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Modeling of co- and post-seismic surface deformation and gravity changes of $M_{\rm W}$6.9 Yushu, Qinghai, earthquake*

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Abstract Based on the elastic dislocation theory, multilayered crustal model, and rupture model obtained by seismic waveform inversion, we calculated the co- and post-seismic surface deformation and gravity changes caused by the Yushu $M_{\rm W}$6.9 earthquake occurred on April 14, 2010. The observed GPS velocity field and gravity field in Yushu areas are disturbed by the co- and post-seismic effects induced by Yushu earthquake, thus the theoretical co- and post-seismic deformation and gravity changes will provide important modification for the background tectonic movement of Yushu and surrounding regions. The time relaxation results show that the influences of Yushu earthquake on Yushu and surrounding areas will last as long as 30 to 50 years. The maximum horizontal displacement, vertical uplift and settlement are about 1.96, 0.27 and 0.16 m, respectively, the maximal positive and negative value of gravity changes are 8.892×10^{-7} m·s^{-2} and -4.861×10^{-7} m·s^{-2}, respectively. Significant spatial variations can be found on the co- and post-seismic effects: The co-seismic effect mainly concentrates in the region near the rupture fault, while viscoelastic relaxation mostly acts on the far field. Therefore, when using the geodetic data to research tectonic motion, we should not only consider the effect of co-seismic caused by earthquake, but also pay attention to the effect of viscoelastic relaxation.

Key words: **Yushu earthquake; viscoelastic relaxation; surface deformation; gravity**
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1 Introduction

At BT 7:49 on April 14, 2010, an earthquake of moment magnitude 6.9 occurred in Yushu County, Qinghai Province in China. The epicenter locates at 33.2°N and 96.6°E, and the focal depth is about 14 km (Chen et al., 2010; Ni et al., 2010). The rupture mainly occurred on the NW-SE Ganzi-Yushu fault (Chen et al., 2010). Geological survey shows that the rupture fault is a left-lateral strike-slip fault, and may connect with the Xianshuihe fault to the southeast; these two rupture faults form the dextral strike slip fault system in the east part of the Tibetan Plateau and the north boundary of the Sichuan-Yunnan tectonic block. Therefore, the studies on the seismic activity of Ganzi-Yushu fault, the stress filed impact on this dextral strike slip fault system, the deformation, and the gravity changes on the surrounding tectonic blocks caused by the Yushu earthquake, are critically significant for studying on the tectonic movement and the evolution process of the Tibetan Plateau (Tapponnier, 1982; Zhang et al., 2003; Wen et al., 2003).

Previous studies showed that co- and post-seismic effects caused by earthquake dislocation maight lead to changes of various physical fields, such as deformation and gravity fields near the epicenter (Shen et al., 2008; Tan et al., 2009; Xu et al., 2010; Deng et al., 2008). Thus, the co- and post-seismic effects may disturb the observations on the long term tectonic move-

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ment or inter-seismic deformation field and should be removed from the observations. For example, the M_S8.1 Kekexili earthquake occurred in 2001, caused significant changes on the deformation and gravity fields and lasted for a long time. For this reason when Gan et al. (2007) studied the present-day crustal motion of the Tibetan Plateau, they found the velocities observed by GPS measurements were strongly disturbed by the M_S8.1 Kekexili earthquake and have to be corrected by the earthquake effects. Based on the method of Niu et al. (2005), Gan et al. (2007) calculated the theoretical co-seismic displacement caused by Kekexili M_S8.1 earthquake, removed the seismic-induced effects from observations and got a reasonable tectonic pattern of Tibetan Plateau. Similar example comes from the study of the tectonic movement of Mongolia-Baikal area, Calais et al. (2003) pointed out that post-seismic effect caused by the 1905 Bolnay earthquake could produce 1 mm/a offsets in GPS observations at Mongolia-Baikal area during 1997 and 2000, which has a duration time about 100 years.

Tibetan Plateau is an ideal place for studying continental evolution, tectonic deformation, and mechanisms of continental dynamics. However, there are only sparsely distributed GPS observation stations in this region, and the number of continuous observations is even fewer. Hence, the GPS and gravity observations are usually obtained by repeated measurements. In this situation, the co- and post-seismic effects caused by earthquakes may have serious disturbance on the observed results. Consequently, using these observations to research the tectonic motion in Yushu and surrounding areas, the various effects caused by Yushu earthquake must be taken into account and should be removed as possible as we can.

