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Analysis on the Characteristics of Crustal Structure and Seismotectonic Environment in Zigui Basin, Three Gorges

Yunlong Wu[1,2,3], *Junling Pei*[4,5]*, *Ze Wang*[6], *Yi Zhang*[1,2] *and Huaqing Yuan*[1,2]

[1]*Key Laboratory of Earthquake Geodesy, Institute of Seismology, China Earthquake Administration, Wuhan, China,* [2]*Hubei Earthquake Administration, Wuhan, China,* [3]*College of Disaster Prevention Science and Technology, College of Geological Engineering, Sanhe, China,* [4]*Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, China,* [5]*Key Laboratory of Paleomagnetism and Tectonic Reconstruction, The Ministry of Land and Resources, Beijing, China,* [6]*GNSS Research Center, Wuhan University, Wuhan, China*

The Zigui Basin in the Three Gorges area is a syncline running in the north-south axial direction; the sediments in the basin are mainly late Triassic-late Jurassic sandy and argillaceous rocks. Since the Three Gorges Project began undergoing impoundment in May 2003, nearly 20,000 mini-earthquakes have occurred in the Zigui–Badong region, including five earthquakes with magnitudes greater than Ms 5.0. Herein, a 3D gravity inversion method was introduced to investigate the density structure of the Zigui Basin and its adjacent areas. A comprehensive analysis of the geological structure of the area was carried out, based on focal mechanism solutions of six moderate–strong earthquakes in the area. The Zigui Basin is a low–density area from the periphery, and the sediment in the east is thicker but less dense than in the west. The shallow part of the Zigui Basin is a weak bottom layer prone to slippage, and the deep part (5–10 km) could comprise lithological strata such as limestone, sandstone, and shale, which easily undergo dissolution by leaking reservoir water. Under the action of external forces such as long-term infiltration and unloading of reservoir water, fissures will expand and squeeze then earthquakes are likely induced in the deep strata. Furthermore, new buried faults in the western and southeastern edges of the core area of the Zigui Basin could also trigger an earthquake under long–term pressurization and reservoir water penetration.

Keywords: gravity analysis, 3D gravity inversion, Three Gorges area, Zigui basin, density structure

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Zhejiang University, China

***Correspondence:**
Junling Pei
junlingpei@163.com

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INTRODUCTION

The Zigui Basin in the Three Gorges area is located in the thin–skinned structural zone of Chongqing City, Hunan and Hubei Province, with the Yangtze Plate to the south, the Qinling Orogenic Belt to the north, the Sichuan Basin in the west, and the Huangling Anticline in the east. The entire area is squeezed by the Qinling Mountains and Xuefeng Mountains from north to south. The earthquakes in this area are contributed by a unique geological environment that the Three Gorges Reservoir has been in a state of infiltration for many years due to the slippage and folding of the weak sedimentary layer of the rocks in the area. (Li et al., 1987; Wang K. et al., 2013; Wang J. et al., 2018; Wang W. et al., 2018). According to records, there were two significant destructive earthquakes at the Zigui-Badong region in history: the Ms 5.1 Zigui Longhuiguan earthquake in 1979 and the Ms 5.1 Badong earthquake in 2013. Since the impoundment of the Three Gorges in May 2003, 4 Ms 4.0–4.9 earthquakes have occurred, accompanied by a large number of mini earthquakes with high frequency and low magnitude. This is worthy of in–depth study, as the frequent occurrence of earthquake activities is closely related to the special geological structure background and the water permeability of the Three Gorges Reservoir (Li et al., 2010; Wang Q. et al., 2013; Zhang et al., 2017).

Focusing on the complex geological structure and geophysical background of the Three Gorges area, many scholars have conducted extensive research in this area over the years. The analysis of rock thermal tectonic evolution in this area suggests that the Cretaceous and Cenozoic activation of the Qinling-Dabie Orogenic Belt in the North China and Yangtze Craton is the result of the Pacific subduction–North China back arc extension (Hu et al., 2006a; Hu et al., 2006b; Ge et al., 2013). The Yangtze Plate and the North China Plate collided with the orogenic belt in the late Middle Triassic to form the Qinling-Dabie Orogenic Belt, which in turn affected the periphery of the Yangtze Plate, and the Zigui Basin gradually changed from a marine basin to a foreland basin (Liu et al., 2005; Liu et al., 2015a). Throughout the Mesozoic sedimentary process, the basin underwent a northward, north–eastward, and eastward shift in the sediment source, corresponding to changes in paleocurrent in the southern Qinling Mountains (Liu et al., 2005; Shen C.-B. et al., 2012; Shen C. et al., 2012). The complex geological evolution has resulted in the unique geological environment in the Zigui Basin.

Since the construction of the Three Gorges Dam, there have been many studies on the gravity field and crustal deformation in response to changes in water storage in the Three Gorges and adjacent areas (Zhang et al., 1996; Wang et al., 2002; Wang et al., 2014). The relationship between the subsurface fault distribution and seismic coupling has been discussed using the Bouguer gravity and aeromagnetic anomalies, as well as the seismic sources distribution (Liu et al., 1984; Shen et al., 1990). Some scholars have also used the Bouguer gravity anomaly to investigate the crustal structure and the Moho depth of the Three Gorges area to obtain the layered structure of the crust in the area, and discuss the tectonic significance in the area with the regional faults (Li et al., 1987; Wang et al., 1992; Wang et al., 2012). Li et al. (2011) used seismic P and S wave arrival data and tomography method to obtain the 3D crustal velocity structure of the region, which provided new insights into the development and evolution of deep structures in the Three Gorges area.

