip distribution, as well as seismicity, of the LMSFZ. This structural complexity results in a differential build-up of stress as the Tibetan Plateau is being extruded eastward. Thus, the results of this research can help identify potential natural hazard zones and focus efforts on hazard mitigation.

Keywords: eastern Tibetan Plateau; western margin of the Yangtze block; Longmen Shan fault zone; tectonic activity

Introduction

The eastern margin of the Tibetan Plateau, the Longmen Shan fault zone (LMSFZ), is now recognized as one of the most significant earthquake-prone areas in Asia (Figure 1), and two devastating earthquakes (the Ms 7.9 2008 Wenchuan earthquake and Ms 7.0 2013 Ya'an earthquake) have been recorded. These large earthquakes were notable because they occurred in a heavily populated area and resulted in severe damage and loss of life. Thus, there is great interest regarding the tectonic activity and earthquake hazards along the LMSFZ (e.g. Parsons *et al.* 2008; Shen *et al.* 2009; Tong *et al.* 2010; Wang *et al.* 2010a).

Global positioning system (GPS) and interferometric synthetic aperture radar studies by Shen *et al.* (2009) show that the geometry of the LMSFZ changes along its strike from dipping moderately to the northwest in the southwest to almost vertical dip in the northeast. In addition, the motion along the fault zone changes from predominantly thrusting in the southwest to strike-slip in the northeast. Predicted rates of fault slip on the LMSFZ are also surprisingly different laterally. Along the southwestern fault segments, there is 1.7 ± 0.8 mm/year of right-lateral slip coupled with 1.2 ± 1.0 mm/year of dip-slip. To the northeast, the movement changes to 1.4 ± 1.1 mm/year of right-lateral slip and 3.3 ± 1.3 mm/year of dip-slip (Wang *et al.* 2010a). As a result, the scalar moment accumulation rate varies substantially along the LMSFZ (Wang *et al.* 2010a; Nalbant and McCloskey 2011), being 2.43×10^{17} N m/year along the southwestern segment and 8.17×10^{17} N m/year along the northeastern segment (Wang *et al.* 2010a).

The Ms 7.9 2008 Wenchuan earthquake released some of the moment accumulation along the LMSFZ and caused severe damage and loss of life in the Longmen Shan area. The mainshock of the 12 May 2008 Wenchuan earthquakes sequence was located in the southwestern portion of the LMSFZ (Figure 1). During this devastating earthquake sequence, surface rupture and crustal deformation of the southwestern segment was strongly dominated by thrusting (Shen *et al.* 2009; Tong *et al.* 2010), while the northeastern LMSFZ experienced dextral strike-slip. Between them, the rupture involved oblique dextral thrusting (Xu *et al.* 2009). Coseismic stress modelling of the 2008 Wenchuan earthquake shows decreased Coulomb stress (failure stress) northeastward and increased Coulomb stress in the southern portion of the mainshock rupture (Parsons *et al.* 2008; Nalbant and McCloskey 2011). These studies indicate that the potential for earthquakes in the southwestern Sichuan basin region is significant (Parsons *et al.* 2008; Nalbant and McCloskey 2011). Thereafter, on 20 April 2013, the Ms 7.0 Ya'an earthquake struck the southwestern part of the LMSFZ, which is about 85 km southwest of the epicentre of the 2008 Wenchuan earthquake (Figure 1). According to the

