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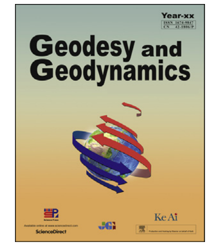

Gravity variation in the Tibet area before the Nepal Ms8.1 earthquake

Hongtao Hao[a,b,*], *Lelin Xing*[a,b], *Ziwei Liu*[a,b], *Yufei Han*[c], *Hui Li*[a,b]

[a] *Key Laboratory of Earthquake Geodesy, Institute of Seismology, China Earthquake Administration, Wuhan, 430071, China*
[b] *Wuhan Base of Institute of Crustal Dynamics, China Earthquake Administration, Wuhan, 430071, China*
[c] *National Earthquake Infrastructure Service, Beijing, 100045, China*

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ABSTRACT

This research utilized two periods of gravity monitoring results from 2010 to 2013 from the Continental Tectonics Environmental Monitoring Network of China, analyzed the correlation between gravity variation in the Tibet area and the Nepal Ms8.1 earthquake, and investigated the gravity variation mechanism in combination with the crust vertical movement and horizontal strain field observed by Global Positioning System (GPS). The research results indicated that (1) the gravity variation exhibited apparent characteristics of a positive anomaly and high gradient zone in the Himalayan frontier. This observation is consistent with the existing recognition of the gravity anomaly and occurrence regularity of a strong earthquake; (2) the gravity variation exhibited apparent consistence with the spacious distribution of the vertical movement and the horizontal deformation field in that area. The crustal vertical movement was not the direct cause leading to the gravity variation. It is assumed that the crust stress–strain accumulation in the Qinghai–Tibetan Plateau and its adjacent areas is the important factor that resulted in the variation of gravity.

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* *Corresponding author*. Key Laboratory of Earthquake Geodesy, Institute of Seismology, China Earthquake Administration, Wuhan, 430071, China.
E-mail address: haoht2004@sina.com (H. Hao).
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1. Introduction

On April 25, 2015, an Ms8.1 earthquake occurred in the Himalaya seismic belt, which is located in the collision zone between the India Plate and the Eurasian continent, and possibly triggered the Dingri County Ms5.9 earthquake on April 25 and the Niemula County Ms5.3 earthquake on April 26 in the China Tibet area. After the earthquake, the focal mechanism provided by China Earthquake Administration (CEA), Geo Forschungs Zentrum (GFZ), United States Geological Survey (USGS) and other various research agencies showed that the earthquake was a low dip and inverse impact seismic event. co-seismic deformation revealed by geodetic showed that it was mainly distributed on the hanging wall of the main Himalayan thrust (MHT) [1]. Inversion results of fracture process showed that the fracture plane of this earthquake exhibited a geometry plane in the near EW direction and a low-angle north slope, and the rupture direction was a single sided rupture with a duration of about 80 s [2–4].

Since the earthquake did not cause apparent ground surface rupture, there was still uncertainty in determining the earthquake fault. In general, this earthquake fault was inferred to be at the Himalayan main boundary thrust (MBT) or MHT [2,5,6] based on the rupture plane and aftershock distribution.

Before this earthquake, based on the spatial and temporal distribution of the historical earthquake and plate convergence rate characteristics disclosed by modern geodetic surveying, some investigators pointed out that the earthquake zone in central Nepal faced the risk of a strong earthquake [7–9], and this earthquake validated this viewpoint. However, since currently published precursor information related to this earthquake is still very scarce, there is no doubt that investigation into more seismic activities prior to the earthquake, as well as crust stress states and geophysical filed variation, will be of important practical significance [5] to disclose the seismogenic and occurrence process of this earthquake [5].