Previous research has shown that the preparation and occurrence of earthquakes are related to the distribution and activity of underground fault structures. While the distribution and changes in the density of the Earth's crust can be considered to reflect the underground material migration, no study has been carried out to analyze the evolution of underground material migration against the background of geological formations and, furthermore, to analyze the relationship between regional faults and seismic tectonics coupling with natural seismic events (Li et al., 1987; Li et al., 2010; Wang K. et al., 2013; Wang Q. et al., 2013; Zhang et al., 2017). In this study, a 3D gravity inversion method with a Lagrange multiplier (Zhang et al., 2015) was introduced to determine the crustal density distribution with the constraints of prior local geological and geophysical information. Combining the focal mechanism solution of the six moderate earthquakes and the geological evolution background, the seismogenic structure and faults distribution in the area were analyzed.

GEOLOGICAL BACKGROUND OF ZIGUI BASIN AND ITS PERIPHERY IN THE THREE GORGES

Zigui basin of the Three Gorges in Western Hubei is an important tectonic unit in the Yangtze River area. This area is a Mesozoic tectonic basin that developed and formed in the late Triassic and early Jurassic eras and is mainly composed of Jurassic continental facies and middle–upper Triassic coastal facies clastic rocks (Yu et al., 2017). As shown in **Figure 1**, the stratigraphic outcrop in the area is relatively complete, Proterozoic dominated by Kongling Group, Shenlongjia Group, and Sinian; Paleozoic dominated by Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian; Mesozoic dominated by Triassic, Jurassic, and Cretaceous; and Cenozoic dominated by Quaternary are all exposed. Large areas of western and southern parts of the basin consist of marine carbonate sedimentary strata, while the eastern part is dominated by carbonate rocks with fine clastic rocks. The Huangling Anticline in the east and the Shennongjia Uplift in the north are mainly composed of gneiss, mixed rock, and granite in the Proterozoic Kongling Group (Qu et al., 2009).

The rock distributions and their density parameters are shown in **Table 1**. Gneiss and dolomite–dominated carbonate rocks are low–density materials with densities of approximately 2.58–2.74 g/cm^3, while dolomites, granites and metamorphic complexes are high–density materials with a density of approximately 2.72–3.2 g/cm^3. In this work, the rock density constraints in **Table 1** were used to carry out the gravity inversion.

As shown in **Figure 2**, the Badong-Zigui region is located in a low–medium mountainous area with deep canyons. The fault structures in the area are mainly NE- and NW-oriented, such as the NNE-directed Xinhua–Shuitianba fault and Niukou–Zhoujiashan fault, NE–directed Gaoqiao fault, NW-directed Wuduhe fault and Tianyangping fault, NNW-directed Xiannvshan fault, and EW-directed Maluchi fault. In terms of earthquake distribution, small-medium earthquakes in the Badong-Zigui region are concentrated in the Gaoqiao, Zhoujiashan, and Xiannvshan faults. 2 Ms 5.1 earthquakes have occurred near Xietan, and some studies took the Zhoujiashan fault into account as the seismogenic structure of the Zigui Longhuiguan Ms 5.1 earthquake in 1979 (Wuhan Earthquake Engineering Research Institute, 2010). From a spatial point of view, the small-medium earthquakes in this area are mainly concentrated in the wedge–shaped tectonic unit formed by the abovementioned faults.

3D GRAVITY INVERSION METHOD

The algorithm adopted in this work is based on the 3D gravity inversion method developed originally by Li and Oldenburg (1996, 1998); Oldenburg (1974). With the addition of the Lagrange multiplier, prior geological and geophysical information can be processed during the inversion by Zhang et al. (2015). The algorithm effectively reduces the problems of ill–posed and multi–solution in the gravity inversion and also improves the quality of the results.

The study area was divided into a series of rectangular units with constant density. Inversion is a process of iterations to

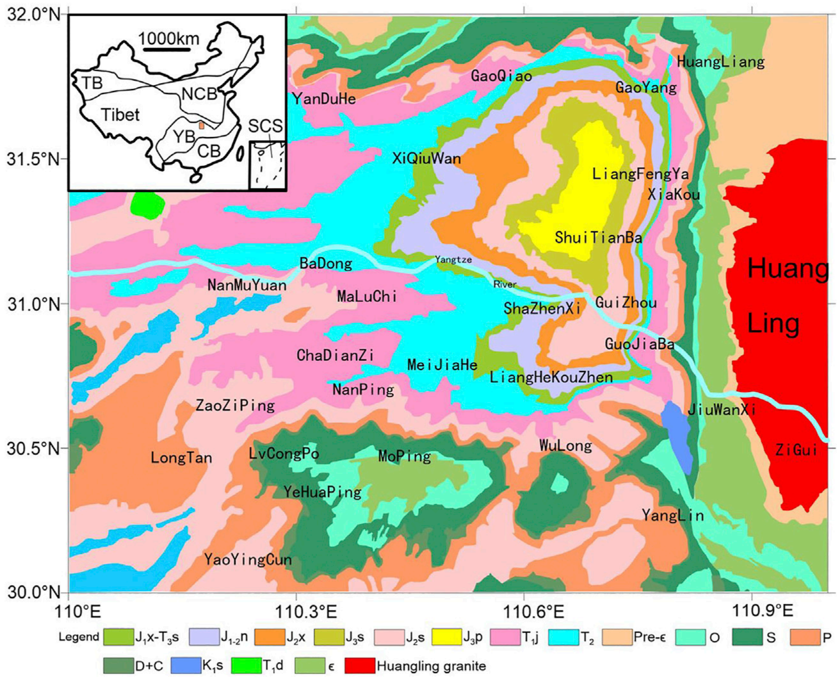

FIGURE 1 | Geographic location and the tectonic map of the Three Gorges reservoir area [from Zhang et al. (2018). J1x-T3s: Lower Jurassic (Xiangxi Formation)-Upper Triassic (Shazhenxi Formation), J1-2n: Middle Jurassic (Niejiashan Formation), J2x: Lower Jurassic (Shaximiao Formation), J3s: Upper Jurassic (Suining Formation), J2s: Upper Jurassic (Shaximiao Formation), J3p: Jurassic (Penglai Town Formation), T1j: Lower Triassic (Jialingjiang Formation), T2: Middle Triassic, Pre-ε: Precambrian, O: Ordovician, S: Siluric, P: Permian, D+C: Devonian-Carboniferous, K1s: Cretaceous (Shimen Formation), T1d: Lower Triassic (Daye Formation), ε: Cambrian].