In this paper, with the PSGRN/PSCMP software developed by Wang et al. (2006), using multiple subfaults rupture model and multi-layered crust model, we calculate and analyze the surface deformation and gravity changes of co- and post-seismic caused by the Yushu earthquake, and try to provide modification data for the geodetic observations (GPS and gravity, etc) in these areas.

2 Theory and model

Wang (1999) proposed an orthogonal normalization method to calculate the Green's function of seismic stress field. Based on this method and a viscoelastic multi-layered model, he established the co- and post-seismic deformation model and produced corresponding numerical methods (Wang et al., 2003; Wang and Kuempel, 2003). With the PSGRN/PSCMP software (2006), and using earthquake slip model inverted from seismic waveform modeling, we calculated the theoretical deformation and gravity changes caused by the Yushu earthquake.

2.1 Crustal layered model

Based on the structure model provided by Crust2.0, considering the lower crust and mantle viscoelastic relaxation effects, we established a multi-layered lithosphere model in Yushu area. The model parameters are listed in Table 1. The thicknesses of upper crust, middle crust and lower crust are 22, 24 and 24 km, respectively, layer under 70 km is the upper mantle. In this study, we applied the methods of Shen et al. (2003) and Shao et al. (2008) and set the upper crust as pure elastic layers whereas the middle crust, lower crust and mantle are set as viscoelastic layers because of their rheological behaviors, the viscosities of the middle crust, lower crust and mantle are set as 6.3×10^{18} Pa·s, 6.3×10^{18} Pa·s and 1.0×10^{20} Pa·s, respectively (Shen et al., 2003). With the increase of depth in the crust, high pressure and temperature prevent rock from brittle manner; instead, they flow viscously in response to stress (Kirby and Kronenberg, 1987). Two kinds of phenomena result from this characteristic: (1) For the co-seismic deformation, the viscous regions behave as elastic media; (2) For the long term post-seismic period, these regions begin to relax and the stored elastic strains transfer upward to the seismogenic upper crust, leading to stress and strain changes in the upper crust. Therefore, during the study of Yushu M_W6.9 earthquake, we analyzed the co-seismic effect under

Table 1 Multi-layered structure model for Yushu M_W6.9 earthquake

Serial No.	Layer	Depth/km	v_P/km·s^{-1}	v_S/km·s^{-1}	Density/kg·m^{-3}	Steady-state viscosity/Pa·s
1	Upper	0.0–22.0	6.000 0	3.500 0	2 700.0	∞
2	Middle crust	22.0–46.0	6.400 0	3.700 0	2 850.0	6.3×10^{18}
3	Lower crust	46.0–70.0	7.100 0	3.900 0	3 100.0	6.3×10^{18}
4	Upper mantle	$\geq$70.0	8.000 0	4.600 0	3 450.0	1.0×10^{20}

Note: ∞ means that this layer is set as purely elastic.

the elastic state, but for the analysis of long-term deformation and gravity changes of post-earthquake we focused on the viscoelastic relaxation effects of lower crust and mantle.

2.2 Finite fault rupture model

Using the finite fault rupture model inversion method (Ji et al., 2002), we inverted the rupture model of Yushu earthquake (Figure 1) with broadband seismograms recorded by Global Seismic Network (GSN) broadband seismographs with the strike and dip angles of 120° and 80°, respectively. In order to get a high resolution image of the rupture process, the fault plane is divided into 420 subfaults with spatial dimension of 2.0 km by 2.0 km. Inversion result shows that the rupture starts from the northwest end of the fault and extends to the southeast end, the maximum of slip locates near to the surface. From hypocenter to Jiegu County the rupture length is about 35 km, which is almost consistent with the result (30 km) given by Ni et al. (2010).