Gravity variation is closely related to tectonic activity and has played an important role in prediction of a series of recent medium and strong earthquake over the Chinese mainland [10–12]. The China Tibet area is adjacent to the Himalayan earthquake zone. Since this earthquake was the result of the dynamic effect of subduction of the India Plate and collision with the Eurasian continent, the spatial range of its seismogenic area must involve the larger areas of the Qinghai–Tibet Plateau. Therefore, investigation into the gravity variation in the Tibet area is helpful to understand the seismogenic and development processes of this earthquake. Kang et al. [13] investigated the long-term background of gravity variation based on the gravity data in the Tibetan area since 1998. Their investigation indicated that the long-term gravity variation featured an apparent nonuniformity and gravity variation zoning phenomena with respect to the spatial distribution, and the Himalayan active stenotic zone exhibited an apparent positive gravity variation tendency within 15 years. However, because the gravity network in the Tibetan area apparently varied during 2010, the time range of calculated long-term background of gravity variation was not unified. Chen et al. [14] studied observation results from the four absolute gravimetric stations in the southern range of the Himalayas from 2010 through 2013, and they found that the maximum gravity variation during this period reached +22.40 μGal/yr, and it might be related to the interseismic mass change around the locked plate interface under the Himalayan–Tibetan Plateau. Due to the lack of absolute gravimetric stations, this result was insufficient with respect to spatial resolution.

Based on the above findings, this paper aimed to utilize two periods of gravity monitoring results from 2010 through 2013 from the Continental Tectonics Environmental Monitoring Network of China, analyze the relationship between gravity variation in the Tibet area during that period and the Nepal Ms8.1 earthquake, and investigate the variation mechanism of gravity.

2. Data and processing

Gravity observation is an important part of a National key Scientific Infrastructure Project, the Chinese mainland tectonic monitoring network. The gravity network consists of approximately 700 gravimetric stations, and there are about 70 gravimetric stations in Tibet and its adjacent areas, of which 9 stations are absolute gravimetric stations; the detailed distribution is shown in Fig. 1. Since 2010, the gravity network of Continental Tectonics Environmental Monitoring Network of China has been reoccupied by 2 complete measurement campaigns. Since 2014, the Yutian Ms7.3 earthquake and the Pishan Ms6.5 earthquake occurred in the network area. The Nepal earthquake was located at the southern edge of the network area, and it serves as an earthquake example to study the gravity variation and the occurrence rule of strong earthquakes in that area.

In the data processing, this paper first establish a initial benchmarks and a control network using the absolute gravity data. In the absolute gravity data processing, correction for Earth tide, land water loading, atmospheric pressure, polar motion, vertical gradient are made. Then, reference data were obtained for relative gravity observation data processing through linear interpolation or extrapolation to the relative gravity observation time. Finally, we carried out overall adjustment calculations over the relative gravity data and reference data according to the classical adjustment using the LGADJ software [15]. The relative gravity data were subjected to solid tide correction, barometer correction, and instrument elevation correction in the adjustment calculations. In addition, in order to eliminate or minimize the disturbance caused by systematic errors of the instruments, scale parameters of the relative gravimeters were calculated using the absolute gravity observations as the controlling points. The treatment results indicated an average precision within 5×10^{-8} m s^{-2} for the gravity value at all points in each campaigns.

3. Results and discussion

3.1. Characteristic analysis of gravity variation

Fig. 2 presents the achieved gravity variation images of the research areas from 2010 through 2013 based on

