# Imaging the crustal structure beneath the Longmenshan fault zone and geodynamics for Wenchuan Mw 7.9 and Lushan Ms 7.0 earthquakes

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## Abstract

Although many velocity and electrical models have been proposed in the Longmenshan fault zone (LFZ) and its neighboring areas, the deep structure of seismic gap and the geodynamics of two different earthquakes remain uncertain. Based on aeromagnetic and gravity data, the Sichuan basin shows two NE-trending banded and strong positive magnetic anomalies and high Bouguer gravity anomalies. The banded magnetic anomalies represent the Neoproterozoic magmatic events in the center of Sichuan basin, rather than the rigid Neoarchean and Paleoproterozoic crystalline basement. The Songpan-Ganzi fold belt (SGFB) is weak positive magnetic and low Bouguer gravity anomalies. The LFZ is the boundary of two anomaly areas but similar to the feature of Sichuan basin. Three models are created by 2D magnetic and gravity forward modeling and provide more reliable and integrated geophysical interpretation for the deep structure of earthquake epicenter and seismic gap. The models reveal that the crust of Sichuan basin consists of double layer magnetic basement. More importantly, the basement subducted to about 33km west of the Wenchuan-Maoxian fault with low dip angle beneath the middle segment of the LFZ, whereas the distance decrease to about 17 and 19 km under the south segment. So, the crust of Sichuan basin beneath the middle segment extends further than the one beneath the south segment with the seismic gap as transition zone. Therefore, we propose the irregular shape of basement in western margin of Sichuan basin maybe the main reason for the different focal mechanism and geodynamic of Wenchuan and Lushan earthquakes.

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**Keypoint:**

1. The crust of Sichuan basin beneath the middle segment of the LFZ extends further than the one beneath the south segment.

2. The basement of Sichuan basin has double layer magnetic structure. Two earthquakes are occurred in the crust of Sichuan basin.

3. The different focal mechanism and geodynamics of two earthquakes may be constrained by the irregular basement shape of the Sichuan Basin.

**Abstract**

Although many velocity and electrical models have been proposed in the Longmenshan fault zone (LFZ) and its neighboring areas, the deep structure of seismic gap and the geodynamics of two different earthquakes remain uncertain. Based on aeromagnetic and gravity data, the Sichuan basin shows two NE-trending banded and strong positive magnetic anomalies and high Bouguer gravity anomalies. The banded magnetic anomalies represent the Neoproterozoic magmatic events in the center of Sichuan basin, rather than the rigid Neoarchean and Paleoproterozoic crystalline basement. The Songpan-Ganzi fold belt (SGFB) is weak positive magnetic and low Bouguer gravity anomalies. The LFZ is the boundary of two anomaly areas but similar to the feature of Sichuan basin. Three models are created by 2D magnetic and gravity forward modeling and provide more reliable and integrated geophysical interpretation for the deep structure of earthquake epicenter and seismic gap. The models reveal that the crust of Sichuan basin consists of double layer magnetic basement. More importantly, the basement subducted to about 33km west of the Wenchuan-Maoxian fault with low dip angle beneath the middle segment of the LFZ, whereas the distance decrease to about 17 and 19 km under the south segment. So, the crust of Sichuan basin beneath the middle segment extends further than the one beneath the south segment with the seismic gap as transition zone. Therefore, we propose the irregular shape of basement in western margin of Sichuan basin maybe the main reason for the different focal mechanism and geodynamic of Wenchuan and Lushan earthquakes.

**Keywords:** aeromagnetic and gravity, crustal structure, seismic gap, Longmenshan fault zone, Wenchuan earthquake, Lushan earthquake, geodynamics

## 1. Introduction

In 2008 and 2013, the devastating Wenchuan Mw 7.9 and Lushan Ms7.0 earthquakes struck the LFZ along the eastern margin of the Tibetan Plateau successively. The two events caused great losses to human lives and property in China.

A lot of researches involving the focal mechanism, coulomb failure stress and deep structure have been carried out in this area in order to find the relation between the two events and potential seismic hazard area along the LFZ. There are at least four differences between the two events: (1) The Wenchuan earthquake occurred in the Yingxiu-Beichuan fault in the middle section of the LFZ, while the Lushan earthquake occurred in a blind reverse fault east of the Shuangshi-Dachuan fault in the south segment (Li et al., 2013; Wang et al., 2014a; Chen et al., 2013), (2) The Wenchuan Earthquake is thrust faulting associated with a dextral strike-slip with surface rupture extending over 300 km toward NE (Chen et al., 2013). The Lushan Earthquake is dominated by pure thrust faulting with the rupture zone restricted in 30 km underground and no obvious surface rupture (Zhao et al., 2013; Chen et al., 2013), (3) The Lushan earthquake is located in the area where the Coulomb stress increased after the Wenchuan earthquake (Wu et al., 2013; Shan et al., 2013; Wang et al., 2017b), (4) High velocity (Vp, Vs), low Poisson's ratio, and high resistivity were determined at the 2013 Lushan hypocenter, whereas high velocity (Vp, Vs), high Poisson's ratio and high resistivity were imaged at the 2008 Wenchuan hypocenter (Lei and Zhao, 2010; Pei et al., 2010; Wang et al., 2009, 2015; Zhan et al.,2013). The key issue has been shifted to deep structure of seismic gap since the Lushan earthquake took place because these differences are constrained by an approximately 50km wide seismic gap. The recent achievements suggest the deep of seismic gap exist low velocity (Vp, Vs), high Poisson’s ratio and high conductivity materials interpreted as a fluid-bearing ductile crust (Pei et al.,2014; Wang et al., 2015; Liu et al.,2018). However, the formation of seismic gap and geodynamic of two earthquakes with different focal mechanism is still unclear（Teng et al., 2014；Wang et al., 2013；Chen et al., 2013；Xu et al., 2013；Wu et al., 2016）.

As we known, the uplift of LFZ is controlled by the interaction of Yangtze block and Tibet Plateau. The crustal structure of Yangtze block plays an important role in the thrusting and deformation of the LFZ because the Yangtze block as a rigid and stable Craton prevents the eastward expansion of the Tibetan Plateau. However, we still know a little about the structure of Yangtze block beneath the eastern Tibet Plateau because of thick sedimentary cover and less geophysical data. The geodynamic process of the LFZ and its constraint on the genesis of two different earthquakes remain uncertain. Several models have been proposed regarding the different emplacement styles of Yangtze block under the eastern Tibet Plateau (Guo et al., 2013; Yin et al.,2010); (1) Underthrusting of the Yangtze crust beneath the Songpan-Ganzi terrane (Clark et al.,2005; Jiang and Jin, 2005), (2) Indentation of the Yangtze crust beneath the Songpan-Ganzi terrane (Cai et al.,1996; Zhang et al.,2004). (3) Yangtze crystalline crust including rigid and highly thrusted portion extending beneath the eastern most Tibetan Plateau to the LRQF (Guo et al., 2013). These models are insufficient to explain the difference between two earthquakes due to the lack of detail crustal image along the LFZ. The purpose of this study is to provide more information on crustal structure beneath the middle and south segment of LFZ by 2D forward modeling of aeromagnetic and gravity data, and to give another perspective for understanding of the deep structure and geodynamic of LFZ.

## 2. Tectonic setting

The LFZ is formed by a series of parallel imbricate thrust fault with strike of NE-SW, the transition zone of Songpan-Ganzi fold belt and Sichuan Basin (Fig. 1a). This belt is bounded by the Mianxian-Lueyang suture (abbreviated to Mian-Lue suture) to the north and Xianshuihe fault to the south. There are four main reversed thrust and strike-slip faults from NW to SE, including the Wenchuan - Maowen Fault (F1), the Yingxiu - Beichuan Fault (F2), the Pengxian - Guanxian (Pengguan) Fault (F3), and Guangyuan - Dayi concealed fault (F4) (Figure 1b). The fault zone can be divided into three segments along the strike with the boundary of Beichuan-Anxian and Wolong-Huaiyuan. The north segment developed imbricate thrust fault system in front of outcropped Proterozoic Jiaoziding complex and Tangwangzhai syncline. The middle and south segments are characterized by the outcrop of Proterozoic Pengguan and Baoxing complex respectively. Both of them developed klippes along the front of the complexes. The geological observation suggests the time of deformation is getting younger, the deformation is more brittle and extensive, and the Cenozoic activity is more intense from northeast to southwest along the LFZ（Li et al., 2008）. The Wenchuan earthquake is located in the middle segment of the LFZ, while the Lushan earthquake lies in south segment.

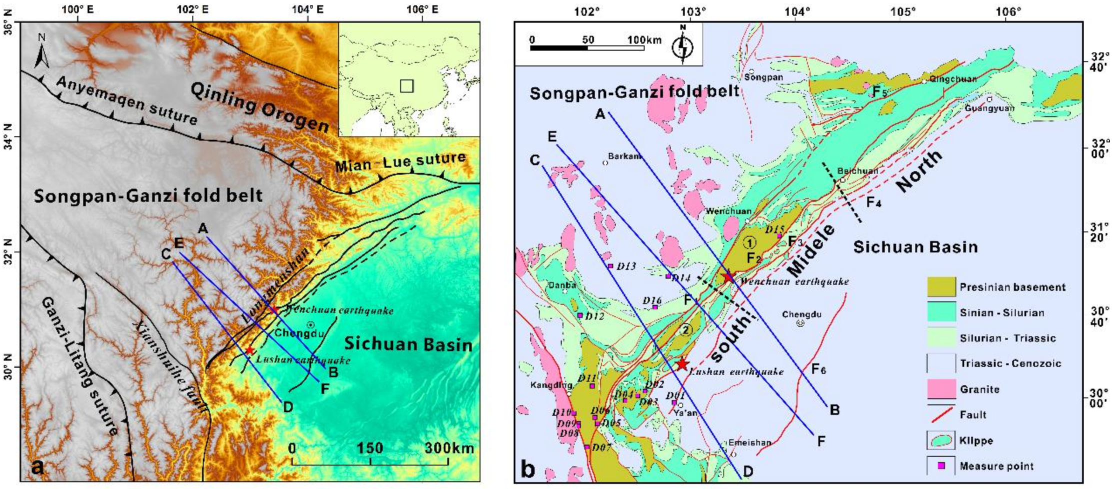


Fig.1 (a) Topographic map of the eastern Tibetan Plateau and Sichuan basin, showing the location of modeling profiles as blue lines. (b) Geological map of the LFZ (modified after Li et al., 2008 and Yan et al., 2011).