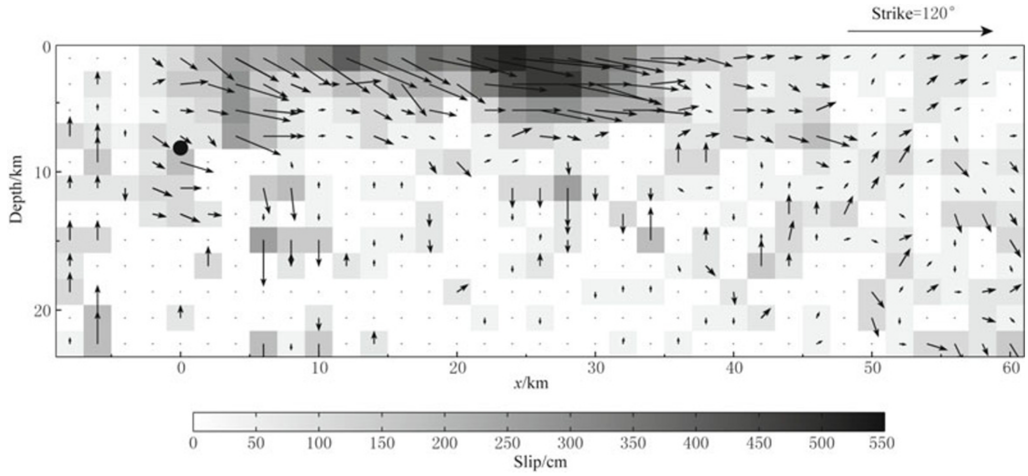

Figure 1 The co-seismic slip model of Yushu M_W6.9 earthquake. The white arrows represent the amplitude and the direction of the rupture slip.

Based on the finite fault rupture model (Figure 1) and a multi-layered structure model (Table 1), we further calculated the co- and post- seismic surface deformation and gravity field changes induced by the Yushu M_W6.9 earthquake with the PSGRN/PSCMP software (Wang et al., 2006), and obtained the temporal evolution of these physical fields.

3 Simulated results of surface co- and post-seismic deformation and gravity changes

3.1 Relaxation time of viscoelastic relaxation model and stability testing

Since the relaxation time of lower crust and mantle has strong relationship to the scale of spatial and temporal effects of an earthquake, and is critically important to understand the seismicity pattern and the tectonic movement, we firstly analyzed the duration of the post-seismic effect of Yushu earthquake.

Before the occurrence of the Yushu earthquake some permanent observatory sites have been deployed by the Crustal Movement Observation Network of China to detect the crustal movement of the Tibetan Plateau. Near Yushu city there is a permanent GPS observatory site JB49 close to the rupture fault of the Yushu earthquake, which provides us an important chance to analyze the time variation of the post-seismic effect. In order to compare our simulated results with the observation data obtained by the JB49 GPS station, we calculated the theoretical co- and post-seismic gravity changes on JB49 station induced by viscoelastic relaxation effect of the lower crust and mantle in 100 years (Figure 2). The simulation shows the co-seismic gravity changes induced by Yushu M_W6.9 earthquake is 1.6×10^{-7} m/s^{-2} at this site. Since a warm and viscous lower crust and upper mantle can not sustain such kind of stress and strain, they will migrate to the upper crust and further affect the deformation and gravity field at the surface. Therefore, during the first 20 years after earthquake the viscoelastic relaxation effect is obvious, and the magnitude of gravity change increases up to 2.8×10^{-7} m/s^{-2} from 1.6×10^{-7} m/s^{-2} at JB49 site induced by Yushu earthquake, and then tends to get stable gradually after 30 to 50 years.

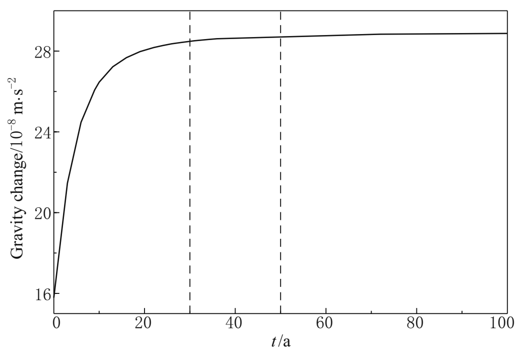

Figure 2 Co- and post-seismic gravity changes of point JB49.

Furthermore, we tested different viscosity coefficients of lower crust and mantle to check the stability of our results, the results of different viscosity coefficients indicate that the smaller the coefficient of viscosity is, the shorter the viscoelastic relaxation will last. However, even though we employed different coefficients of viscosity, the final gravity changes are almost identical at the same site, which shows that the viscoelastic coefficient rather control the time of relaxation than change the amplitude of the gravity. Consequently, using multi-layered structure model, we calculated the theoretical value of surface deformation field and gravity field of co-seismic and the snapshot of 50 years after earthquake induced by Yushu $M_{\rm W}$6.9 earthquake.