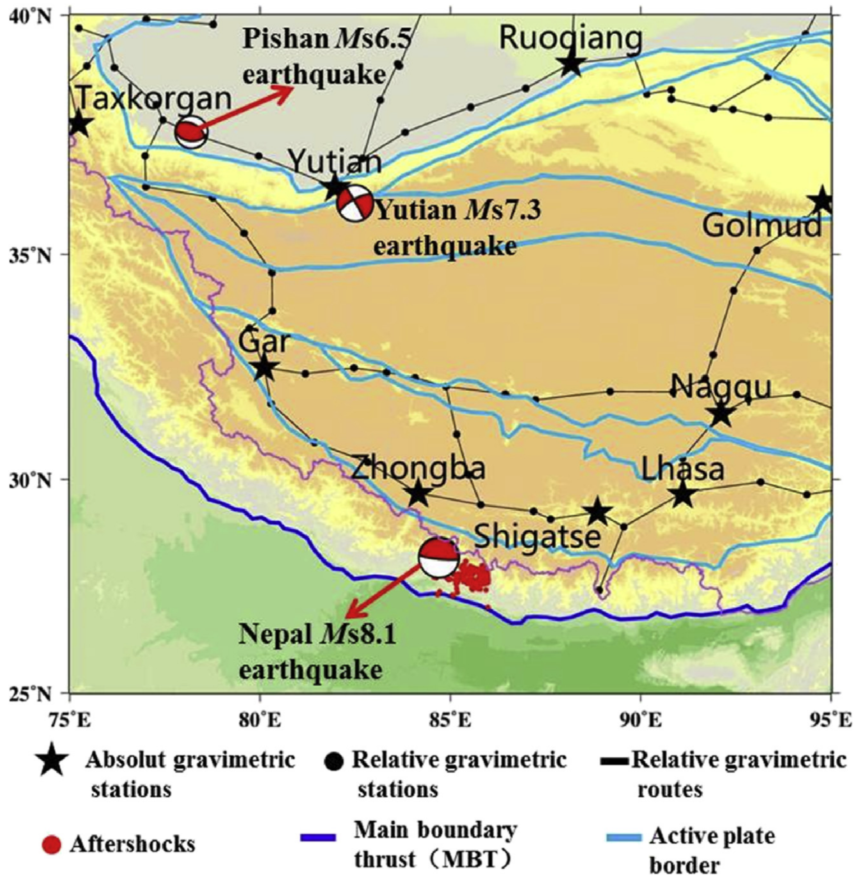

Fig. 1 – Gravity monitoring network overview.

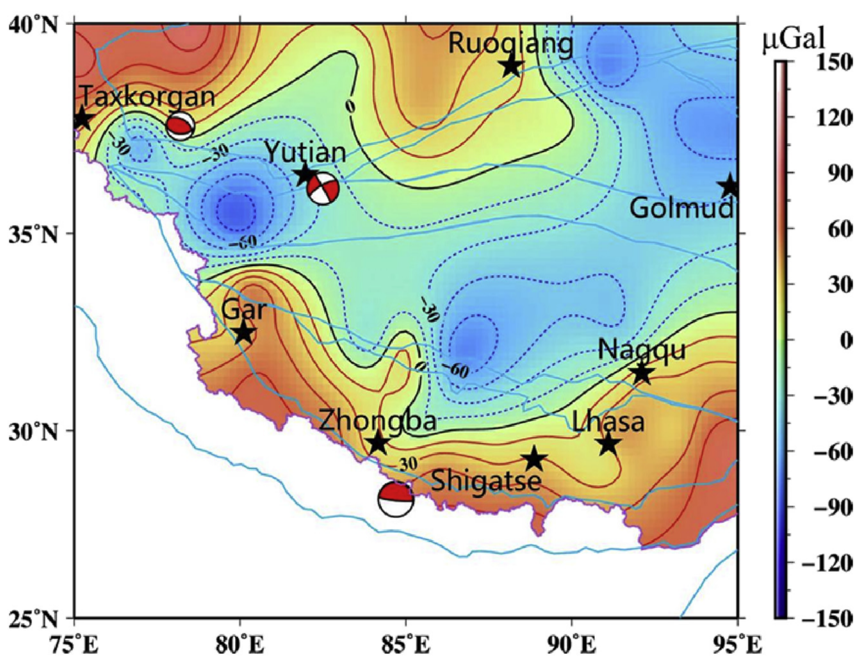

Fig. 2 – Gravity field variation image during 2010–2013.

the above data processing. The gravity field exhibited overall varying characteristics from the southeast to the northwest and alternative distribution of positive and negative variations.

The southern region of the network along the Himalayan frontier is a positive variation area with a maximum magnitude of approximately 60 microgal and forms a consistent differential gradient zone along the direction of the

Himalayas. The Nepal earthquake was approximately located at the contour turning point of South Zhongba. The interior of the Qinghai–Tibet Plateau generally exhibits low value negative variation. The Ruoqiang western area, which is located on the east and west sides of the Aerjing Fault, the southwestern area of Yutian, and the northern area of Zhongbaxi located in the middle of the Bangong Lake–Lujiang joint zone are three local negative variation high value areas with a maximum magnitude of about −70 microgal. The Pamir Plateau area in the northwestern region of the network exhibits positive gravity variation with a maximum magnitude of about 60 microgal and forms an approximately consistent differential gradient and 0 contour with the Kangxiwa Fault. Around the negative variation high value area on the western side of the Aerjing Fault, the Yutian Ms7.3 earthquake and Pishan Ms6.5 earthquake occurred on February 2014 and July 2015, respectively. The Yutian earthquake was located on the eastern side of the central negative variation area, and the Pishan earthquake was located on the northern side 0 contour in the high gradient zone. In addition, an Ms7.5 earthquake and an Ms7.2 earthquake occurred in the Hindu Kush area and the Tajikistan area on October 26 and December 7, 2015, respectively. These two earthquakes represent violent tectonic activity in the western antenna area of the north-squeezing India Plate, which has a background strongly consistent with gravity variation.