TABLE 1 | Stratigraphic distribution and lithologic parameters in Badong–Zigui region.

Locations	Lithology and density parameters
Western and southern of ZGB	Marine carbonate sedimentary strata of the Middle–Lower Triassic Daye Formation, Jialingjiang Formation, and Badong Formation are exposed (Qu et al., 2009), with a density of approximately 2.6–2.9 g/cm^3
Eastern of ZGB	Sedimentary strata, dominated by carbonate rocks (i.e., dolomite), mixed with fine clastic rocks (Qu et al., 2009), with a density of approximately 2.58–2.75 g/cm^3
Northern of ZGB	Mainly Paleozoic marine strata (Qu et al., 2009), with a density of approximately 2.62–2.68 g/cm^3
SLJU area	Mainly the Mesoproterozoic and Paleozoic erathem, dominated by the marine carbonate rocks (i.e., dolomite), pyroclastic rocks, tuffaceous sandstones, and shales (Li et al., 2009; Liu et al., 2016), with a density of approximately 2.7–2.9 g/cm^3
HLA area	Mainly the Huangling granite, Proterozoic Kongling gneiss, and metamorphic complexes (Qu et al., 2014; Liu et al., 2015b), with the density of gneiss and granite being approximately 2.5–2.8 g/cm^3 and 2.73–3.2 g/cm^3, respectively

obtain the optimal solution. **Eq. 1** is the objective function proposed by Li and Oldenburg (1996, 1998):

$$\min : \phi(\boldsymbol{m}) = \phi_d + \mu\phi_m \tag{1}$$

where φ_d is the data misfit, the differences between the observations and the forward values of inversion results; φ_m is the model objective function, and μ is the regularization parameter used to balance the weight of the two items.

Based on the abovementioned inverted objective function, geological constraints are imposed on each grid cell, and a slack variable function is introduced (Zhang et al., 2012; Zhang et al., 2015),

$$\boldsymbol{s_i}(\boldsymbol{m}, \boldsymbol{z}) = \boldsymbol{s_i}(\boldsymbol{m}) + \boldsymbol{z}_i^2 = 0 \tag{2}$$

where $s_i(m)$ is a constraint function to deal with the bound constraints in the inversion, and z_i denotes the slack variables used to convert the upper or lower bound into equal constraints. the Lagrange multiplier and penalty function were further introduced to obtain the objective function:

$$\min : \boldsymbol{F}(\boldsymbol{m}, \boldsymbol{z}) = \phi(\boldsymbol{m}) + \sum_{i=1}^{N_Z} \boldsymbol{\lambda_i}\left[\boldsymbol{s_i}(\boldsymbol{m}) + \boldsymbol{z}_i^2\right] + \frac{1}{2}\boldsymbol{M}\sum_{i=1}^{N_Z}\left[\boldsymbol{s_i}(\boldsymbol{m}) + \boldsymbol{z}_i^2\right]^2 \tag{3}$$

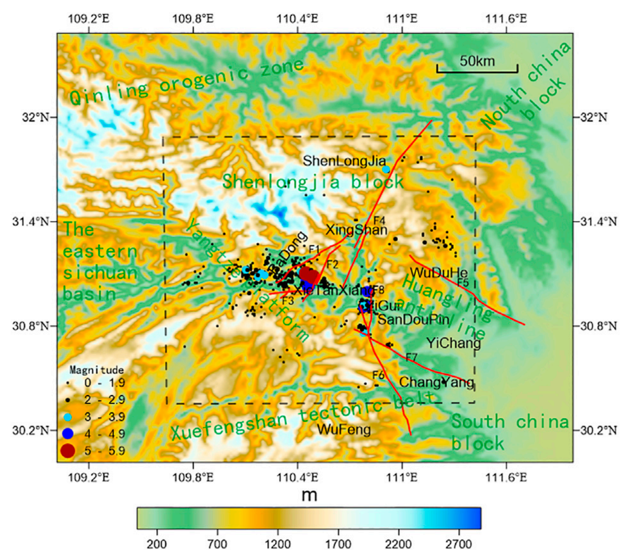

FIGURE 2 | Digital elevation model, location of major earthquakes, and fault distribution in the Badong–Zigui and adjacent areas (F1 Gaoqiao fault, F2 Niukou–Zhoujiashan fault, F3 Maluchi fault, F4 Xinhua–Shuitianba fault, F5 Wuduhe break, F6 Xiannvshan fault, F7 Tianyangping fault, and F8 Jiuwanxi fault).

where λ, M, and Nz denote the Lagrange multiplier, the penalty function, and the number of slack variables, respectively. In each step of the iteration, the density and slack variables were calculated simultaneously.