$F_1$:Wenchuan-Maoxian fault, $F_2$: Yinxiu-Beichuan fault, $F_3$: Pengxian-Guanxian fault, $F_4$: Guangyuan-Dayi concealed fault, $F_5$: Pingwu-Qingchuan fault, $F_6$: Longquanshan fault; ①Pengguan complex;②Baoxing complex

The strata are successive distributed from Proterozoic to Cenozoic in the LFZ. These outcrops record a lot of messages for tectonic evolution of the LFZ and provide important information for understanding the concealed basement in Sichuan basin. In order to study the aeromagnetic anomaly in the LFZ and surrounding areas, the magnetic susceptibility is measured for different kinds of rocks with each point test for 30 times. The result shows Proterozoic serpentine has the strongest magnetism with the average magnetic susceptibility value of $7645\times10^{-5}$SI. Proterozoic quartz diorite has moderate magnetic susceptibility of $2381\text{-}4873\times10^{-5}$SI with an average value of $3774\times10^{-5}$SI, while Proterozoic granite is $20\text{-}2466\times10^{-5}$SI with an average value of $679\times10^{-5}$SI. The Triassic and Jurassic granite is widely distributed in the west of the LFZ, the magnetic susceptibility is $1179\text{-}2012\times10^{-5}$SI, and the average value is $1670\times10^{-5}$SI. The magnetic susceptibility of Siguniangshan granite is $767\text{-}1614\times10^{-5}$SI with the average value of $1231\times10^{-5}$SI. Most sedimentary strata are non-magnetic except for the formations consisting of volcanic rocks. In general, the outcropped Proterozoic medium-acidic intrusive rocks are commonly strong magnetism.

Table 1 Statistic of rock magnetic susceptibility in the LFZ

| Period | lithologic | min | max | average | Point No. |
|---|---|---|---|---|---|
| Neoproterozoic | quartz diorite | 2255 | 5617 | 4069 | D04 |
| Neoproterozoic | granite | 8 | 285 | 50 | D05 |
| Neoproterozoic | granite | 132 | 816 | 405 | D06 |
| Neoproterozoic | granite | 94 | 477 | 318 | D07 |
| Neoproterozoic | granite | 1349 | 3590 | 2466 | D08 |
| Neoproterozoic | quartz diorite | 157 | 5417 | 2381 | D09 |
| Neoproterozoic | quartz diorite | 1440 | 8677 | 4873 | D10 |
| Neoproterozoic | granite | 153 | 2239 | 819 | D11 |
| Neoproterozoic | Serpentine (Not in-suit) | 4903 | 12030 | 7645 | D15-1 |
| Neoproterozoic | granite | 8 | 77 | 20 | D15 |
| Devonian | Mica schist | 710 | 8401 | 2497 | D12 |
| Permian | Basalt (Not in-suit) | 615 | 7099 | 3613 | D16 |
| Triassic | granite | 460 | 2387 | 1179 | D02 |
| Triassic | granite | 1053 | 2587 | 1820 | D03 |
| Triassic | Syenite (Not in-suit) | 1215 | 2428 | 2012 | D13 |
| Jurassic | granite | 767 | 1614 | 1231 | D14 |
| Cretaceous | Mudstone | 25 | 180 | 106 | D01 |

# 3. Method

## 3.1 Aeromagnetic data processing method

The aeromagnetic data used in this study are collected from Chinese 1/5,000,000 aeromagnetic maps that compiled by China Aero Geophysical Survey and Remote Sensing Center for Natural Resource (Xiong et al., 2013). The data grid is 1km×1km with the flight height set to 1km. Due to the effect of tilt magnetization, the magnetic anomaly center may not correspond to the location of geological body. Therefore, the frequency-domain dipole-layer changing inclination method is conducted for reduction to the pole to reduce the influence caused by the change of latitude (Xiong et al., 2013). In order to separate anomalies caused by deep-sourced magnetic bodies, upward continuation is performed through setting observation surface to 20km above the ground surface. Meanwhile, vertical first derivative calculation is used to study the distribution of shallow geological bodies and structures.

## 3.2 Two-dimensional (2D) forward modeling

Based on the previous seismic profile, the sequential modeling of the original gravity and aeromagnetic data afforded reasonable interpretation results as opposed to model each data individually. Velocity can not only provide Moho distribution and crustal layering for initial model, but also guiding for density modeling by speed-density empirical calculation formula (Christensen and Mooney，1995；Brocher，2005）. Then physical properties of different rocks were modeled, magnetic susceptibility contrast for aeromagnetic data and density for gravity data. So, the linked modeling of the three datasets produced integrated and less ambiguous results. Meanwhile, this method can easily add priori geological and structural information and the understanding of geologists to increase the interpretability of the model.

The models were created using 2D gravity/magnetic interactive modeling package running on GM-SYS Program, through Oasis Montaj Programs. The sequential gravity-magnetic modeling was done first by defining the depths to upper, middle, lower crust and Moho discontinuities from seismic image. The density values of initial model referred from the previous density structure in the Longmenshan area and were constrained by the seismic velocity results (Wang et al., 2014b; Zhang et al., 2014). The initial magnetic susceptibility was given by the measured data. The magnetic susceptibility of basement rock in Sichuan basin referred the outcropped Proterozoic intrusive rocks in the LFZ. Then the position, shape, dimensions, and physical property contrast of basement rock were adjusted to get the best fit between the observed and calculated data.

# 4. Aeromagnetic and gravity anomaly feature

## 4.1 Aeromagnetic anomaly feature

The aeromagnetic △T anomaly map shows that the magnetic anomaly feature of the Sichuan Basin is obviously different from the SGFB, Youjiang Basin, and Qinling Orogen (Fig. 2a). The Sichuan Basin is mainly characterized by NE-trending banded positive and negative magnetic anomalies with large scale and high intensity. The positive anomalies are mostly 200-400nT, and the negative anomalies can reach -300nT. According to the magnetic susceptibility measurement results of the exposed basement rock in the LFZ, the Proterozoic granites and diorite have strong magnetism with the average value of $679\times10^{-5}$SI and $3774\times10^{-5}$SI respectively. Therefore, the concealed basement rocks of the Sichuan basin causing large scale banded aeromagnetic anomalies may infer as the Proterozoic igneous rocks belt that some of them were outcropped on the surface by the thrusting of the LFZ. The SGFB and Youjiang basin present a weak and wide positive anomaly with an anomaly intensity of 10-60nT. The Qinling Orogen shows two distinct magnetic features. The eastern Qinling Orogen is linear distributed positive magnetic anomalies which are bounded by the Mian-Lue suture to the south, while the western Qinling is weak and negative magnetic anomalies with the Anyemaqen and Mian-Lue sutures bounded to the south. The sutures are usually characterized by beaded positive magnetic anomalies along a certain strike, because the mafic and ultramafic rocks emplaced along the active margin are strong magnetism, such as the Ganzi-Litang, Mian-Lue and Anyemaqen sutures. The Xianshuihe fault plays an important role in adjusting and absorbing the eastward extrusion of the Tibet Plateau. It is a sinistral strike slip fault separating Youjiang basin and Sichuan basin with different magnetic anomaly feature.

The magnetic anomaly feature of the LFZ is totally different from the Xianshuihe fault and sutures in this area. It is characterized by gradient zone of strong positive and negative anomalies that is more similar to the magnetic feature of the Sichuan basin in the $\triangle$T image (Fig.2a). According to the processing of reduction to the pole, the positive anomalies in Sichuan basin shifted toward north and their associated negative anomalies disappeared (Fig.2b). The LFZ lies in the banded positive anomalies that produced by rigid basement of Sichuan basin. Therefore, the location of fault zone on the surface is not consistent with the magnetic boundary of Sichuan basin and SGFB which is in the northwest of the LFZ. This result strongly suggests the LFZ thrusts above the basement of the Sichuan Basin causing the uplift of Longmenshan Mountain. More importantly, according to the anomaly feature of the △T anomaly image, the fault zone could be divided into the south, middle, and north segments along the strike with the boundary of Xiling-Qionglai and Nanba-Wulian. The south and middle sections are mainly characterized by positive magnetic anomalies and associated negative anomalies, but they are not continuous with the boundary of Xiling-Qionglai. The seismic gap is just located between two discontinuous magnetic anomalies. The north segment shows small scale linear magnetic anomaly zone on the negative background field. In addition, The Longquanshan fault (F6) doesn't break the magnetic anomaly of crystalline basement in the central of Sichuan basin, which suggests it is a shallow structure responding to the thrust and napping of the LFZ.

After 20km upward continuation of RTP image, magnetic anomalies caused by ultrabasic rock in the western Sichuan Basin have disappeared and are replaced by the magnetic anomalies of Sichuan basin (Fig.3a). The banded magnetic anomalies are connecting with each other and form a huge magnetic block. The Siguniangshan and Danba granite showing obvious positive anomalies in upward continuation image suggest that these plutons have large scale and buried depth. Both the Wenchuan earthquake and the Lushan earthquake occurred on the edge of the banded strong magnetic anomaly (Yan et al., 2016), but the Lushan earthquake was closer to the center of the magnetic body than the Wenchuan earthquake.