3.2 Simulation of co- and post-seismic surface deformation

Based on multi-layered structure model, we calculated the surface deformation of co- and post-seismic by employing the program PSGRN/PSCMP, simulation results as shown in Figures 3 and 4.

The horizontal displacement caused by Yushu earthquake is shown in Figure 3. The motion of co-seismic surface deformation is mainly left-lateral strike-slip, with a largest horizontal co-seismic displacement near the epicenter about 1.96 m, and the displacement caused by Yushu earthquake decreases with increase of the distance from the epicenter. In order to study the influence of viscoelastic relaxation effect, we calculated the difference between surface horizontal co-seismic displacement and the displacement after 50 years caused by Yushu earthquake (Figure 3b), and found that after 50 years the largest horizontal post-seismic displacement near the epicenter only decreases from 1.96 m to 1.94 m, which is an obvious evidence that the viscoelastic relaxation pays little effect on the near field of the rupture fault. As can be seen from the Figure 3b, the viscoelastic relaxation effects in the northeast and the southwest part are stronger than those in the southeast and the northwest. The farther the areas away from the rupture fault, the more the proportion of post-seismic effect. After 50 years, the horizontal displacement caused by the viscoelastic relaxation effect is about 10 cm in near-field areas, while in the areas 200 km away from the epicenter which is about 5 cm, which means

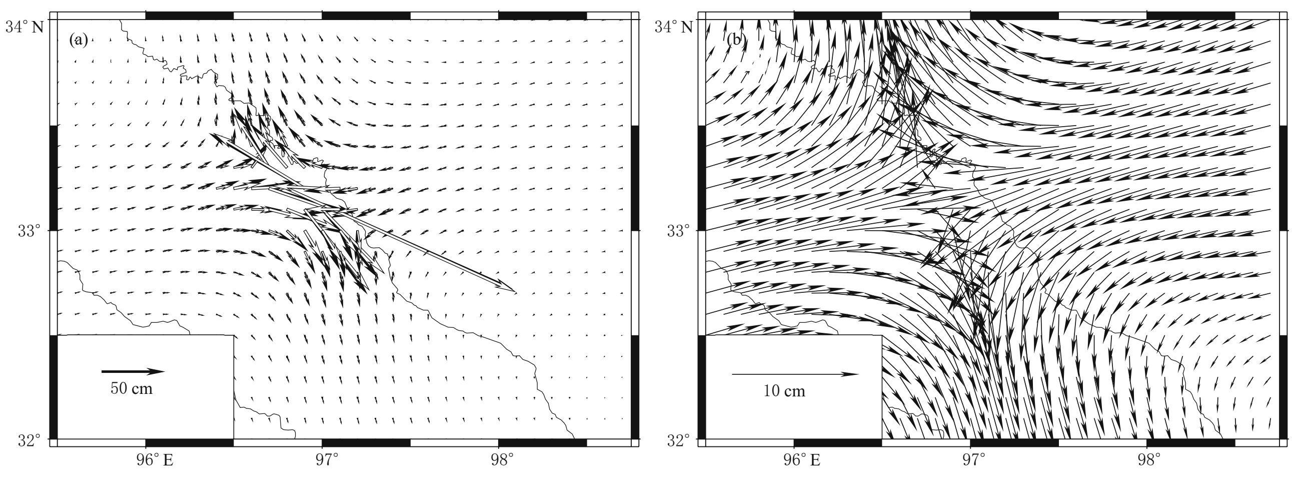

Figure 3 Co- and post-seismic surface horizontal displacement caused by Yushu $M_{\rm W}$6.9 earthquake. (a) Co-seismic simulation result. The open arrows represent co-seismic result and the solid arrows represent the simulation result 50 years after the earthquake. (b) Post-seismic horizontal displacement in 50 years.

that the Yushu earthquake will lead to 1–2 mm/a horizontal displacement for GPS observations in future 50 years.