GRAVITY DATA AND PREPROCESSING

Figure 3 shows the Bouguer gravity anomaly in Badong-Zigui region and its adjacent area. The data were obtained from the China Geological Survey, with a scale of 1:200,000. As shown from the map, Badong and its adjacent areas are located on the Taihang–Wuling gravity gradient belt extending in an NNE direction. The Bouguer gravity is a negative anomaly as a whole, and the anomaly values gradually increase from NW to SE, showing a SE-NW arc-shaped distribution (Yang et al., 2014; Liang et al., 2016). On the Shiyan-Baokang-Zigui-Wufeng line, the Bouguer gravity contours are dense and on the east and west sides away from the gravity gradient belt, the anomaly contours tend to be gentle, mostly in the form of local closed circles. The existence of the entire NNE-trending gravity gradient belt indicates that there is a large-scale structural variation zone in the depth. Since the Neotectonic period, the entire area has been characterized by large, continuous arched uplifts. The modern topographical structure and shallow source earthquakes are controlled by the faults in the area (Li et al., 1987).

The depth change of the Moho surface in the inversion area is relatively gentle. The least squares polynomial fitting method takes the minimum sum of squared residuals as the judgment criterion. It is a suitable method for an area with small extent and simple geological conditions (Zeng, 2005). We adopted the fifth-order least squares polynomial fitting method (Zeng, 2005) to separate the Bouguer gravity into regional (**Figure 4A**) and local anomalies (**Figure 4B**). The regional anomaly (**Figure 4A**) basically corresponds to the Moho variation in this area (Jiang, 2004; Liang et al., 2016). It can be clearly seen that the Moho in this area gradually tilts from east to west. The large negative gravity anomaly in the area of Pingli–Zhenping–Wuxi indicates that there might be roots under the Daba Mountain Range.

In the inversion area, the negative gravity anomaly was caused by the sediments in the Zigui Basin during late Triassic to late Jurassic; to the east of the basin, the horseshoe–shaped Huangling Anticline obliquity causes a high gravity anomaly (**Figure 4B**), as well as the Shennongjia Uplift. According to a previous investigation (Gong et al., 2014), the sediments of the basin are characterized by migration and denudation from the periphery to the basin. And the Zigui Basin is a part of the extension as a transitional bay from the Sichuan Basin to the east into the Three Gorges Region, with the feature of sea-land interaction and land-land facies deposition vertically.

3D GRAVITY INVERSION RESULT

The geometry of the inversion area is 170 km in both EW and NS directions, and the depth is 30 km. During the 3D constraint inversion, because the objective function **Eq. 3** is an ill-posed problem, the larger the vector **m**, the more serious the non-uniqueness of inversion. Through a lot of experiments (Wang, 2020), we divided the inversion region into 34 × 34 × 15 rectangular grids with a single grid size of $5 \times 5 \times 2\,km^3$, the inversion time reduced and inversion result was satisfied. According to **Eq. 3**, the initial value of the penalty factor, the

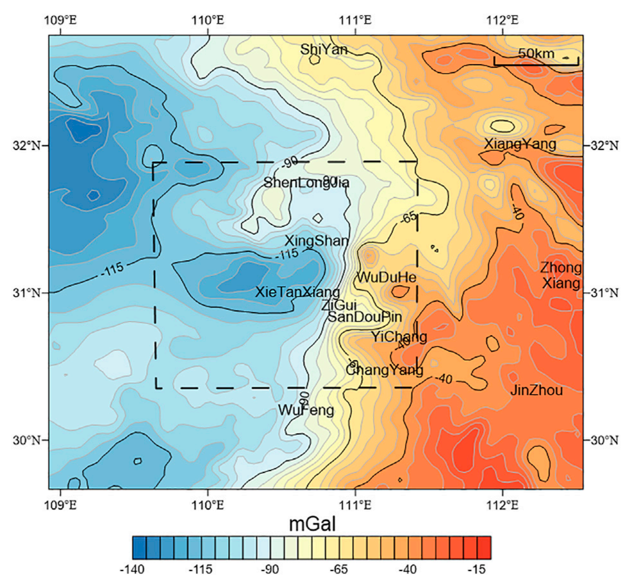

FIGURE 3 | Bouguer gravity anomalies in the Badong–Zigui area. The dashed line represents the inversion area.

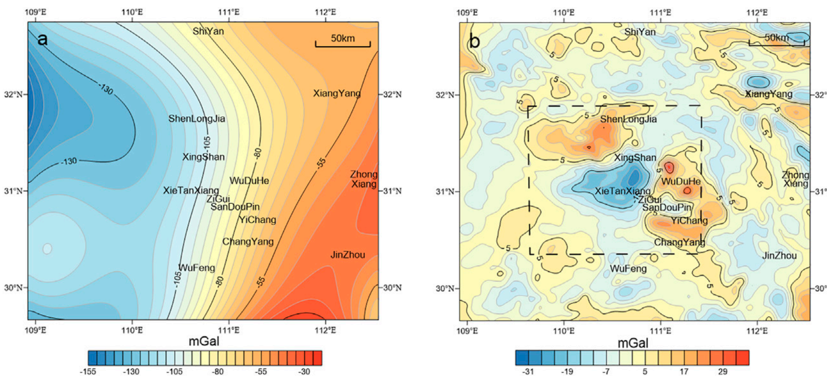

FIGURE 4 | (A) Regional gravity anomalies and **(B)** local gravity anomalies in the Badong–Zigui area. The dashed line represents the inversion area.

depth weighting function, and the termination criterion were set at 1.0×10^{-6}, 2, and 1.0×10^{-8}, respectively. Based on analysis of the geological information of the inversion area in *Geological Background of Zigui Basin and its Periphery in the Three Gorges*, the lower bound was set uniformly for all inversion grid cells as 2.58 g/cm^3, with an upper bound of 2.90 g/cm^3. There is no prior reference model used in the inversion, only a constraint of density with range of 2.58–2.9 g/cm^3. Different regularization parameters were introduced for iteration to obtain the Tikhonov curve (Li and Oldenburger, 1996, 1998; Zhang et al., 2015), and the regularization parameter was selected to balance the model complexity and data misfit at the same time. As a result, the obtained underground density distributions were shown in **Figure 5**.