There is an obvious magnetic boundary from Daofu, Danba to Chengdu, which separates two distinct magnetic anomaly areas (Fig.2a). This boundary is divided into two parts by the Longmenshan fault zone in the middle. It is inferred as a concealed fault that the west segment merges into the Xianshuihe fault, and the east segment extends into the Sichuan Basin. The west segment is distributed along Ganzi-Danba-Daxuetang where the magnetic anomaly features are totally different on both sides. The magnetic anomalies on the north side of the fault are mainly caused by Triassic and Jurassic granites and syenites, and the one on the south side is mainly caused by strata consisting of volcanic rocks. The east segment lies in Xilingzhen-Dayi-Chengdu which is characterized by the linear discontinuity of magnetic anomalies. The change happened in the weak or non-magnetic basement with relatively negative magnetic anomaly. Therefore, the EW-trending linear discontinuity is not clear on the △T and RTP image, but it is obvious on the vertical first derivative image of RTP aeromagnetic △T data (Fig.3b). The small change suggest that the fault is possibly formed by the differential uplift of the weak magnetic basement in Sichuan basin.

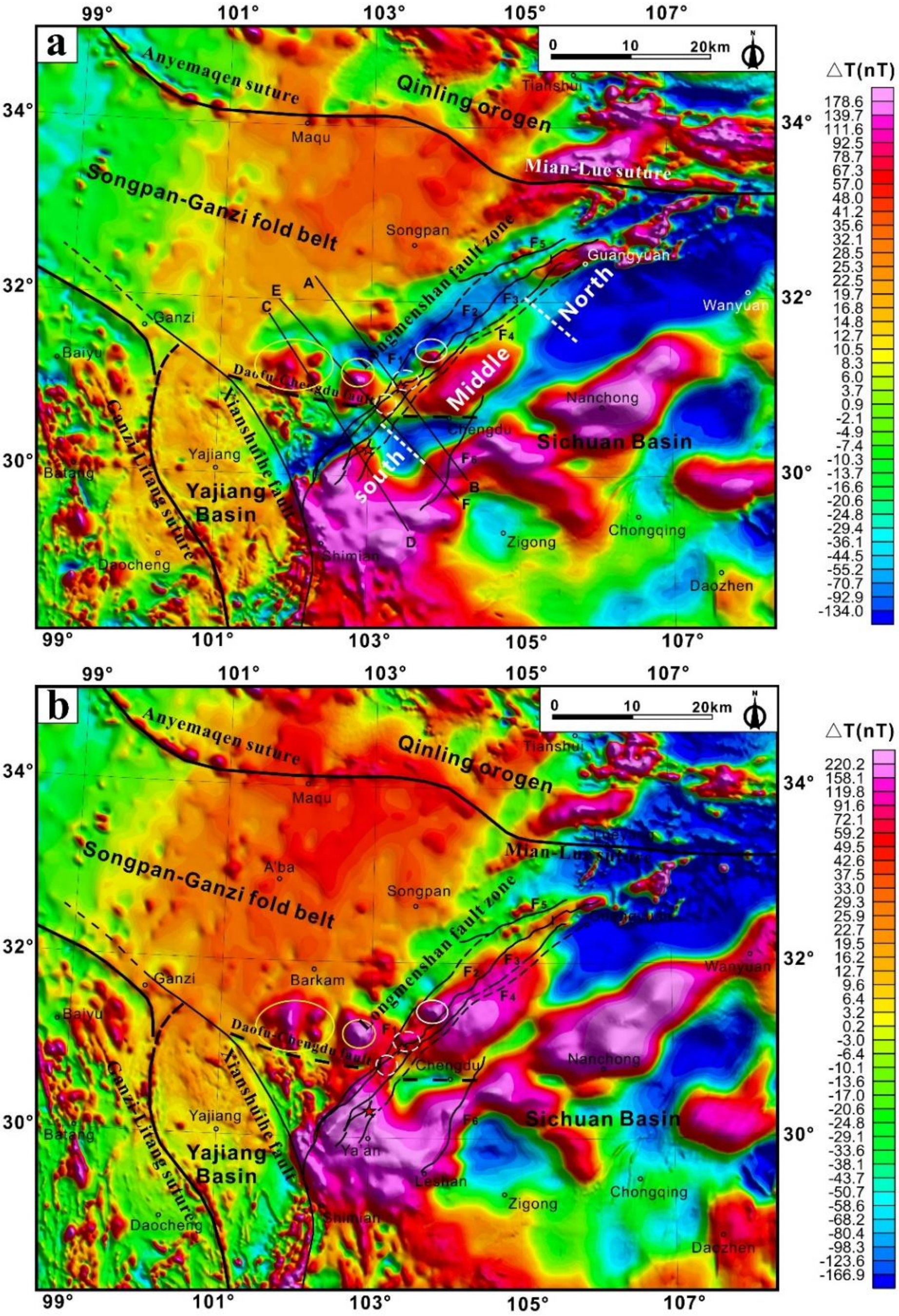


Fig.2 (a) Aeromagnetic △T anomaly image of the LFZ and adjacent area, (b) Reduction to the pole (RTP) image of aeromagnetic △T data in the Longmenshan and adjacent area.

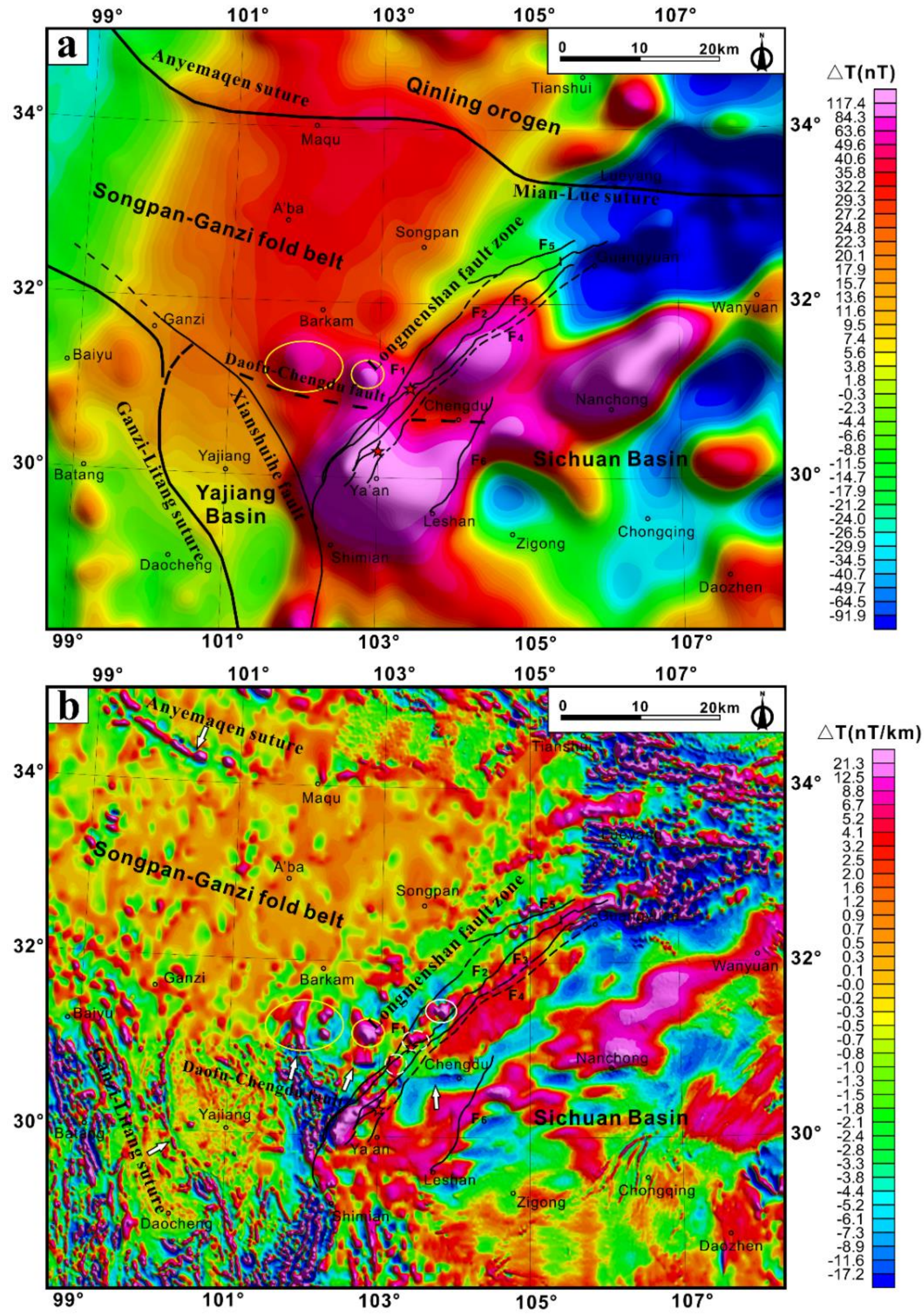


Fig.3 (a) 20km upward continuation image of RTP aeromagnetic △T data in Longmenshan and adjacent area, (b) Vertical first derivative image of RTP aeromagnetic △T data in Longmenshan and adjacent area

## 4.2 Bouguer gravity anomaly feature

According to the 1/500,000 bouguer gravity anomaly image (Fig. 4), the Sichuan Basin shows high bouguer gravity anomaly with value ranging from -185 to -90 mgal. The SGFB is relatively low bouguer gravity anomaly with value of -435 to -250 mgal. The LFZ is characterized by gradient zone between two blocks with a gravity value of

-290 to -185 mgal. Obviously, the crust of Sichuan basin has a higher density than the one in Songpan-Ganzi fold belt. The gravity anomaly feature in the LFZ is similar with the anomaly produced by the basement of the Sichuan Basin. More importantly, the gravity anomaly feature also could be divided into two segments along the fault strike with the boundary of Xiling-Qionglai. The bouguer gravity value of middle segment is -250～-185mgal, while the southern segment is -290～-215mgal. The segmentation of the LFZ through gravity anomaly is consistent with result divided by magnetic anomaly on the aeromagnetic △T image. The epicenter of Wenchuan earthquake is located in a relatively high gravity anomaly area with the value ranging from -215 to -225 mgal, while the Lushan earthquake is low gravity value of -250 to -260 mgal. The seismic gap is a transition zone where the epicenters of two earthquakes on both sides show different gravity anomaly features.