*Corresponding author. Email: guomichele@gmail.com

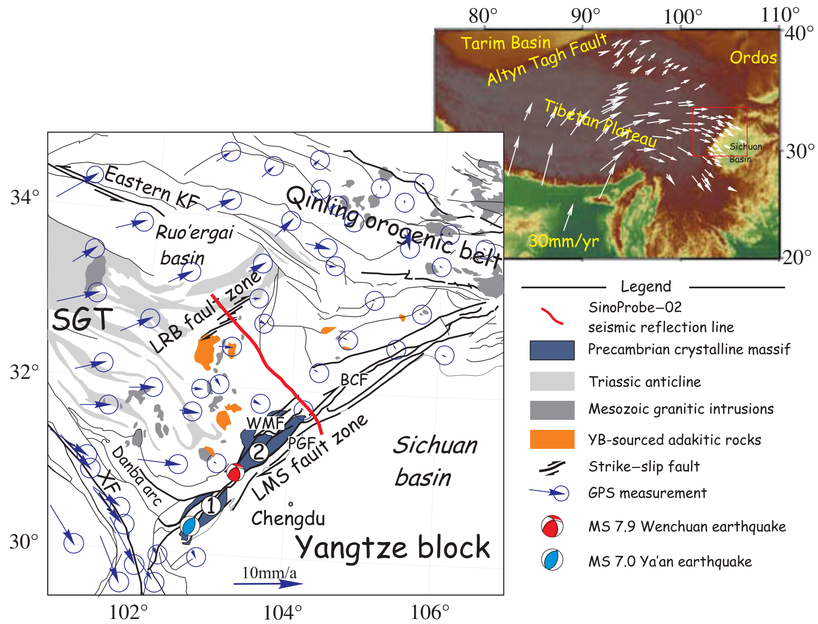

Figure 1. Generalized geological map of the eastern Tibetan Plateau (based on the 1:2.5 million scale geological map of China) showing the location of SinoProbe-02 deep seismic reflection profile as a red line. GPS velocity vectors (Shen *et al.* 2005, 2009; Zhu and Zhang 2010; Zhang and Wei 2011) are plotted relative to the YB (see insert figure for regional GPS measurements and research area in red box). TB, Tarim basin; NCB, North China block; SCB, South China block; SGT, Songpan-Ganzi terrane; TP, Tibetan Plateau; LMS, Longmen Shan; LRBFZ, Longriba fault zone; WMF, Wenchuan-Maowen Fault; BCF, Beichuan Fault; PGF, Pengguan Fault; QCF, Qingchuan Fault; KF, Kunlun Fault; XF, Xianshuihe Fault; ① Baoxing Massif; ② Pengguan Massif.

USGS, the surface rupture was mainly dominated by thrusting. However, the seismic moment stored along the southwestern LMSFZ was not fully released by the Ya'an mainshock as evidenced by the subsequent aftershocks along the southwestern segment (Liu *et al.* 2013).

Although some researchers have recognized the long-term regional hazards within and around the western Sichuan basin (e.g. Densmore *et al.* 2007; Parsons *et al.* 2008; Wang *et al.* 2010a), the cause of variation in tectonic activity along the LMSFZ and the resulting large earthquakes remains uncertain. In this study, we carry out an integrated analysis of gravity, seismic reflection, and tectonic data to evaluate the crustal structure. The results will in turn be used to evaluate the tectonic activity along the LMSFZ and therefore to constrain the stress regime of easternmost Tibetan Plateau. Our intent is to provide new information to inform regional tectonic studies and assess the regional natural hazards along the LMSFZ.

Tectonic setting

During the early Mesozoic, the Songpan–Ganzi terrane (SGT) was originally a remnant ocean prior to the Indosinian orogeny (late Permian–Early Jurassic). It was then filled with thick Triassic flysch derived from adjacent orogenic belts (e.g. Yin and Nie 1993; Liu *et al.* 2013) during the Indosinian orogeny. Contemporaneously, due to coeval subduction zones in the north and southwest of the Songpan remnant ocean, northeast–southwestward crustal shortening began to deform the Songpan remnant ocean and its sedimentary fill, which was followed by southeast-directed thrusting (e.g. Reid *et al.* 2005; Roger *et al.* 2011). As a result, Yangtze block (YB)-sourced syn-tectonic adakite-type granitoids intruded the upper crust as evidenced by their distribution in the eastern SGT (Figure 1) (Roger *et al.* 2010). In addition, owing to the southeast-directed thrusting towards the western passive margin of the YB (Roger *et al.* 2010), the LMSFZ (Figure 1) was initiated as a convergent zone between the SGT and YB (Burchfiel *et al.* 1995). The eastern SGT was tectonically quiescent between the Late Jurassic to early Cenozoic after the amalgamation of the SGT and YB, and the lack of major tectonic events was evidenced by low cooling (Roger *et al.* 2011).

Today, continent–continent collision is ongoing between the Indian and Eurasian plates (e.g. Shen *et al.* 2005). As a response, the Tibetan Plateau is currently undergoing eastward block motion (Shen *et al.* 2005) (Figure 1). In eastern Tibet, GPS measurements detect a puzzling velocity gradient zone, across which there is dramatic decrease in rate and change in direction of the eastward extrusion velocity from the Longriba fault zone (LRBFZ) to the east (Shen *et al.* 2005, 2009) (Figure 1). Obviously, unknown deep-seated features beneath the easternmost Tibetan Plateau have absorbed some stress and altered the eastward movement. However, no existing model has been proposed to account for this scenario. Here, combined with a 310 km-long deep seismic reflection image, we employ the gravity and aeromagnetic anomalies to analyse the structure of the region and implications for the variations in tectonic activity along the LMSFZ.

Integrated analysis of geophysical data

Analysis of gravity anomalies

There have been several previous gravity studies in the region (e.g. Zhang *et al.* 2010; Jiang *et al.* 2012). Zhang *et al.* (2010) employed satellite gravity anomalies in their study that focused on the Longmen Shan. Jiang *et al.* (2012) employed surface gravity data to model the crustal thickness and block tectonics in the region. For our study, gravity anomaly data were extracted from the International Center for Global Earth Models (ICGEM), and these data were plotted and filtered with the Geosoft/Oasis Montaj processing and analysis package. As also shown by Zhang *et al.* (2010) and Jiang *et al.* (2012), anomaly values range widely, indicating major structural variations. To minimize topographic effects, we applied Bouguer and terrain corrections to the data using a sea level datum and a reduction density of 2.67 g/cm^3 to obtain complete Bouguer anomaly (CBA) values. As shown in Figure 2(a), the entire region is associated with large negative CBA values, which indicates isostatic compensation of topography at depth. The trend of the gravity anomalies in the region surrounding the LMSFZ region is generally parallel to the NE–SW trend of the fault zone. All values decrease westward and are associated with the westward deepening of the Moho under easternmost Tibet and the westward decrease in upper mantle velocities (Yang *et al.* 2012). The gravity gradient between the LMS and LRBFZs is pronounced (Figure 2(a)), and the high gradient zone narrows toward the southwest. However, it does not correlate well with the surface structures mapped in that area.