The density structure at this depth of 0–2 km was evenly distributed, there are small areas of low density on the SW side of Badong-Xietanxiang-Zigui, with a density of approximately 2.62–2.64 g/cm^3, and areas of high density on the NE side of Zigui-Sandouping, with a density of approximately 2.67–2.692 g/cm^3. Taking into account the analysis, these two areas should be reflections of the Zigui Basin and the Huangling Anticline at the shallow surface.

The heart-shaped Zigui Basin, horseshoe–shaped Huangling Anticline, and Shenlongjia Uplift are clearly visible. The red high-density zone in the Wuduhe-Sandouping-Changyang region is the Huangling Anticline with an inversion density of 2.69–2.725 g/cm^3. In its central part, there is an area of low density that approximately encompasses an elliptical region where the Three Gorges Dam is located.

The blue low-density area of the Zigui Basin is a sedimentary layer of Jurassic clasts (Qu et al., 2009) with inversion density ranging from 2.6 to 2.64 g/cm^3. The seismogenic mechanism with high frequency and low magnitude is mainly found in the sediment layer of the Zigui Basin. In the middle of Zigui and Huangling, a large number of tremors are concentrated, and 2 Ms $\geq$ 4.0 earthquakes have occurred. The induction of these earthquakes may be related to the slow uplift of the Huangling Anticline at slow uplift and the relative subsidence of the Zigui Basin. On December 16, 2013, an Ms 5.1 earthquake occurred in Badong, with the epicenter shown as the red dot in the figure. In the west of the epicenter, an Ms 5.1 earthquake also occurred in Longhuiguan. This indicates strong tectonic movement in the Zigui Basin. The high–density area in the northwestern part of the basin is the Shenlongjia Uplift, which is a large anticline. It is a geologic structure dominated by carbonate rocks interspersed with multiple layers of clastic layers, with an inversion density of 2.69–2.72 g/cm^3.

The profiles of the Zigui Basin and Huangling Anticline in **Figure 5C** show similar patterns to those in **Figure 5B**. The inversion density values of the Huangling Anticline and the Shenlongjia Uplift decrease compared with those in **Figure 5B**, with density values ranging from 2.69 to 2.705 g/cm^3, indicating a gradual shallowing of the base of the two anticlines. The density of the Zigui Basin is 2.62–2.64 g/cm^3, and the density in the area around Xingshan is smaller than that around Badong. It indicates that the basin sedimentation is uneven. Most earthquakes in this depth region are concentrated in the Huangling Anticline and the middle of the basin and the western margin of the basin.

The Shenlongjia Uplift, Huangling Anticline, and Zigui Basin are still clearly delineated in **Figure 5D**. The density value of the Huangling Anticline is around 2.675–2.69 g/cm^3, and the amplitude decreases significantly compared to **Figures 5B,C**. The crystalline substrate is further accentuated. The outline of the Zigui Basin is significantly reduced, with density values of approximately 2.63–2.65 g/cm^3, and the sedimentary base is basically prominent and close to the surrounding density nearby Badong. The density values are small near Xingshan, showing that the Zigui Basin deepens from west to east. According to previous geological studies, a NE–oriented ancient river exists between the Huangling and Shenlongjia Uplift in the direction of Xinhua–Xingshan, which continuously provides material for the sedimentary filling of the basin from NE to SE (Gong et al., 2014). This may be responsible for the lower density and deeper basement in the eastern part of the basin compared to the western part, and the sedimentary material in the western part of the basin should also have been eroded from the eastern Xingshan-Xinhua area.

The bottoms of the two tectonic units, the Zigui Basin and the Huangling Anticline, are shown to reach essentially the