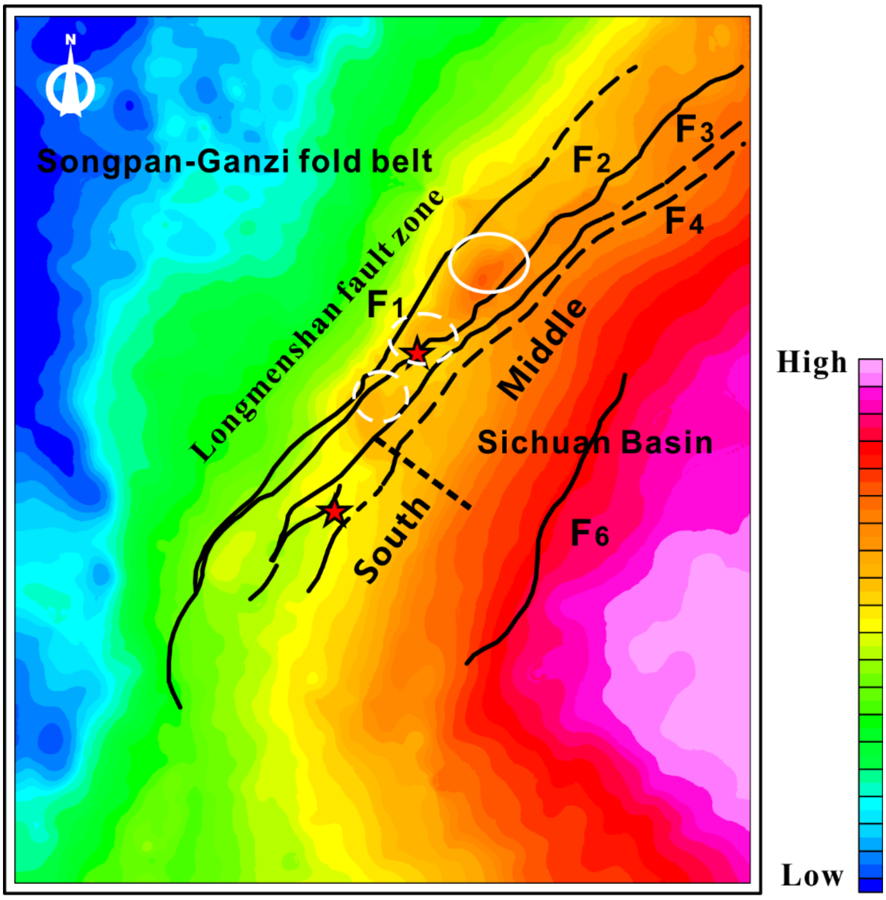


Fig.4 Bouguer gravity anomaly image of Longmenshan and adjacent area.

## 5. 2D forward modeling results of the LFZ

In recent years, a lot of seismic imaging works have been published to discuss the velocity structure of earthquake epicenters and seismic gap (He et al., 2017; Liu et al, 2018). Three S-wave velocity models are founded by receiver function method based on the seismic data acquired from 57 temporary and fixed seismic station (He et al., 2017). These models show clearly S-wave velocity change beneath the epicenter of two earthquakes and the seismic gap. In order to gain a reliable model of crustal structure in the LFZ, three S-wave velocity profiles were used to constrain the 2D magnetic and density modeling. The calculated models first provide magnetic and density information beneath the Longmenshan and adjacent areas.

**(1) Profile AB**

Profile AB passed through epicenter of Wenchuan earthquake (Fig. 5). The southeast of the profile shows strong magnetic and high gravity anomaly values suggesting the basement of Sichuan basin is strong magnetic and high density. The SGFB is relatively weak magnetic and low density. The modeling results indicate the magnetic susceptibility and density of magnetic basement are 1885-4398×$10^{-5}$SI and 2.65-2.75g/$cm^3$ respectively in Sichuan basin. The depth to the top of the magnetic basement is 5-7 km, and the thickness is about 15-20 km. The thickness of magnetic basement is stable in the basin, but it gradually thins through the LFZ and disappeared near Lixian. In contrast, the values are 125-188×$10^{-5}$SI and 2.68-2.70g/$cm^3$ in Songpan-Ganzi area respectively. The depth to the top of basement is about 4-10km, and thickness is 12-18km. There is a non-magnetic area between two basements with low density, which is a vertical low-velocity zone that extends downward to the crustal low-velocity zone in the Vs model. This zone is probably a weak and brittleness area formed by the collision of Sichuan Basin and the Songpan-Ganzi fold belt.

The model indicates the crust of Sichuan basin is double-layer magnetic structure. Strong magnetic basement have high average magnetic susceptibility of

3142-4398×$10^{-5}$SI in the southeast end of the profile, which is corresponded to the NE-trending positive magnetic anomaly belt in the central of Sichuan basin on the aeromagnetic △T image. The basement dips to southeast. The medium magnetic basement extends beneath the LFZ from central Sichuan basin with an average magnetic susceptibility of 1885×$10^{-5}$SI. The medium magnetic layer is covered by the strong one. Moreover, there is a magnetic body with thickness of 16 km under the strong magnetic anomaly zone in the middle of Sichuan Basin with a magnetic susceptibility of 4398×$10^{-5}$SI, which infers to the Proterozoic igneous rocks. Meanwhile, Deep seismic reflection profile shows that there is a paleo subduction zone preserved in the middle of the Yangtze Craton with the depth about 42km (Gao et al.,2016; Wang et al., 2017a).

The LFZ is clearly the boundary of gravity anomaly in the profile, but not for the magnetic anomaly. The gravity value is slightly increased in the Longmenshan area, which could be well modeled by the uplift of high density geological body to the shallow surface through the thrust of the LFZ. The modeling magnetic basement of the Sichuan Basin obviously extends beneath the LFZ, which displays a high velocity zone in the Vs model (He et al., 2016). The gravity value decreases rapidly from Yinxiu-Beichuan fault to northwest, but the higher gravity value than the northwest end of profile may also shows the influence of the subducted basement. Moreover, the front edge of the magnetic basement is consistent with the rigid basement of the Yangtze crust given by the deep seismic reflection profile (Guo et al., 2013). The result strongly suggests the basement of the Sichuan Basin has been subducted to the west of the Wenchuan-Maoxian fault. The low-velocity zone of the middle-upper crust extends below the magnetic basement of the Sichuan Basin. The Wenchuan earthquake and its aftershocks are distributed inside the rigid magnetic basement of the Sichuan basin above the front of low-velocity layer.

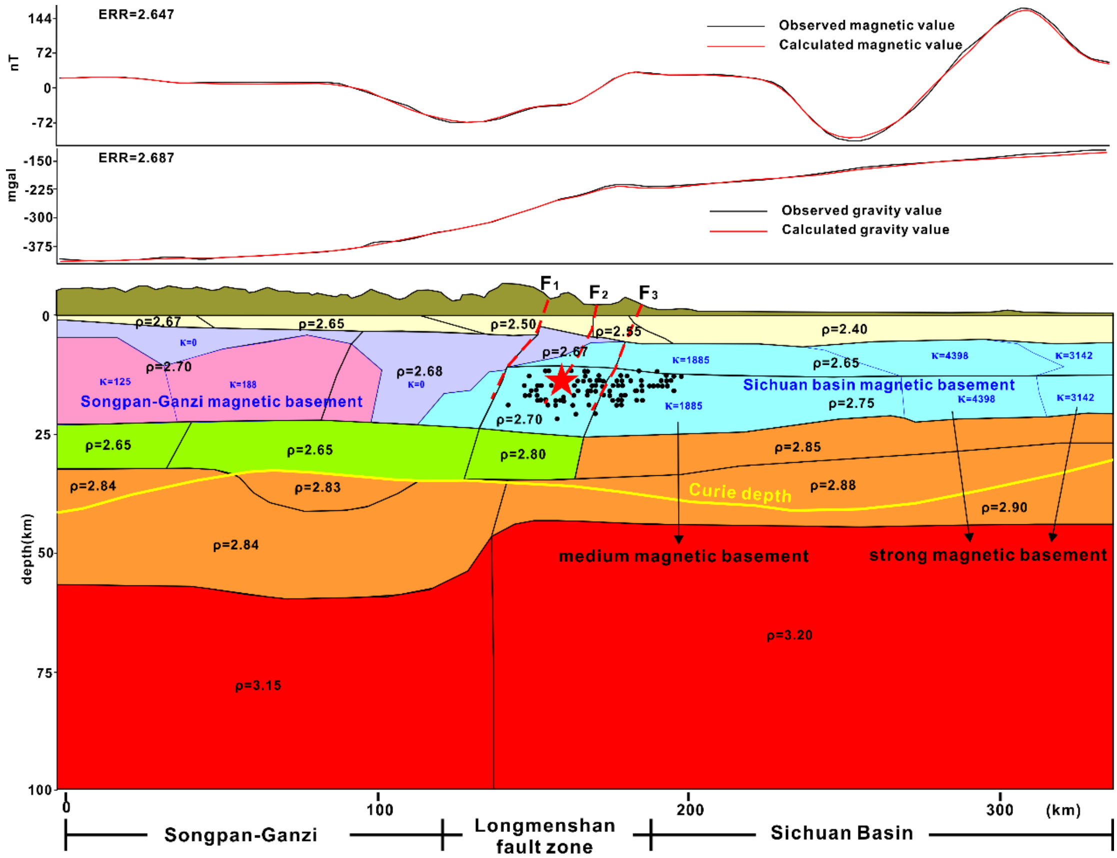


Fig.5 Two-dimensional gravity and magnetic model and interpreted crustal structure along the seismic profile AB. ρ marks density with the unit of g/cm$^3$, κ marks magnetic susceptibility with the unit of $10^{-5}$SI. Black line is the boundary of density block, blue line is the boundary of magnetic block.