In order to highlight the regional tectonic framework and detect the lateral boundaries associated with the main gravity anomalies, we smoothed the anomalies by upward continuation to 30 km and then calculated the total horizontal gradient (THG) to detect the boundaries of the high gradient zone. This technique for delineating boundaries of deep-seated sources has been tested and has often proved useful (e.g. Miller and Singh 1994; Cooper and Cowan 2008). The THG map shows high gradient values with a general NE–SW trend that is related to the structures to the west of the LMSFZ (Figure 2b) and better delineate the high gradient zone in Figure 2(a). Interestingly, the high gradient zone is wider to the northeast, where it is bounded by the LMSFZ and LRBFZ, and narrows to the southwest. The southwestern edge of the high gradient zone generally coincides with the southwestern segment of the LMSFZ.

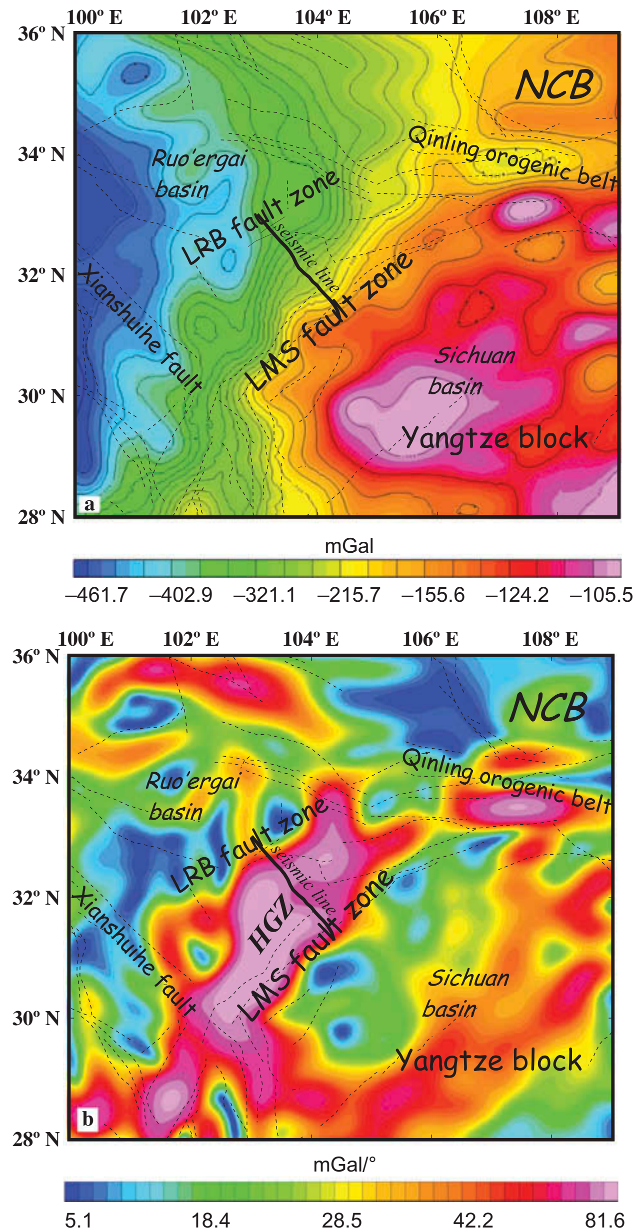

Figure 2. (a) Complete Bouguer anomaly map of the research area with a contour interval of 10 mGal; (b) THG of the Complete Bouguer anomaly after 30 km upward continuation; dashed lines indicate the faults; NCB, North China block; LMS, Longmen Shan; LRB, Longriba fault zone; HGZ, high gradient zone.

The high gradient zone between the LRBFZ and the LMSFZ is primarily an expression of the crustal structure of that area. The most likely interpretations are either large variations of crustal thickness or large lateral variations of crustal density, and/or a combination of both of these effects.

Analysis of magnetic anomalies

Magnetic anomaly data were extracted from the earth magnetic anomaly grid (EMAG3), and these data were also plotted and filtered with the Geosoft/Oasis Montaj processing and analysis package. We applied reduction-to-pole to the total magnetic data so that the anomalies associated with near surface features could be more clearly identified, and many anomalies showed good correlation with a variety of geological features (Figure 3).