The research results from the gravity variation and earthquake occurrence rules indicate that the seismogenic activity and occurrence of great earthquakes are generally accompanied with high gravity anomaly variation, a differential varying gradient zone, contour turning and other phenomena. A high gravity anomaly is beneficial for the accumulation of earthquake energy, but a gravity variation gradient zone contributes to shear rupture [11,16,17]. Through the above analysis, it was easily found that the recent three strong earthquakes in the research area were all accompanied with a high gravity anomaly: the Yutian Ms7.3 earthquake was located at the edge of the negative anomaly area on the western side of the epicenter, the Pishan Ms6.5 earthquake was located in the differential gradient zone and 0 contour of the Kangxiwa Fault frontier, and the Nepal earthquake was located in the positive anomaly area and the inflection point of the differential gradient zone along the Himalayan frontier. These characteristics once again validate the existing recognition for predicting the great earthquake occurrence location using the gravity anomaly.

3.2. *Discussion on variation mechanism of gravity*

The factors leading to the variation of ground surface gravity are complex and varied. Except for the atmosphere, water loading and other environmental effects, the general factors are those that mainly reflect the vertical movement of the crust and the distribution variation of underground substances, as well as those that are related to tectonic movement. This paper considered the correction of the atmospheric effect in data processing, and utilized corrected initial benchmark values to eliminate or weaken the impacts of the water-loading effect. Consequently, this research extracted gravity variation information that resulted from structural factors.

The vertical movement of the crust has depended on leveling observations for a long time, but the long observation period is a shortcoming. In addition, the Tibet area is located near the Qinghai–Tibet Plateau, making it difficult for field observations. Except for three national high precision leveling observations conducted from 1951 to 1969, 1976 to 1984, and 1991 to 1999, there is no current literature on other leveling observation results from the Tibet area, and the time ranges of the above three periods of leveling observation data are very different from the gravity data in this paper. In recent years, high precision GPS observations have been increasingly used in the research of crust vertical movement [18–22]. For example, Liang et al. (2013) [22] investigated the three-dimensional crust movement characteristics of the Tibetan area over the above time ranges based on GPS observational data from 1998 to 2013. To compare with gravitation variation results, this paper utilized the vertical movement contour map drawn from the velocity rate results of the vertical movement from the information provided by Liang et al. [22] (Fig. 3). The data presented in Fig. 3 is within ±5 mm/yr in magnitude, which is about the maximum value of 1.5 μGal/yr in gravity variation and is not sufficient to cause 10 microgal of gravity variation for the maximum number in Fig. 2. Secondly, in the areas of the Himalayan frontier where isogal gravity exhibits positive variation, the vertical movement represents uplift and is opposite to the positive gravity variation direction; therefore, the crustal vertical deformation is not the primary cause of gravity variation. However, further analysis of the spatial distribution characteristics of vertical movement revealed that the typical regional distribution of vertical movement had a better consistency with gravity variation. From eastern Tibet to the Himalayan frontier to the Taxkorgan area, the gravity variation exhibits a positive to negative to positive characteristic. In the central area of the Bangong Lake–Nujiang River joint zone, the vertical movement represents a significant settlement, and gravity has a high negative variation. In the northeastern region of Golmud in the network area to the Ruoqiang area, the vertical movement represents a significant uplift, and the corresponding gravity exhibits a high negative variation. These characteristics indicate that gravity and the vertical movement of the crust that are two different observation approaches respectively reflect the gravity field and ground deformation features caused by structural factors in the Qinghai–Tibet Plateau, but the vertical movement of the crust is not the direct cause of gravity variation.