**(2) Profile CD**

Profile CD passes through the epicenter of Lushan earthquake (Fig.6). In contrast to the profile AB, the bouguer gravity anomaly value gradually decreases from Sichuan basin to SGFB without obvious change through the LFZ. The values only slightly increase in the Longmenshan area, which are produced by the uplift of high density geological body. However, the magnetic anomaly values show big change on the both side of the LFZ. The values are high in the Sichuan basin and decrease rapidly in the LFZ. Therefore, the modeling result shows the basement of the Sichuan Basin is strong magnetism with magnetic susceptibility of 2500-4396×$10^{-5}$SI. The density is 2.65-2.70g/cm$^3$. The magnetic layer dip to the northwest. The depth to the top of magnetic basement is about 5-11km, and the thickness is about 17-23km. The magnetic layer thins from northwest to the middle of the basin and reaches about 17km in the middle. Meanwhile, there is a magnetic body with medium magnetic susceptibility of $1256\times10^{-5}$SI in the west of Wenchuan-Maoxian fault. The depth to the top of the magnetic body is 3-6km, and the thickness is 16-20km. The density is 2.73-2.75g/$cm^3$. The magnetic body is inferred as extensive medium-acid intrusive rocks formed in the west margin of Sichuan basin, because there are many Triassic and Jurassic granite, syenite, and granodiorite plutons outcropped on the surface with certain magnetism. The basement of SGFB has low magnetic susceptibility of 125-$377\times10^{-5}$SI in the northwest end of the profile. The depth to the top of the magnetic basement is about 4-7km, and the thickness is about 13-16km.

The magnetic basement of Sichuan basin also extends beneath the LFZ, but the subduction distance and occurrence are different from profile AB. For instance, there is no double layer magnetic structure in this profile. The magnetic basement subducts beneath the LFZ with a low angle and thins immediately in profile AB. However, the basement shows a high angle under the LFZ in profile CD. And, the top of magnetic basement shows large fluctuation. The result suggests the crystalline basement is highly thrusted and deformed in the southwest margin of Sichuan basin. The low-velocity layer in the middle-upper crust extends below the magnetic basement of the Sichuan Basin. The Lushan earthquake and its aftershocks are distributed inside the rigid magnetic basement of the Sichuan Basin above the low-velocity layer.

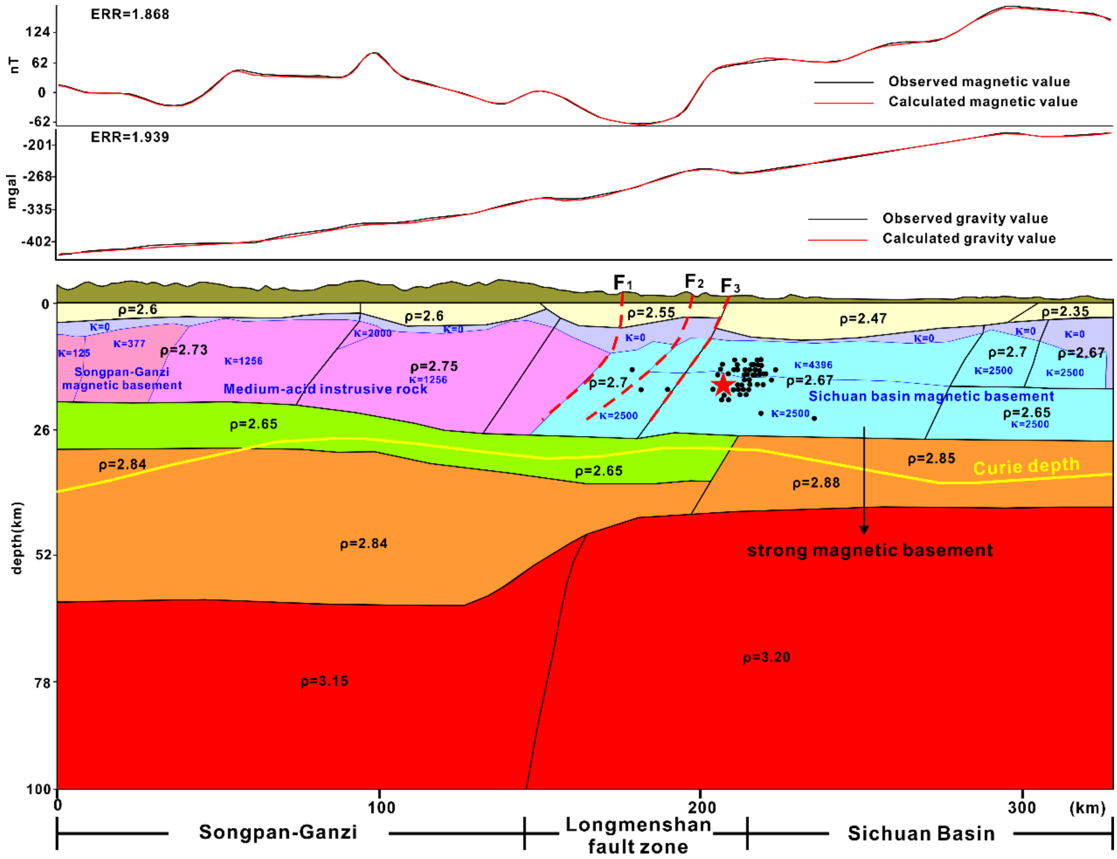


Fig.6 Two-dimensional gravity and magnetic model and interpreted crustal structure along the seismic profile CD. ρ marks density with the unit of g/cm$^3$, κ marks magnetic susceptibility with the unit of $10^{-5}$SI. Black line is the boundary of density block, blue line is the boundary of magnetic block.

**(3) Profile EF**

Profile EF passes through seismic gap (Fig.7). The bouguer gravity anomaly values show obvious change from Sichuan basin to SGFB with the boundary of the LFZ. The values slightly increase in the Longmenshan area, which are produced by the uplift of high density geological body. The magnetic anomaly values also show big change. The basement of Sichuan basin shows double layer magnetic structure, which is the same as profile AB. The strong magnetic basement distributes in the middle of Sichuan basin with the magnetic susceptibility of 1508-3770×$10^{-5}$SI. The depth to the top of the magnetic basement is 4-10km, and the thickness is about 15-19km. The medium magnetic basement is locally distributed beneath the Longmenshan area with a magnetic susceptibility of 1257×$10^{-5}$SI. The thickness gradually decreases and disappears in the west of the Beichuan-Yingxiu fault. However, the contact of double-layer magnetic basement does not show the feature that strong magnetic basement covers the medium one directly as in profile AB. A large area of non-magnetic sedimentary cover or basement is distributed between the two magnetic layers. Moreover, the strong magnetic basement dips to northwest, rather than the southeast in profile AB.

The magnetic anomaly values increase rapidly in the northwest of the LFZ, which is caused by the outcropped Siguniangshan granite with magnetic susceptibility of 1257×$10^{-5}$SI. The modeling result shows the pluton extends downward to the low-velocity zone of the middle-upper crust from surface and the thickness is about 22km. The magnetic basement under the Longmenshan area of this profile does not have a complex thrust and nappe structure like the previous two profiles. The low-velocity layer in the middle and upper crust doesn't extend below the magnetic basement in the Sichuan Basin.

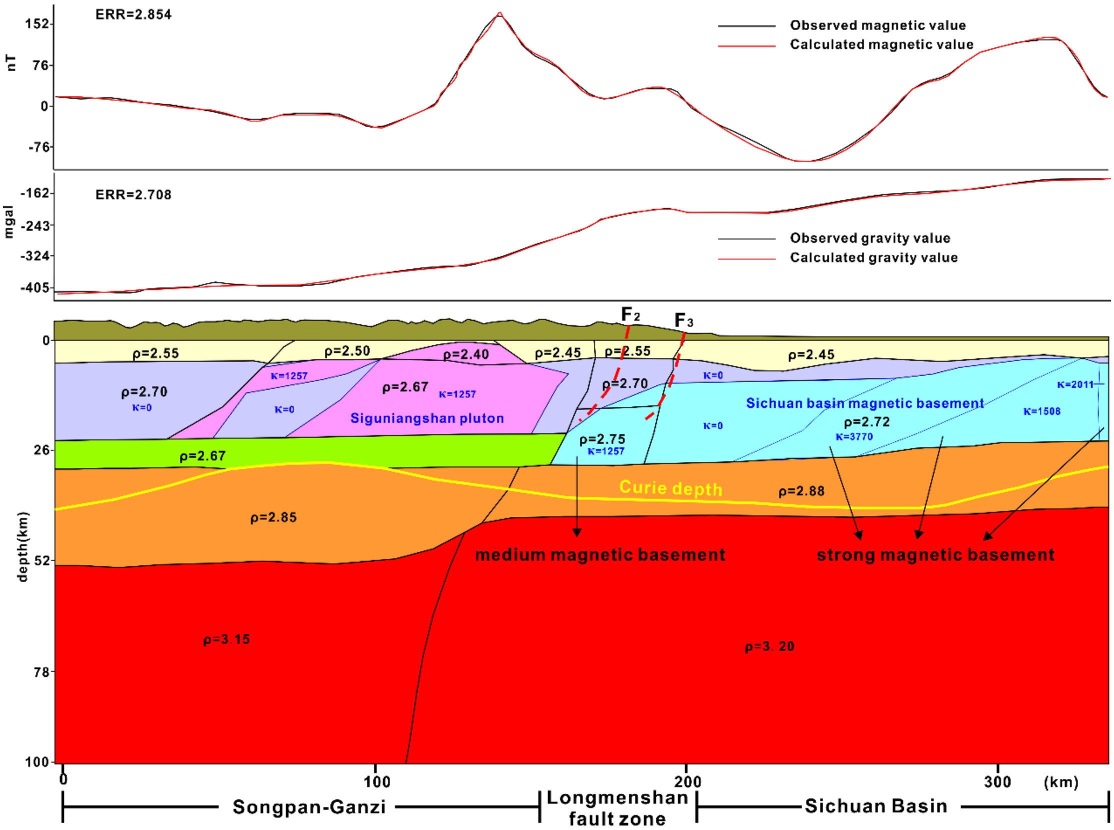


Fig.7 Two-dimensional gravity and magnetic model and interpreted crustal structure along the seismic profile EF. ρ marks density with the unit of g/cm$^3$, κ marks

magnetic susceptibility with the unit of $10^{-5}$SI. Black line is the boundary of density block, blue line is the boundary of magnetic block.