Substantial efforts have been made to determine density and magnetic susceptibility values for different rocks in the LMS region (e.g. Zhang *et al.* 2010). Relative to the widely distributed Proterozoic Yangtze crystalline basement (Sichuan basin), granites exposed in the SGT should not be a major factor causing pronounced magnetic anomalies due to their small size relatively to the resolution of the satellite data. However, major tectonic features, such as the Danba dome (anomaly 'a' in Figure 3) and the Rilongguan A-type granite (anomaly 'b' in Figure 3) are clear in the magnetic map.

The LMSFZ shares the same magnetic properties with those of the Sichuan basin (Figure 3), strengthening the widely held view that the LMSFZ is underlain by the same crystalline basement as that of the Sichuan basin (Zhao *et al.* 2012), i.e. the YB crystalline basement. Some positive magnetic anomalies extend from the LMSFZ to the LRBFZ, and similar anomalies are not present to the southwest in the area of the Xianshuihe Fault zone (Figure 3). The positive anomalies extending from the Sichuan basin into easternmost Tibet may indicate the westward extension of the Yangtze crystalline basement beyond the LMSFZ to the LRBFZ. Alternatively, given the extremely thick and highly deformed Triassic flysch sediments in the SGT, further extension of the YB to the west is not definitive based on the magnetic anomalies since the temperature of a large part of the crystalline crust could be above the Curie depth. However, the combination of gravity and magnetic anomalies indicates that the western margin of the YB extends at least some amount beyond the area of the LMSFZ and would probably have approached the area of the LRBFZ. Thus, we have included seismic data on deep structure in our analysis.

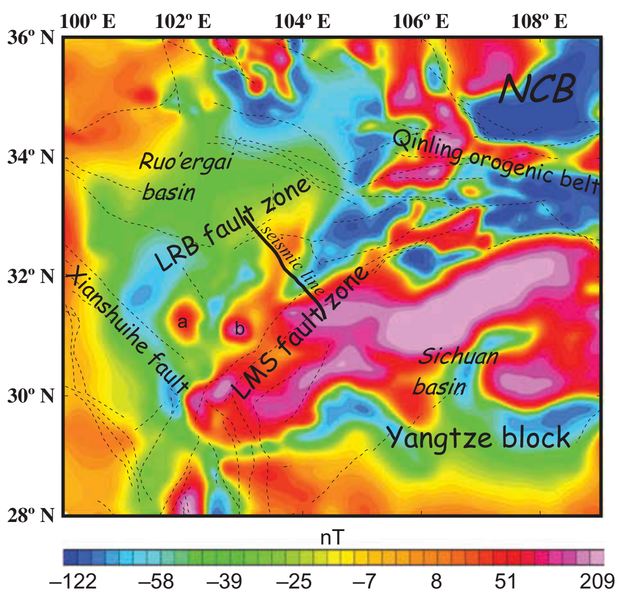

Figure 3. Reduction-to-pole magnetic anomaly map of the research area; dashed lines indicate the faults. NCB, North China block; LMS, Longmen Shan; LRB, Longriba fault zone.

Deep seismic reflection image

The SinoProbe-02 effort is one part of China's ambitious SinoProbe Project, a leading Chinese research effort to investigate lithospheric structure across China using a variety of geophysical methods (Dong *et al.* 2011). A 310 km-long deep SinoProbe-02 seismic reflection profile was collected in 2011 and extends roughly NE–SW from the SGT to the Sichuan basin (Figure 1). Acquisition and processing of these seismic data are described in Guo *et al.* (2013), and these basic data acquisition and processing procedures have been used successfully in all of the SinoProbe-02 reflection profiles. The full length of the interpreted seismic reflection image (refer to Guo *et al.* (2013) for high-resolution image of this seismic profile) shows an extremely thick cover of Triassic flysch as suggested by previous studies (Zhou and Graham 1993; Nie *et al.* 1994) and diverse reflectivity and structure along the profile (Figure 4).

As discussed by Guo *et al.* (2013), two reflection boundaries are predominantly revealed in the seismic reflection image (Figure 4). The upper reflector represents the top of the basement (crystalline upper crust), which is clear but discontinuous along the profile. The lower one that can be continuously traced represents the Moho and is characterized by bivergent dipping high-amplitude reflectors between 14 and 18 s (t.w.t.). Extension of the strong upper reflector terminates in the northwestern segment of the seismic reflection image, where distinct southeast-dipping reflections in the middle crust appear to represent the thick flysch deposits. Between these two areas of distinct reflectivity that appear in the upper crust of the northwestern segment, a band of northwestward dipping events is present, separating these areas of the image and extending from near the Moho well up into the upper crust and possibly to the surface. A fault interface that coincides with the LRBFZ is thus suggested to represent this abrupt change in reflection character (Figure 4).