The vertical displacement caused by Yushu earthquake is shown in Figure 4. Yushu $M_{\rm S}7.1$ earthquake is mainly characterized by left-lateral strike-slip, so the distribution of co- and post- seismic vertical displacement is with a pattern in four quadrants. The two NNW and SSE uplifting lobes were caused by the stress compression, the maximal vertical uplift is 0.27 m; and the other two ENE and WSW descending lobes were caused by the tensile stress, the maximal vertical decline is −0.16 m. After the occurrence of the earthquake, owing to the influence of viscoelastic relaxation effect, vertical displacement field changes significantly, the distribution of post-seismic vertical displacement also has four quadrants, and the influence of co-seismic effect near the epicenter becomes weaker with an exemption of vertical displacement. Overall, compared with the horizontal deformation, the vertical displacement is smaller, which is also consistent with the characteristics of this earthquake.

3.3 Simulation of co- and post-seismic gravity change on the surface

The fault dislocation leads to the correspondent gravity changes inevitably. According to the simulated results, surface gravity changes are mainly influenced by vertical displacement in the near-field (Figure 5), The image of gravity changes is in good consistent with the image of vertical field deformation. Four quadrants can be found in the distribution pattern of co-seismic gravity changes, and the maximal positive and negative variations are 8.792×10^{-7} m/s^{-2} and -4.553×10^{-7} m/s^{-2}, respectively. The gravity field varies dramatically in a small area near the source region, and the gradient of gravity change is quite steep; on the contrary, in the far field, the change of gravity is relatively smaller, and its attenuation is slower, which make the variation area is larger in size.

In order to further clarify the characteristic of post-seismic surface deformation and gravity changes caused by Yushu earthquake, we calculate postseismic gravity changes in 50 years after the earthquake (Figure 5b). Compared with co-seismic results, the distribution of post-seismic gravity changes also exhibits a pattern with four quadrants, the maximal positive and negative variation are 8.892×10^{-7} m/s^{-2} and -4.861×10^{-7} m/s^{-2}, respectively, and the influence caused by the viscoelastic relaxation effect is weak. However, the area with obvious gravity changes in the near field gets larger, and the variation of the gravity changes becomes smaller. Another striking phenomenon is that the signs of the gravity changes in the near field are almost opposite to those in the far field, and the gravity field still has 3×10^{-8}–5×10^{-8} m/s^{-2} change caused by the post-seismic effect at the area where is about 100 km away from the rupture fault.

4 Discussion and conclusions

Based on the finite fault rupture model, we calculated co- and post-seismic surface deformation and gravity changes of Yushu earthquake, and analyzed the influence of co- and post-seismic surface deformation, gravity changes, and the dynamic mechanism on the eastern Tibetan Plateau. According to the simulation results, the deformation and gravity changes caused by Yushu earthquake have the following main characteristics.

1) The relaxation adjustment of post-seismic deformation varies dramatically in the first 10 years after the main shock and then tends to get stable gradually. The influence of co- and post-seismic of $M_{\rm W}6.9$ Yushu earthquake will last for 30–50 years.

2) The deformation caused by Yushu earthquake is mainly influenced by co-seismic effect near the rupture plane, on the contrary, post-seismic deformation is caused by viscoelastic relaxation far from the rupture fault. Horizontal displacement caused by viscoelastic relaxation effect is about 10 cm near the source region, and 200 km away from the epicenter is about 5 cm, which will lead to an average change of 1–2 mm/a for GPS observations in 50 years after Yushu earthquake. This shows that the post-seismic relaxation influence is equal to or larger than the accuracy of GPS observation. Therefore, using the geodetic data to research tectonic movement, we should not only consider the co-seismic effects caused by earthquake, but also take the viscoelastic relaxation effect into account.

3) The temporal changes of post-seismic effect are controlled by viscosities. Larger viscosity coefficient results in longer time of relaxation and vise versa. However, when reaching the steady state, theoretical gravity values are almost identical.

It should be noted that the complexities of rupture have a significant impact on the model computation, especially in the areas near the rupture fault. There are some discrepancies between the rupture model used in this paper and surface rupture observed by InSAR(http://www.cgs.gov.cn/JRgengxin/9_9517.htm),