# 6. Discussion

## 6.1 The basement of Sichuan basin

The result not only provides 2D magnetic and density information for the crust of Sichuan basin, but also the geometry of different geological unit. The characteristics of gravity and magnetic anomaly are totally different between Sichuan Basin and SGFB. The Sichuan Basin shows NE-trending banded positive and negative magnetic anomalies with intensity ranging from -200 to 300 nT. The magnetic anomalies become large scale magnetic block after 20 km upward continuation. The feature suggests the geological bodies produced the anomalies are large scale and deep source. The Sichuan Basin also has high Bouguer gravity values ranging from -185 to $-90\times10^{-5}$m/s$^2$. The aeromagnetic field in the Songpan-Ganzi region is reflected as a broad positive and negative anomaly area with low anomaly intensity of -40～40nT. When the magnetic data is conducted upward continuation to 20 km, the magnetic anomaly shows the same feature. The SGFB is relatively low bouguer gravity anomaly with value of -435 to -250 mgal. The results indicate the crust of SGFB is weak magnetic and low density compared with the crust of Sichuan basin.

Based on the understanding of previous geological survey, the basement rocks are mainly composed of Neoarchean - Paleoproterozoic crystalline basement and Meso- to Neoproterozoic folded basement in Sichuan basin (SBGMR， 1991). The Neoarchean-Paleoproterozoic crystalline rock is represented by the Kangding group with high grade metamorphism. The Meso- and Neoproterozoic folded basement rocks are represented by a sequence of low grade metamorphism strata, such as the Qiasi， Yanbian, Huangshuihe, Tongmuliang, Huodiya, Huili, E'bian, Dengxiangying and Lengjiaxi Groups. However, a large amount of geochronological and geochemical evidences have shown that the Kangding complex has arc signatures, representing metamorphic products of Neoproterozoic, arc-related acidic plutons, rather than Neoarchean and Paleoproterozoic crystalline basement (Zhou et al., 2002; Lai et al., 2015; Chen et al., 2005; Du et al., 2007; Kang et al., 2017; Liu et al., 2009; Geng et al., 2007). Meanwhile, a few zircon U–Pb data has shown the Huangshuihe and Yanjing Groups also formed in the Neoproterozoic, and the E' bian group formed in late Mesoproterozoic (Ren et al., 2013; Du et al., 2005; Chen et al., 2018). These late Mesoproterozoic and Neoproterozoic assemblage outcropped in western margin of Sichuan basin are well matched with the positive magnetic anomalies on RTP aeromagnetic △T anomaly image (Fig.8). According to the field observation of magnetic susceptibility, the Neoproterozoic quartz diorite usually has strong magnetism, while the Neoproterozoic granites have relatively low magnetic susceptibility values. Both of them could produce strong positive magnetic anomalies. Therefore, the banded positive magnetic anomaly is closely related to the Neoproterozoic magmatic events, rather than the present of rigid Neoarchean and Paleoproterozoic crystalline basement in the center of Sichuan basin. The result strongly suggests the Sichuan basin formed a uniform block by the converging of ancient micro blocks along the concealed magmatic rock belt during Late Mesoproterozoic and Neoproterozoic. The belt produced large scale banded magnetic anomalies in the central of Sichuan basin.

More importantly, magnetic anomaly feature provides essential information for spatial and temporal distribution of basement in Sichuan Basin. The calculating models suggest the basement of Sichuan basin has double layer magnetic structure in profile AB and EF, which indicate the basement may be formed by two blocks with different rock assemblage (Fig.5 and Fig.7). The strong magnetic layer covers the medium magnetic layer directly in profile AB. However, the strong magnetic layer covered by non-magnetic sedimentary formation or basement, and the medium magnetic layer locally distributed in the west margin of Sichuan basin in profile EF. Meanwhile, there is only one layer magnetic basement in profile CD. This may indicate the basement composition is different along the western margin of Sichuan basin (Fig.9). More importantly, the magnetic basement wedges beneath the LFZ with the distance about 33km west of Wenchuan-Maoxian fault in profile AB. The result is consistent with the model inversed by magnetotelluric data (Zhu et al., 2008).

However, the distance is 17km and 19km in profile CD and EF. Therefore, the subducted distance of the basement has big lateral change which is the same as the composition along the western margin of Sichuan basin. The basement beneath the middle segment of the LFZ extends farther than the one under the south segment, which formed a "stair-shape" along the Longmenshan fault (Fig.9). The Wenchuan and Lushan earthquakes occurred on different step surfaces.

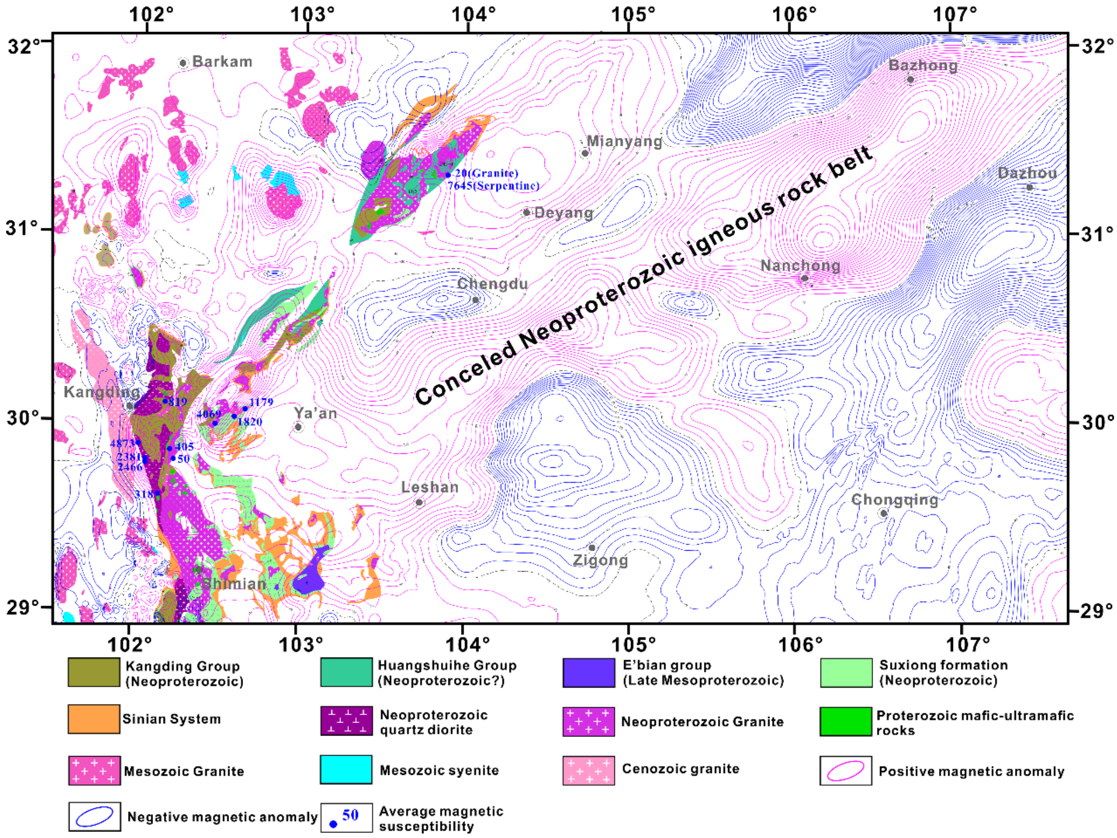


Fig.8 RTP aeromagnetic △T anomalies contour and outcrops of Precambrian basement and intrusive rocks in the western margin of Sichuan basin (modified after 1:1, 000, 000 digital geological map of China (Li, 2005) and reference from Zhou et al.(2002)).

The modeling results indicate two disastrous earthquakes and their aftershocks are mainly distributed in the magnetic basement of the Sichuan Basin (Fig.7 and Fig.9). The magnetic basement has undergone a strong deformation because the top of the layer has obvious fluctuation beneath the LFZ. Meanwhile, the thickness has gradually decreased when the magnetic basement wedges in the eastern Tibet Plateau. However, the deformation of magnetic basement is not obvious beneath the seismic gap. The seismic images show the crustal low velocity zone extends beneath the epicenter of Wenchuan and Lushan earthquake, but it doesn’t extend under the seismic gap (He et al., 2017). Therefore, the happening of two earthquakes may be closely related to the destruction of the magnetic basement through the detached upper crust of SGFB collision with the Yangtze’s crust. The western margin of Yangtze block also shows several obvious discontinuities in the Moho surface on the seismic sounding profile (Guo et al., 2013).