This interpretation is consistent with the gravity and magnetic anomalies that suggest extension of crystalline basement from the Sichuan basin to the area near the LRBFZ (Figure 4). The seismic image shows that no large variations in crustal thickness occur along the profile

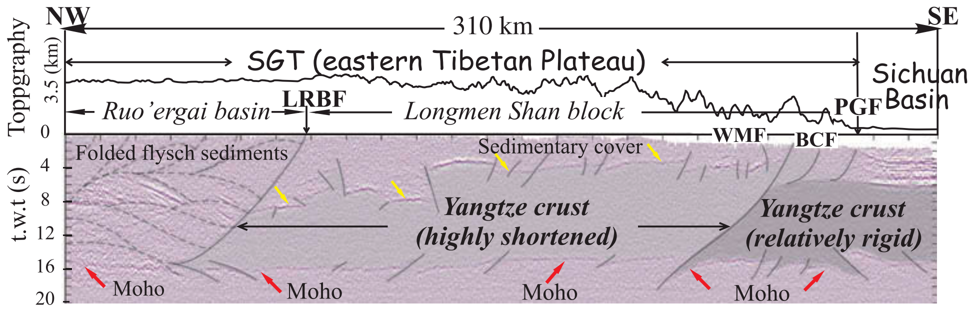

Figure 4. Interpreted deep seismic reflection profile extending from the Songpan-Ganzi terrane across the Longmen Shan block to the Sichuan Basin (see Figures 1, 2, and 3 for location) (modified from Guo *et al.* (2013)). No vertical exaggeration and 6 km/s average seismic velocity is assumed. LRBF, Longriba Fault; PGF, Pengguan Fault; WMF, Wenchuan-Maowen Fault; BCF, Beichuan Fault; SGT: Songpan-Ganzi terrane.

between the LMSFZ and LRBFZ, so we conclude that lateral variations in density within the crust, and possibly the uppermost mantle, produce the high gravity gradient. In addition, an abrupt thickening of the sedimentary cover west of the LMSFZ to as deep as 8 s (t.w.t) (~15 km) (Figure 4) could account for the appearance of negative magnetic anomalies that are present between the LRBFZ and LMSFZ (Figure 3).

Overall, the integrated analysis of geophysical data supports the hypothesis of Guo *et al.* (2013) that the Yangtze crystalline basement extends from the Sichuan basin to the easternmost Tibetan Plateau. We have named this region the Longmen Shan block (Figure 4). Thus, the high gravity and magnetic gradient zones are a result of large lateral variations of crustal density, and also a possible contribution from the east to west decrease in upper mantle velocity across the area (Yang *et al.* 2012). This interpretation is consistent with previous geochemical and geological studies (Burchfiel *et al.* 1995; Roger *et al.* 2010; Fielding and McKenzie 2012), as well as the distribution pattern of anticlines in the Triassic flysch in the eastern Tibetan Plateau (Figure 1).

Discussion

Viewing these results of integrated geophysical analysis in a regional perspective integrated with the GPS data and distribution of the Triassic flysch anticlines (Figure 1), we observe a pattern that provides an explanation for the variation in tectonic activity along the eastern edge of Tibet (Figure 1). Our results indicate that the western margin of the Yangtze crustal block is irregular, extending westward beyond the LMSFZ to the northeast and merging gradually with the LMSFZ to the southwest. This irregular margin geometry is consistent with the distribution of Triassic anticlines and YB-sourced adakitic granitoids (Figure 1), as well as the variation of the direction and rate of eastward movement of the Tibetan Plateau.

An additional consideration is that the historical earthquakes in the eastern Songpan–Ganzi region mostly occurred in the east–central to northeastern area (Wang *et al.* 2010a), which is illustrated in Figure 5 that shows the distribution density of historical earthquakes in the eastern SGT. This distribution density of the earthquakes was calculated using a 10 km × 10 km grid. Owing to the

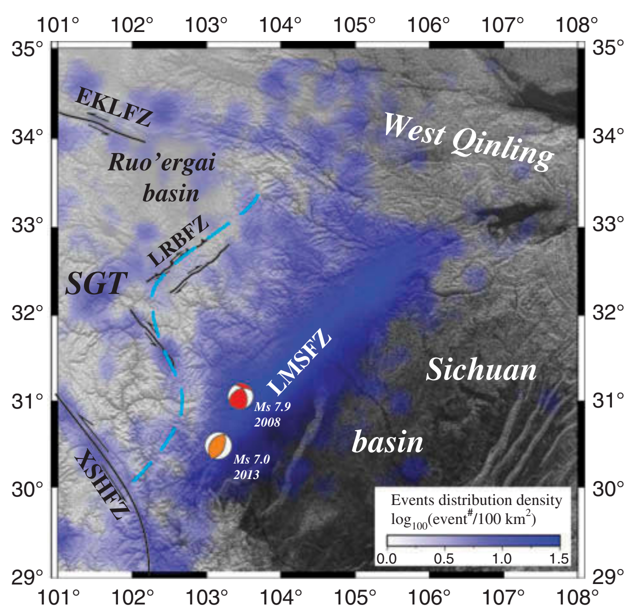

Figure 5. Distribution density of seismic events in the Longmen Shan region from 1959 to 21 July 2013 with magnitude ≥3.0. The data set is derived from IRIS (http://www.iris.edu/SeismiQuery/sq-events.htm). Note that the earthquakes in eastern SGT are mainly distributed in the east-central and northeastern areas between the Longmen Shan fault zone and the Longriba fault. Event# indicates the number of seismic events in a 10 km × 10 km grid cell (please see text for details); fault information is from Xu *et al.* (2009) and Nalbant and McCloskey (2011). SGT, Songpan-Ganzi terrane; LMSFZ, Longmen Shan fault zone; LRBFZ, Longriba fault zone; EKLFZ, Eastern Kunlun fault zone; XSHFZ, Xianshuihe fault zone.