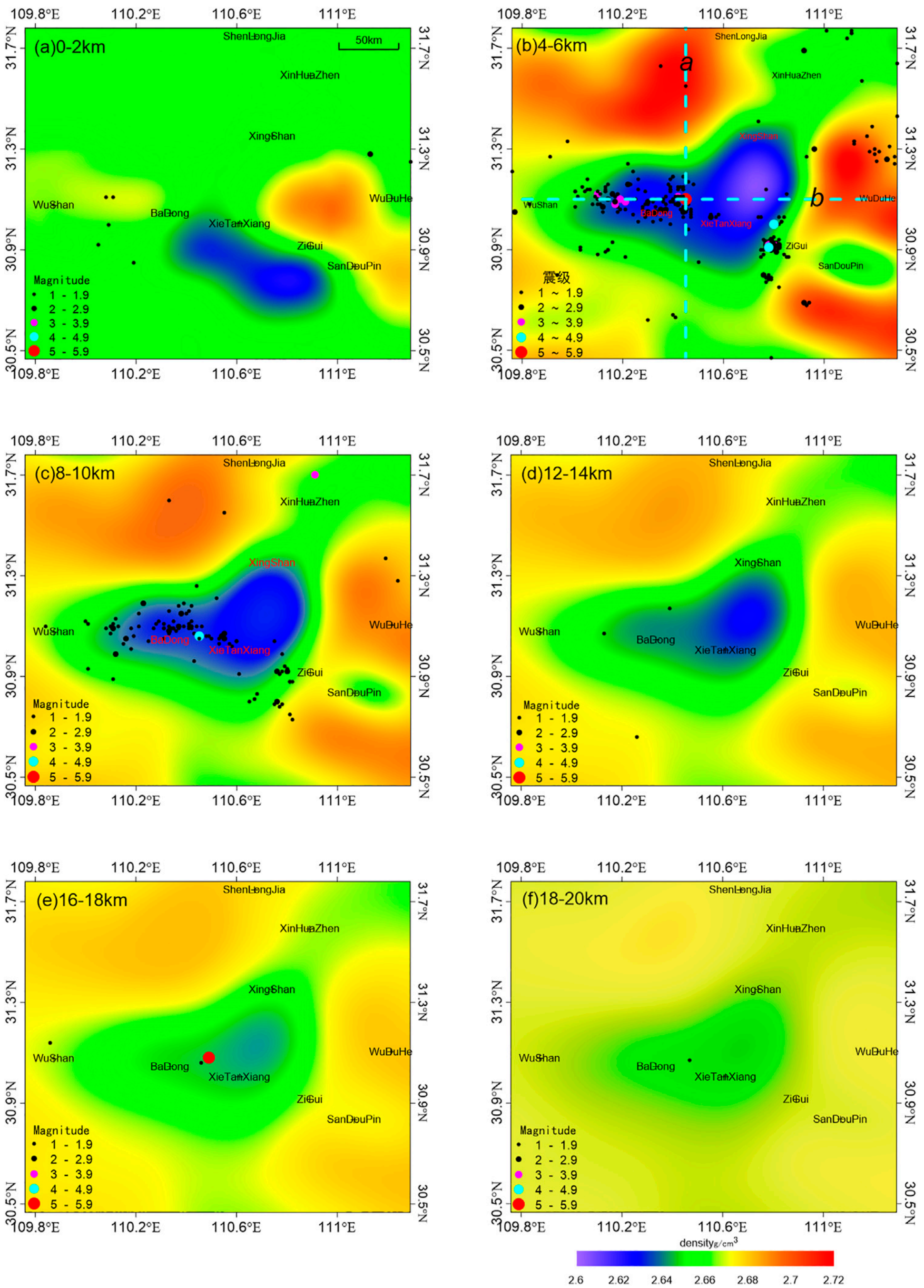

FIGURE 5 | Badong–Zigui region underground density distribution: **(A)** 0–2 km, **(B)** 4–6 km, **(C)** 8–10 km, **(D)** 12–14 km, **(E)** 16–18 km, and **(F)** 18–20 km.

maximum depth in **Figures 5E,F**. The sedimentary depth at Zigui Basin is approximately 13–16 km, and the crystalline base at Huangling is approximately 15–19 km, which is greater than the tectonic depths of Li et al. (2010). This is due to the blur effect of the L_2 norm, which is used in the inversion method. The anomaly inversion amplitude is small and flat, which makes the energy unfocused, resulting in a slight "inflation" of the profile.

STRUCTURAL CHARACTERISTIC ANALYSIS

The inversion results indicate that the sedimentary strata at the Zigui Basin are mainly carbonated rocks with fine clastic rocks in low density. Since the first Three Gorges Reservoir impoundment in May 2003, a large number of moderate and small earthquakes, and micro-seismic activities have occurred in the headland area.

TABLE 2 | Focal mechanism solution of five earthquakes.

	Epicenter N (°)/E (°)		Ms	Depth (km)	Nodal plane1	Nodal plane2	Seismogenic nodal plane
1979 Zigui	31.08	110.49	5.1	16	296/73/*	37/59/*	37/60–80
2008 Zigui	30.98	110.78	4.1	7	213/81/110	326/22/25	Nodal plane1
2013 Badong	31.09	110.42	5.1	5	117/28/–136	347/71/–68	265.5/85/–120.7
2014 Zigui	30.92	110.80	4.5	7.7	45/79/158	139/68/12	Nodal plane1
	30.91	110.82	4.9	9.1	46/68/164	142/76/23	Nodal plane1
2017 Badong	31.03	110.44	4.3	3.8	160/88/45	67/45/177	strike NEE/dip SE/
	31.04	110.45	4.1	2.4	155/83/27	62/63/173	pure strike–slip

The "" indicates that the dip angle of the seismic nodal plane is unknown.*

Most micro–seismic activity is spatially and temporally concentrated.

Since the Three Gorges seismic network was operated from 2001, the focal mechanism solution of moderate earthquakes in this area has been studied systematically. The seismic mechanism solutions for the five earthquakes obtained in this paper are shown in **Table 2**.

The 1979 Longhuiguan Ms 5.1 earthquake at Zigui has the property of left-rotation thrust fault and is a tectonic earthquake under the action of the regional tectonic stress field (Wang, 1981). The 2008 Zigui Ms 4.1 earthquake has the property of strike–slip and thrust and is related to the adjustment of tectonic stress field and the Xiannushan fault (Wei et al., 2013; Li et al., 2019). The 2013 Badong Ms 5.1 earthquake has the property of normal fault strike-slip under nearly east-westward, which belongs to the tectonic earthquake induced by reservoir (Chen et al., 2014). The 2014 Zigui Ms 4.5 and Ms 4.9 earthquakes are characterized by strike–slip and a small amount of thrust dislocation, and controlled and affected by Xiannvshan fault and Jiuwanxi fault activity (Wu et al., 2015). The 2017 Badong Ms 4.3 and Ms 4.1 earthquakes have the property of pure strike-slip. The seismogenic mechanism may be the shear dislocation caused by fracture and instability of Triassic limestone in the area due to long-term seepage and dissolution of reservoir water (Li et al., 2019).

According to the focal mechanism solutions and the nodal planel information of the above five earthquakes, the local dislocation of the seismic fault at the source were projected onto the horizontal plane to obtain the local dislocations at the source of the five earthquakes. Then, the spatial distribution of the seismic sequence and the crustal movement trend of the source area were drew combined with the density inversion results (see **Figure 6**).