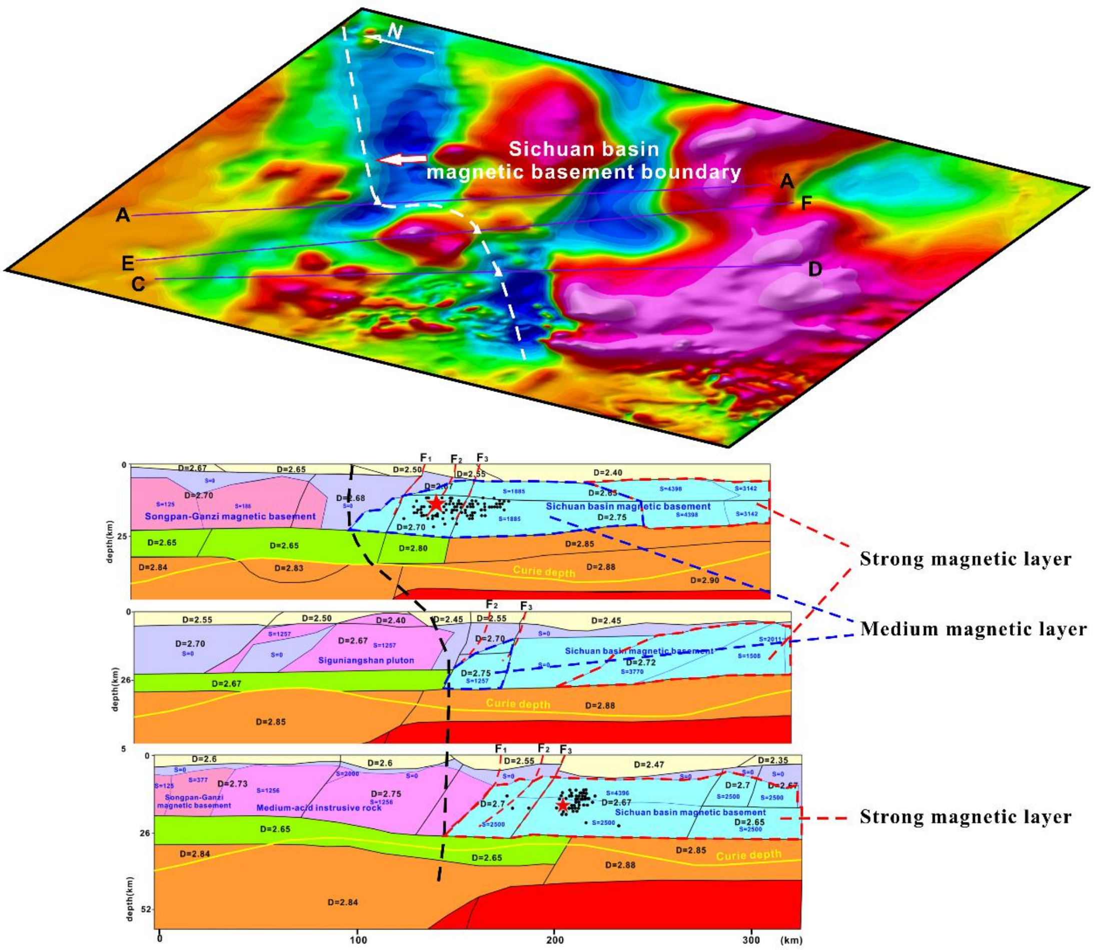


Fig.9 Western margin of magnetic basement in Sichuan basin.

## 6.2 Seismogenesis mechanism of the LFZ

The LFZ is the transition zone of Tibet Plateau and Yangtze Craton. A lot of researches suggest the LFZ has been thrust above the Sichuan basin (Wang et al., 2015; Zhu et al., 2008；Guo et al., 2013；Xiong et al., 2016). This hypothesis could be well proved by magnetic and gravity data. The magnetic anomaly feature of LFZ is represented by the feature of Sichuan basin, because the thrusted sedimentary covers are commonly non-magnetic. The gravity anomaly feature in the LFZ is similar with the anomaly produced by the basement in the Sichuan Basin. As we known, the Sichuan basin has been subducted beneath the SGFB during the Late Indosinian - Early Yanshanian. The process caused partial melt of the crust and formed a series of intermediate-acid intrusive rock in the SGFB. The isotope and chronology data show that these rocks have Proterozoic clastic zircon cores and Nd model ages ($T_{DM}$), which indicate there is Proterozoic Yangtze-type continental crust beneath the Songpan-Ganzi area (Dai et al., 2011；Hu et al., 2005；Zhao et al., 2007a，b). The modeling results confirm the basement of the Sichuan basin has extended to the west of the Wenchuan-Maoxian fault and reached the deep of the SGFB. Therefore, The LFZ doesn’t show unique feature on the magnetic and gravity image, because it is a transition zone that the crust of Sichuan basin dose exists under the SGFB.

The gravity and magnetic anomalies show obviously lateral change along the strike of the LFZ, which could be divided in to south, middle and north segments (Fig.2a and Fig.6). The south segment is characterized by the magnetic anomaly gradient zone and the low Bouguer gravity anomaly, while the middle segment is the magnetic anomaly gradient zone and high Bouguer gravity anomaly. The Wenchuan and Lushan earthquakes are distributed in the middle and south segment respectively. The boundary between the two segments is the gap with rare seismic events when two earthquakes happened. The northern segment is characterized by a negative magnetic field with some linear magnetic anomaly zone superimposed. The division based on geophysical data is the same as the surface deformation of the LFZ (Li et al., 2008). The 2D modeling results suggest the lateral change of magnetic and gravity anomaly is attributed to different extending distance and formation of magnetic basement of Sichuan basin beneath the LFZ. It strongly suggests that the distribution of magnetic basement controls the evolution and deformation of shallow structures in western margin of Sichuan basin.

The Wenchuan earthquake occurred in the Yingxiu-Beichuan fault, which belongs to the central-front range fault system in the middle segment of the LFZ. The Lushan earthquake took place in a blind reverse fault to east of the Shuangshi-Dachuan fault, which belongs to the front range fault system in the south segment of the LFZ. Although the two segments are separated by the seismic gap with small distance, the geological deformation is quite different. The front range structure in the southern segment is much more complicated than that in the middle segment. Meanwhile, the range of latest structural deformation increases from 30km in the middle segment to 150km in the south segment (Xu et al., 2013). The focal mechanism shows the Lushan earthquake is a pure thrust event without obvious rupture on both sides (Chen et al., 2013). The axis of the maximum horizontal stress lies in NW-SE (Luo et al., 2015). However, the Wenchuan Earthquake is dominated by thrusts with a dextral strike-slip component. The surface rupture mainly extends toward northeast with the distance about 300km. The axis of the maximum horizontal stress presents several different directions (Luo et al., 2015). These features indicate that the deformation mechanism of the middle and south segment is different. High-resolution geodetic data shows the surface deformation has obvious change on the both side of seismic gap (Wang et al., 2011). Therefore, this study proposes the differences for the focal mechanism of the two earthquakes may be closely related to differential thrusting mechanism caused by the irregular basement shape in the western margin of the Sichuan Basin.

Both earthquakes and their aftershocks occurred in the rigid magnetic basement of the Sichuan Basin, where is characterized by high velocity area in seismic image (Wang et al., 2015). There is a seismic gap with low Vp and Vs, high Poisson's ratio, and high conductivity between the two earthquakes. It is inferred as a fluid-rich ductile crust extending to the middle and lower crust (Pei et al., 2014; Zhan et al., 2013; Wang et al., 2015). According to the modeling result, the seismic gap also has magnetic basement. But the magnetic anomalies appear discontinuity along Xiling Town-Dayi-Chengdu, which is inferred as a fault zone that cut the basement of

Sichuan basin. Because the sedimentary covers are commonly non-magnetic in Sichuan basin that could not cause the change of magnetic anomaly. The magnetic anomaly decays obviously after 5km upward continuation, which suggests the displacement is small between the hanging wall and foot wall. The fault cuts the magnetic anomaly and extends to Longquanshan Mountain. The seismic result shows the ductile crust extend 20-30km in deep and cuts the curst of Sichuan basin（Wang et al., 2015；He et al., 2017）. The fault may be closely related to the early activities of Longmenshan fault and the uplift of Longquanshan Mountain.

This contributes proposed a schematic model (Fig.10). The rigid basement of the Sichuan Basin wedges beneath the Songpan-Ganzi fold belt during Late Indochina-early Yanshanian. The basement beneath the middle and north segment of the LFZ wedges further than the one under the south segment. The lateral change of the basement could cause the Songpan-Ganzi fold belt to tear into two pieces with different mechanic system (slab 1 and slab 2 in Fig.10). Different mechanical systems lead to different activities of the two slabs that forms a series of extension environment for the emplacement of intermediate and acid intrusive rocks. This tectonic framework has been preserved until now. With the continuous uplift of the Tibet Plateau, the compression stress is increasing in the western margin of Sichuan basin. In 2008 and 2013, two earthquakes with different focal mechanism happened successively in the middle and south segment of the LFZ. Two earthquakes are located in the different basement of Sichuan basin. The Lushan earthquake was blocked by the irregular basement of the Sichuan Basin and the Siguniangshan pluton to the northeast, and was constrained by the Xianshuihe fault to the southwest. But the Wenchuan earthquake only was controlled by the Siguniangshan pluton to the southwest. Apparently, the central Sichuan basin maybe involved in the early thrust process of the south segment of the LFZ, which is represented by the displacement of basement and uplift of Longquanshan Moutain.