fact that earthquakes are mostly concentrated along the LMSFZ, it appears as the feature with by far the highest distribution density. Thus, we applied a base 100 logarithmic function to the gridded values in order to better view the variations in the areas to the west of the LMSFZ (Figure 5). The relatively higher distribution density of earthquakes in the east–central and northeastern SGT supports our hypothesis that the intervening Yangtze crystalline crust between the LRBFZ and the LMSFZ is capable of brittle failure as indicated in the seismic reflection image.

Therefore, we propose that the variation of tectonic activity along the LMSFZ is due to the presence of two regions along the fault (Figure 6) that are caused by the irregular margin of the YB and are therefore experiencing different strain accumulation rates. The Tibetan Plateau is undergoing northeastward to eastward block motion, which is oblique to the western margin (the LMSFZ) of the Yangtze crust in the southwest and changes to subparallel to the block margin (the LRBFZ) to the northeast (Figure 6). Given the relatively rigid features of the intervening Yangtze crust seen in the seismic reflection image between the LRBFZ and the LMSFZ (Figure 4), some stress generates intracrustal earthquakes when transferring through the rigid Yangtze crystalline crust and some is transferred to the Longmen Shan range front and creates elastic shortening accumulation in Zone I (Figure 6) when it meets the rigid Sichuan basin. However, in Zone II, the structural integrity of the thick flysch deposits in the SGT is less than that of the adjacent rigid Sichuan basin. As a result, collision between the southeastern SGT and the southwestern Sichuan basin is absorbed by crustal thickening to over 60 km (Wang *et al.* 2007; Robert *et al.* 2010; Wang *et al.* 2010b) and thrusting towards the rigid Sichuan basin. This scenario is consistent with the strong thrust component of focal mechanisms in the southwestern LMSFZ (Figures 1 and 5). Thereby, the stress that is transferred to the southwestern LMSFZ (Zone II in Figure 6) is low compared to the northeastern segments of the LMSFZ (Zone I in Figure 6), where our results show that the crustal thickness is only ~50 km and the relatively rigid YB bounds the fault on both sides. Consequently, this difference in crustal thickness and gross rheology contributes to variations in fault geometry, slip rates, and strain energy along the LMSFZ.

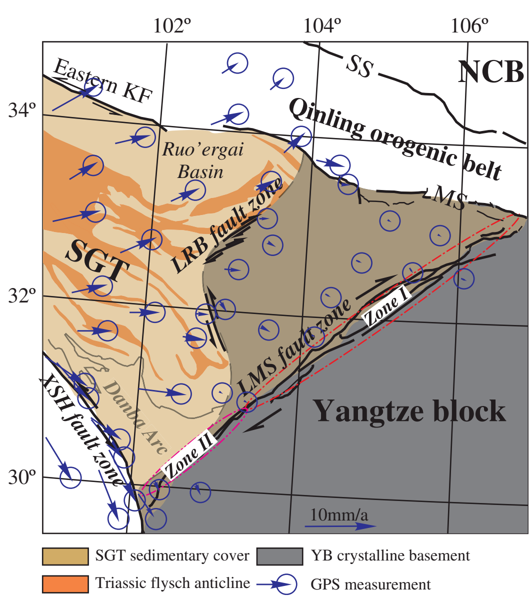

Figure 6. A sketch of the tectonic contact relationship between the SGT and YB (based on the 1:2.5 million scale geological map of China) as a result of our integrated study of gravity and magnetic anomalies and the seismic reflection image. TP, Tibetan Plateau; YB, Yangtze block: NCB, North China block; SGT, Songpan-Ganzi terrane; KF, Kunlun Fault; XSH, Xianshuihe Fault; LRB, Longriba fault; LMS, Longmen Shan; MS, Mianlue suture zone; SS, Shangdan suture zone.

In addition, the epicentre of the 2008 Wenchuan earthquake is located in the Pengguan Precambrian crystalline massif of the southwestern LMSFZ (Figure 1). Therefore, when the Tibetan Plateau moves obliquely and pushes against the Yangtze crustal block, the Precambrian rocks experience compression and faults tend to become locked (Ji *et al.* 2008). This phenomenon can account for some of the relative seismic quiescence along the southwestern LMSFZ before 2008. After a large event, the continued push of the Tibetan Plateau causes another cycle of the accumulation of strain energy, which is likely to be released in a large earthquake or earthquake sequence. Therefore, it is not a coincidence that two large earthquakes of magnitude ≥7.0 were initiated in the southwestern LMSFZ after a long period of quiescence. We thus propose that the pattern of seismicity along the LMSFZ is partly a result of the complex shape of the Yangtze crustal block and its interactions with the eastward block motion of the Tibetan Plateau.