2 Ms 5.1 earthquakes and 4 Ms 4–5 earthquakes are all within the boundaries of Gaoqiao fault, Niukou-Zoujiashan fault and Jiuwanxi fault. Six earthquakes with epicenters close to each other, located west of the center of the Zigui Basin. In combination with **Figure 6**, it appears that this location is at the intermediate junction of high density in the west and low density in the east of the Zigui Basin. By processing the seismic wave parameters of 34 stations, Wang (1981) obtained the focal mechanism solution of the 1979 Longhuiguan earthquake at Zigui, and deduced that the nodal plane at 37° north-east was the fault plane of the earthquake, with the property of left lateral and thrust fault. It should be formed by the NE-NNE uplift folds in the region during the Neotectonic period under the extrusion of tectonic stresses in the NW-NE of the region. For the 2013 Badong Ms 5.1 earthquake, the strike of seismogenic fault was 265.5°, and it can be judged that the focal mechanism was not caused by the Gaoqiao fault and Niukou-Zoujiashan fault. From the perspective of seismography (Chen et al., 2014), the dominant frequency and corner frequency of this earthquake are both low and have the characteristics of collapse earthquake, which indicates that this earthquake was related to the long–term leakage–related dissolution of the water in the Three Gorges reservoir. Based on the analysis of the activity characteristics of Badong Ms 4.3 and Ms 4.1 earthquake sequence in 2017, it is indicated that the unloading of reservoir water makes the compressive stress in this area rebound locally. Then it leads to the expansion of some cracks, and the fractured rock mass that causes dissolution of the reservoir water faces unstable sliding, which finally causes the earthquake. It can be considered that these two earthquakes are different from the tectonic earthquakes caused by the known faults in the region. Moreover, it can also be considered to be independent of the known faults in the region, from aftershock sequence distributions and nodal plane (strike and dip angle) of these two earthquakes. In addition, for the 2018 Zigui Ms 4.5 and Ms 4.1 earthquake, the motion trend of the epicenter region is in the SEE direction, and the aftershocks are also distributed in the SEE direction.

In combination with the analysis of the seismogenic structures of the four abovementioned earthquakes, the results were all considered inconsistent with the strike and dip angle of the existing faults in the area, which indicates that there was no fault structure consistent with the focal mechanism solution of the above earthquakes. From the geological point of view, the whole epicenter of the region is located in the stratigraphy of Badong Group of the middle Triassic and Jialingjiang–Daye Group of the lower Triassic. It has a significantly lower uniaxial compressive strength relative to both its overlying and underlying strata and is a soft substratum prone to slippage (Li et al., 2018). Under the external factors such as long–term leakage dissolution and loading–unloading of the Three Gorges reservoir water, the regional cracks become unstable and slip, and then the earthquake occurs. The study of the tectonic characteristic of Zigui Basin shows that it is held by two anticlines in the north and east directions, the extension of the Sichuan basin in the west and the diffusion of the material density from east to west (Wang et al., 2019). As a whole, the basin has a pattern of mutual movement and extrusion from east to west. In recent 30 years, Ms