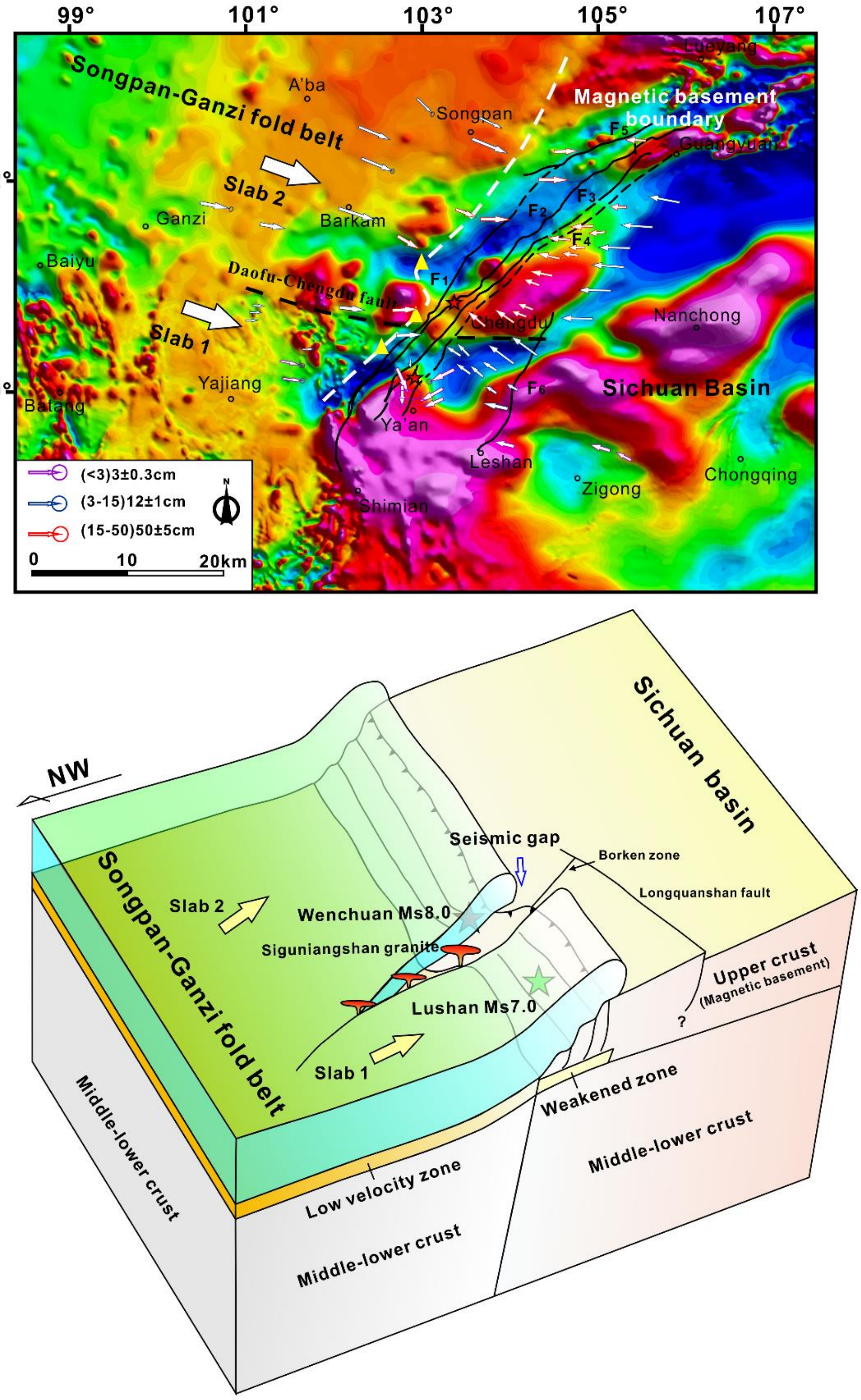


Fig.10 Schematic deep structure model of Longmenshan and adjacent area

The earthquake catalogs are collected from the China Earthquake Networks Center (CENC). The statistical result shows earthquake distribution in Longmenshan area since 1970 with the magnitude above four (Figure 11). It should be noted that there were almost no earthquakes in the southern segment of the LFZ when the

Wenchuan earthquake occurred. However, a lot of earthquakes happened in the middle-north segment when the Lushan earthquake occurred. The results show that the stress mainly accumulated in the middle and north segment of the LFZ before the Wenchuan earthquake. After the Wenchuan earthquake taken place, the stress began to increase in the south segment until the Lushan earthquake was triggered. A lot of studies prove that the Coulomb stress in the southern segment of the LFZ began to increase after the Wenchuan earthquake occurred (Wang et al., 2014c; Jia et al., 2014; Shan et al., 2013; Parsons et al., 2008; Yi et al., 2013). The difference of stress accumulation may be related to the different wedging distance of Yangtze's crust beneath the middle and south segment of LFZ.

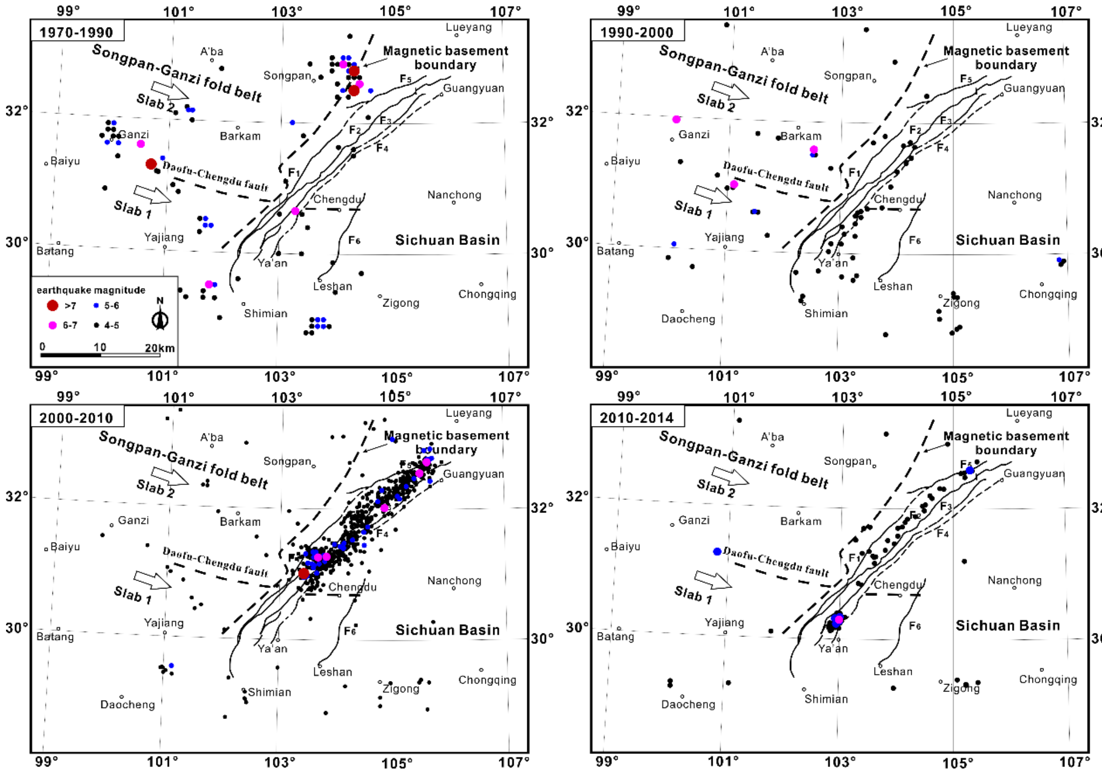


Fig.11 Distribution of earthquakes (magnitude≥4) in Longmenshan area since 1970

Our interpretation of two earthquakes is as follows:

(1) With the uplift of Tibet Plateau, The Songpan-Ganzi block continued to move toward the southeast and first colliding with the basement of the Sichuan Basin beneath the middle-north segment of the LFZ. Stress accumulated in the middle-north

segment and triggered the Wenchuan Ms7.9 earthquake. Due to the obstruction of emplaced Siguniangshan pluton, there was no large scale surface rupture presented to the southwest of the Wenchuan earthquake. But the rupture extended about 340km toward northeast.

(2) The compression stress was completely released in the middle and north sections of the LFZ after the Wenchuan earthquake occurred, which was represented by large-scale surface rupture and dextral strike-slip. Meanwhile, the compression stress shifted to the south segment and finally triggered the Lushan Ms7.0 earthquake. Due to the constraints of Yangtze's irregular crust and Xianshuihe fault on both sides, the Lushan earthquake was a pure thrust event without obvious rupture on both sides. There were some residual compression stresses still work in the middle-north segment, few earthquakes with low magnitude have been observed.

## 7. Conclusion

This study found the difference of gravity and magnetic anomaly between middle and south segment of the LFZ. Then 2D forward modeling was conducted under the constraint of the previous seismic image in this area. Three magnetic-density models were constructed, which passed through epicenter of Wenchuan and Lushan earthquake and seismic gap respectively. The result first proposes the basement of Sichuan basin beneath the middle segment is different from the one beneath the south segment. The basement has double layer magnetic structure and wedges beneath the middle segment of LFZ with a long distance and low dip angle. However, the basement is one layer magnetic structure and wedges beneath the south segment with a short distance and high dip angle. The magnetic basement involves in more intense deformation beneath the epicenter of two earthquakes than the seismic gap. Due to the irregular morphology of the basement and emplaced intermedium-acid intrusive rocks, the thrust mechanism is different in middle and south segment of the LFZ. It provides essential tectonic framework for the genesis of the two earthquakes with different focal mechanism. Meanwhile, the early thrust process in the south segment of the LFZ also caused the differential uplift of the basement on both side of Diya-Chengdu fault. This contribute provides some new geophysical evidence for mapping the deep structure of the LFZ. It is of great significance to study the genesis of earthquakes in the LFZ.

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