We do not mean to suggest that the earthquake hazard is low to the northeast, but we believe that the complex crustal block interactions we have discussed do potentially explain some differences in the tectonic activity, as well as seismicity, along the LMSFZ.

Conclusion

In this paper, we present an integrated analysis of geophysical anomalies, including the analysis of gravity and magnetic anomalies, as well as a crustal-scale seismic reflection image, to investigate crustal structure and some tectonic relationships associated with the devastating events of the 12 May 2008 Ms 7.9 Wenchuan earthquake and 20 April 2013 Ms 7.0 Ya'an earthquake. Our results show that the western margin of the Yangtze crustal block possesses an irregular margin that extends westward beyond the LMSFZ to the northeast and merges gradually with the LMSFZ to the southwest. We interpret this variation in deep structure to create a lateral heterogeneity in the local stress regime that explains the observed variations in fault geometry and slip distribution, as well as seismicity, of the LMSFZ. This structural complexity results in a differential build-up of stress as the Tibetan Plateau is being extruded eastward. Thus, the results of this research can help identify potential natural hazard zones and focus efforts on hazard mitigation.

Acknowledgements

We thank all our colleagues from both China and the USA who have worked in the field to collect and process the seismic data employed in this study.

Funding

This work was supported by the SinoProbe-02 Project, a National Natural Science Foundation of China [grant no. 40830316] and a US National Science Foundation, Partnerships for International Research and Education [grant no. 0730154].

References

Burchfiel, B.C., Chen, Z.L., Liu, Y.P., and Royden, L.H., 1995, Tectonics of the Longmen Shan and adjacent regions, Central China: International Geology Review, v. 37, p. 661–735.

Cooper, G.R.J., and Cowan, D.R., 2008, Edge enhancement of potential-field data using normalized statistics: Geophysics, v. 73, p. H1–H4.

Densmore, A.L., Ellis, M.A.Y., and Li, Y., 2007, Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau: Tectonics, v. 26, TC4005.

Dong, S.W., Li, T.D., Gao, R., Hou, H.S., Li, Y.K., Zhang, S.H., Keller, G.R., and Liu, M., 2011, A multidisciplinary Earth science research program in China: EOS, Transactions, American Geophysical Union, v. 92, p. 313–314.

Fielding, E.J., and McKenzie, D., 2012, Lithospheric flexure in the Sichuan Basin and Longmen Shan at the eastern edge of Tibet: Geophysical Research Letters, v. 39, L09311.

Guo, X.Y., Gao, R., Keller, G.R., Xu, X., Wang, H.Y., and Li, W. H., 2013, Imaging the crustal structure beneath the eastern Tibetan Plateau and implications for the uplift of the Longmen Shan range: Earth and Planetary Science Letters, v. 379, p. 72–80.

Ji, S.C., Wang, Q., Sun, S.S., Xu, Z.Q., and Li, H.B., 2008, Continental extrusion and seismicity in China: Acta Geologica Sinica, v. 82, p. 1643–1667 (in Chinese with English abstract).

Jiang, W.L., Zhang, J.F., Tian, T., and Wang, X., 2012, Crustal structure of Chuan-Dian region derived from gravity data and its tectonic implications: Physics of the Earth and Planetary Interiors, v. 212–213, p. 76–87.

Liu, S.G., Deng, B., Jansa, L., Wang, G.Z., Li, X.H., Wang, C.S., Liu, S., Li, Z.W., Li, J.C., Sun, W., and Ran, B., 2013, Late Triassic thickening of the Songpan-Ganzi Triassic flysch at the edge of the northeastern Tibetan Plateau: International Geology Review, v. 55, p. 2008–2015.

Liu, M., Luo, G., and Wang, H., 2013, The 2013 Lushan earthquake in China tests hazard assessments: Seismological Research Letters (in press).

Miller, H.G., and Singh, V., 1994, Potential field tilt – A new concept for location of potential field sources: Journal of Applied Geophysics, v. 32, p. 213–217.

Nalbant, S.S., and McCloskey, J., 2011, Stress evolution before and after the 2008 Wenchuan, China earthquake: Earth and Planetary Science Letters, v. 307, p. 222–232.

Nie, S., Yin, A., Rowley, D.B., and Jin, Y., 1994, Exhumation of the Dabie Shan ultra-high-pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China: Geology, v. 22, p. 999–1002.

Parsons, T., Ji, C., and Kirby, E., 2008, Stress changes from the 2008 Wenchuan earthquake and increased hazard in the Sichuan basin: Nature, v. 454, p. 509–510.

Reid, A.J., Wilson, C.J.L., and Liu, S., 2005, Structural evidence for the Permo-Triassic tectonic evolution of the Yidun arc, eastern Tibetan Plateau: Journal of Structural Geology, v. 27, p. 119–137.