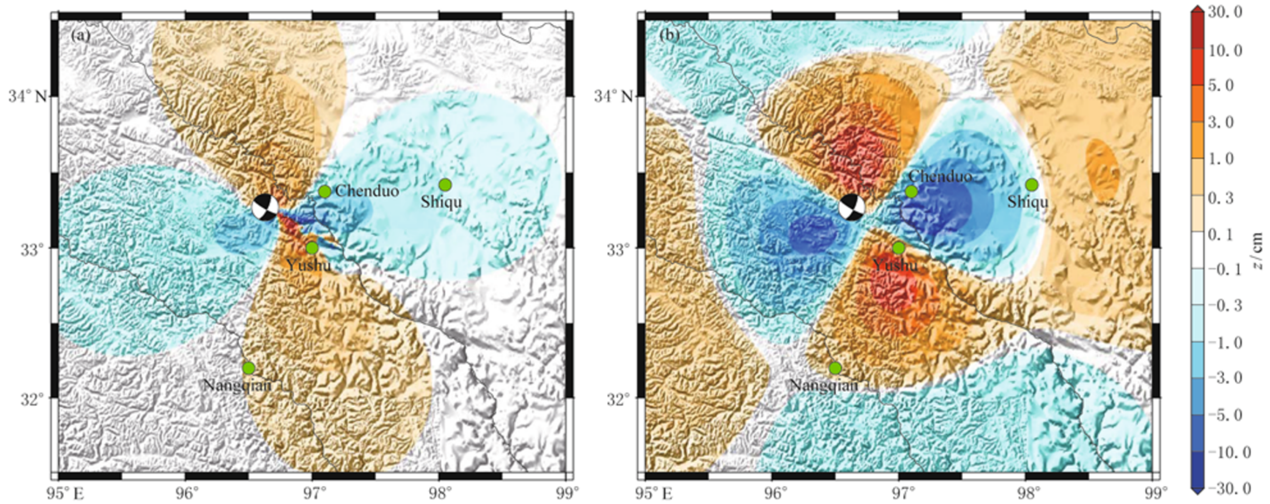

Figure 4 Co- and post-seismic surface vertical displacement caused by Yushu M_W6.9 earthquake. (a) Co-seismic simulation result. (b) Simulation result 50 years after the earthquake.

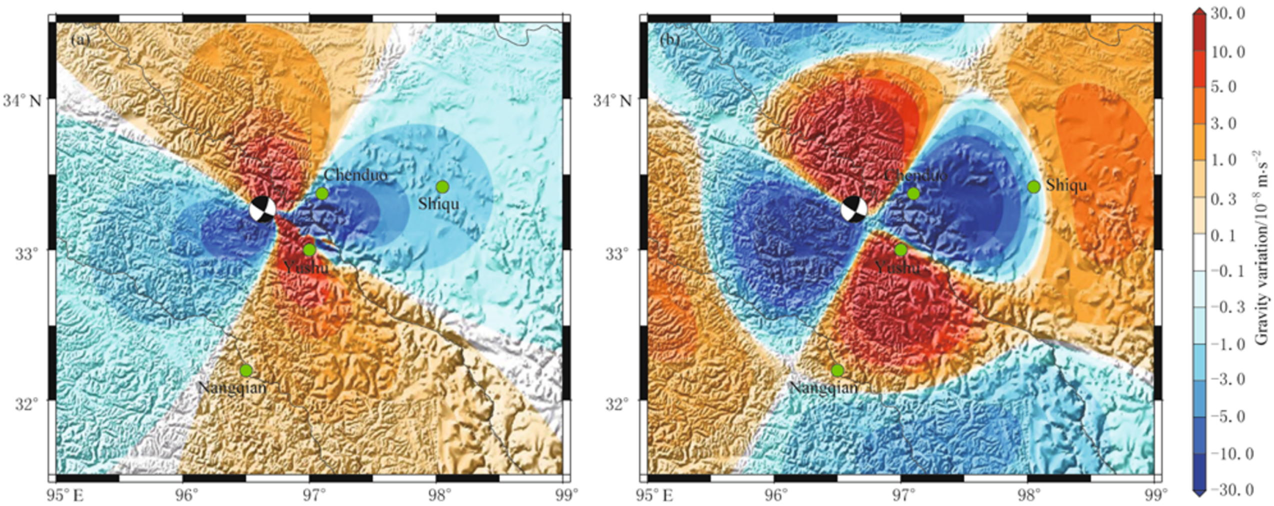

Figure 5 Co- and post-seismic surface gravity changes caused by Yushu M_W6.9 earthquake. (a) Co-seismic simulation result. (b) Simulation result 50 years after the earthquake.

which may have some disturbance on the accuracy of our result, in addition, there are only sparsely distributed GPS observation stations in this region, and only one station is taken into consideration, which will cause some uncertainties of the result. If enough field observations, more geodetic data and higher precise rupture model are available in the future, a better result should be expected.

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