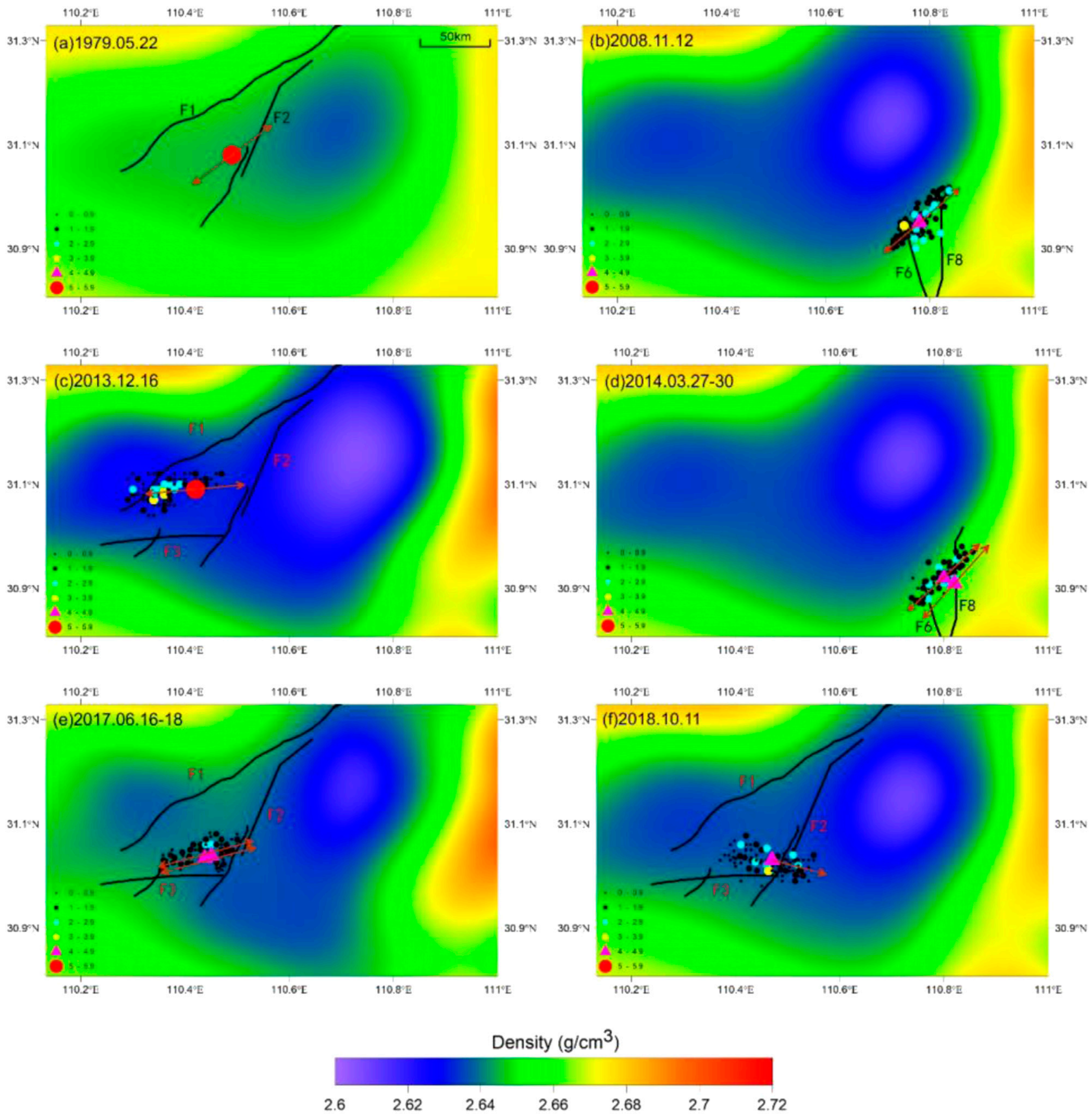

FIGURE 6 | Spatial distribution of seismic sequences and trends in regional crustal movements in seismic source areas. (F1 Gaoqiao fault, F2 Niukou-Zhoujiashan fault, F3 Maluchi fault, F6 Xiannvshan fault, and F8 Jiuwanxi fault. The panel **A** represents the Zigui earthquake in 1979, The panel **B** represents the Zigui earthquake in 2008, The panel **C** represents the Badong earthquake in 2013, The panel **D** represents the Zigui earthquake in 2014, The panel **E** represents the Badong earthquake in 2017, The panel **F** represents the Zigui earthquake in 2018). The red arrow indicates the trend of regional crustal movement at the seismic focus.

4–6 earthquakes occurred intensively in this local region, and it can be considered that the long–term accumulation of tectonic stress in this region is related to the continuous deposition of the Zigui Basin and the east-west material migration movement extrusion.

The 2008 Zigui Ms 4.1 earthquake, the 2014 Zigui Ms 4.5 and Ms 4.9 earthquakes are all located at the junction of high and low densities in the Zigui Basin and the peripheral Huangling Anticline as shown in **Figures 6B,D**. From a spatial perspective, three earthquakes occurred in a fork–shaped area at Xiannvshan fault and Jiuwanxi fault. While the Nodal plane strikes of these 3 Ms 4–5 earthquakes do not coincide with these two faults. The epicenter of the 2008 Ms 4.1 earthquake and 2014 Ms 4.5 earthquake are at the bottom of the sediment cover in the

Zigui Basin, the epicenter of 2014 Ms 4.9 earthquake is within a basal crystalline granite or metamorphic layer. These lithologic strata are upper and Middle Triassic, Upper and lower Permian, upper and middle Silurian limestone, sandstone, and shale. This lithologic-stratigraphic distribution is conducive to reservoir erosion and infiltration. Under the tectonic background of the entire Chinese mainland being compressed by the Indian plate from north to northwest, the Three Gorges and adjacent areas have been moving in the SE direction in the past decades. It can be judged that the whole Zigui Basin has a movement trend in the SE direction; the slow uplifting denudation of the Cenozoic Huangling Anticline provides a material source for the continuous deposition of the Zigui Basin. It is believed that the accumulation of tectonic stress in the local region of the southeast edge of the Zigui Basin is formed by the slow uplifting of the Huangling Anticline and the motion extrusion in the SE direction of the Zigui Basin.

CONCLUSION

In this study, the 3D density structure of the Three Gorges and adjacent areas was obtained using the Bouguer gravity anomaly with regional geological and geophysical data. The Zigui Basin, part of the Huangling Anticline, Shenlongjia Uplift, and other large geological structural units could be seen clearly in the inversion results. The sedimentary layer of the Zigui Basin was shallow in the west and deep in the east, while the sediment density in the east was lower than that in the west. There was also an obvious low–density area in Xingshan-Xietan.

Four earthquakes of magnitude Ms 4–6 have occurred in the west of the core of the Zigui Basin, and the epicenters are relatively close to each other. In terms of density distribution, this area is at the junction of high and low density from east to west. The epicenter motion of the four moderate earthquakes trends in the NE, NEE, and SEE directions, and were all within the boundaries of the Gaoqiao fault, Niukou–Zoujiashan fault, and Jiuwanxi fault. The seismogenic structures were all inconsistent with the strike and dip angle of the existing faults in the area. As the local area is a soft substratum prone region where slippage occurs, the cracks progressively become unstable and slip, and finally the earthquake occurs, owing to dissolution caused by long–term leakage and loading–unloading of the Three Gorges reservoir water. It can be concluded that the long–term accumulation of tectonic stresses in this localized area is related to the continuous sedimentation of the Zigui Basin and extrusion of material migratory movements in the east–west direction. The 2 Ms 4–5 earthquakes that occurred in the southeast side of the Zigui Basin were local earthquakes triggered by the background of Huangling Anticline slow uplift denudation and eastward extrusion of the accumulated stress in the area.

According to the principle of clustering of small earthquakes, it could not be ruled out that there may be one or several NE and NEE small buried faults in the western core area of Zigui Basin, and one NE buried fault exists in the southeast margin of the basin, which was induced by the long–term infiltration of reservoir water and the effect of loading–unloading.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

YW and JP conceived and designed the experiment; YW performed the computation; ZW and HY analyzed the data; YZ and JP interpreted the results; YW and JP discussed the results and polished the manuscript. YW and YZ wrote the paper and all the authors improved it.

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