Robert, A., Pubellier, M., de Sigoyer, J., Vergne, J., Lahfid, A., Cattin, R., Findling, N., and Zhu, J., 2010, Structural and thermal characters of the Longmen Shan (Sichuan, China): Tectonophysics, v. 491, p. 165–173.

Roger, F., Jolivet, M., Cattin, R., and Malavieille, J., 2011, Mesozoic–Cenozoic tectonothermal evolution of the eastern part of the Tibetan Plateau (Songpan-Ganze, Longmen Shan area): Insights from thermochronological data and simple thermal modeling, *in* Gloaguen, R., and Ratschbacher, L., eds., Growth and collapse of the Tibetan Plateau: Geological Society, London, Special Publications 353, p. 9–25

Roger, F., Jolivet, M., and Malavieille, J., 2010, The tectonic evolution of the Songpan-Ganzê (north Tibet) and adjacent areas from Proterozoic to present: A synthesis: Journal of Asian Earth Sciences, v. 39, p. 254–269.

Shen, Z.K., Lü, J.N., Wang, M., and Bürgmann, R., 2005, Contemporary crustal deformation around the southeast borderland of the Tibetan Plateau: Journal of Geophysical Research, v. 110, B11409. doi:10.1029/2004JB003421

Shen, Z.K., Sun, J.B., Zhang, P.Z., Wan, Y.G., Wang, M., Bürgmann, R., Zeng, Y.H., Gan, W.J., Liao, H., and Wang, Q.L., 2009, Slip maxima at fault junctions and rupturing of barriers during the 2008 Wenchuan earthquake: Nature Geoscience, v. 2, p. 718–724.

Tong, X.P., Sandwell, D.T., and Fialko, Y., 2010, Coseismic slip model of the 2008 Wenchuan earthquake derived from joint inversion of interferometric synthetic aperture radar, GPS, and field data: Journal of Geophysical Research, v. 115, B04314. doi:10.1029/2009JB006625

Wang, C.Y., Han, W.B., Wu, J.P., Lou, H., and Chan, W.W., 2007, Crustal structure beneath the eastern margin of the Tibetan Plateau and its tectonic implications: Journal of Geophysical Research, v. 112, B07307. doi:10.1029/2005JB003873

Wang, C.Y., Zhu, L.P., Lou, H., Huang, B.S., Yao, Z.X., and Luo, X.H., 2010b, Crustal thicknesses and Poisson's ratios in the eastern Tibetan Plateau and their tectonic implications: Journal of Geophysical Research, v. 115, B11301. doi:10.1029/2010JB007527

Wang, H., Liu, M., Shen, X.H., and Liu, J., 2010a, Balance of seismic moment in the Songpan-Ganze region, eastern Tibet, Implications for 2008 Great Wenchuan earthquake: Tectonophysics, v. 491, p. 154–164.

Xu, X.W., Wen, X.Z., Yu, G.H., Chen, G.H., Klinger, Y., Hubbard, J., and Shaw, J., 2009, Coseismic reverse- and oblique-slip surface faulting generated by the 2008 Mw 7.9 Wenchuan earthquake, China: Geology, v. 37, p. 515–518.

Yang, Y.J., Ritzwoller, M.H., Zheng, Y., Levshin, A.L., and Xie, Z., 2012, A Synoptic view of the distribution and

connectivity of the mid-crustal low velocity zone beneath Tibet: Journal of Geophysical Research, v. 117, B04303. doi:10.1029/2011JB008810
Yin, A., and Nie, S., 1993, An indentation model for North and South China collision and the development of the Tanlu and Honam fault systems, eastern Asia: Tectonics, v. 12, p. 801–813.
Zhang, J.S., Gao, R., Zeng, L.S., Li, Q.S., Guan, Y., He, R.Z., Wang, H.Y., and Lu, Z.W., 2010, Relationship between characteristics of gravity and magnetic anomalies and the earthquakes in the Longmenshan range and adjacent areas: Tectonophysics, v. 491, p. 218–229.
Zhang, K.L., and Wei, D.P., 2011, Implications from the kinematic pattern of the Longmenshan region: Tectonophysics, v. 504, p. 57–64.
Zhao, G.Z., Unsworth, M.J., Zhan, Y., Wang, L.F., Chen, X.B., Jones, A.G., Tang, J., Xiao, Q.B., Wang, J.J., Cai, J.T., Li, T., Wang, Y.Z., and Zhang, J.H., 2012, Crustal structure and rheology of the Longmenshan and Wenchuan Mw 7.9 earthquake epicentral area from magnetotelluric data: Geology, v. 40, p. 1139–1142.
Zhou, D., and Graham, S.A., 1993, Songpan-Ganzi Triassic flysch complex of the West Qinling Shan as a remnant ocean basin along diachronous Qinling collisional orogen, central China: Geological Society of America Abstracts with Programs, v. 25, p. 118.
Zhu, S.B., and Zhang, P.Z., 2010, Numeric modeling of the strain accumulation and release of the 2008 Wenchuan, Sichuan, China, Earthquake: Bulletin of the Seismological Society of America, v. 100, p. 2825–2839.