After excluding the factors that impact the vertical movement of the Earth's crust, the gravity variation is primarily a reflection of the density variation effect and the material movement processes of the Earth's deep crustal medium [16]. The results from this research showed that a significant positive gravity variation was observed in the Himalayan frontier, but the negative gravity variation was predominant in the interior of the Qinghai–Tibet Plateau. In this conjecture, the underground material of the Himalayan frontier was in an increasing state before the Nepal earthquake, but the material in the interior of the Qinghai–Tibet Plateau was in a loss state. Based on the background of geodynamics, the India Plate entered into

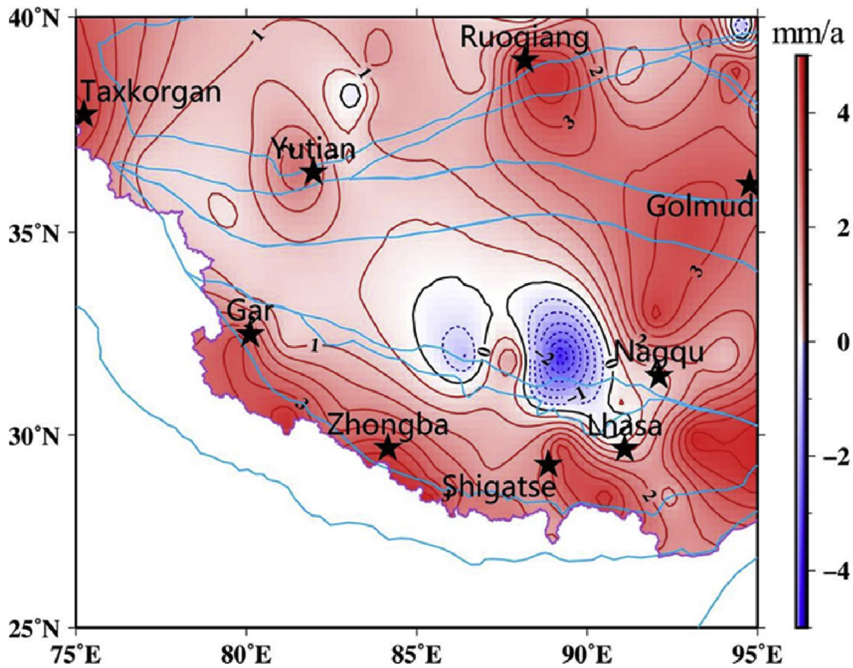

Fig. 3 – Crustal vertical movement observed by GPS (Positive for upward movement; [22].

the Qinghai–Tibet Plateau by the subduction toward the Eurasia [23,24] and possibly formed material accumulation at the boundary area of the Himalayan frontier, but the inner materials of the Qinghai–Tibet Plateau flowed out laterally. The research outcomes of the isostatic gravity anomaly [25,26] of the Qinghai–Tibet Plateau and the adjacent areas indicated that the Himalayan frontier exhibited an apparent positive isostatic anomaly, that is, the crustal materials were in a state of surplus. This meant that area was exposed to a long-term increasing background of crustal materials. Meanwhile, the interior of the Qinghai–Tibet Plateau generally exhibited a negative isostatic gravity anomaly [22], i.e. the crustal materials had a long-term outflow background. Chen et al. [14] further estimated the range of the material distribution of the gravity variation incurred by the Himalayan frontier before the Nepal earthquake based on the epicentroid theory, but they did not analyze the density variation mechanism. Regarding the potential density varying effect and material movement processes of the deep medium during the seismogenic period, some investigators successively proposed hot material upwelling [27], heat expansion of the lower and middle crustal materials [16], Moho plane deformation [28], rock strain [29] and other multiple modes, of which the rock strain mode was experimentally supported to a certain extent. Li et al. [30] conducted gravity variation simulation based on rock mechanical experiments, and their results indicated that the gravity variation incurred by rock stress and strain in a seismogenic area before an earthquake can reach approximately +100 microgal, and this magnitude is basically consistent with the results from this paper. Fig. 4 presents the horizontal strain field [31] of the Qinghai–Tibet Plateau before the Nepal earthquake observed by GPS. There is an apparent consistency between the spatial distribution of horizontal strain field and that of gravity variation. In the gravity positive variation areas of the Himalayas, the northern Taskougan, and others, the horizontal strain exhibits a strong positive strain, but in the gravity negative variation areas of the interior of the Qinghai–Tibet Plateau, the horizontal strain is predominantly tensile strain. These characteristics are in accordance with the mechanical experimental results of a density increase subjected to compressive strain and a density decrease subjected to tensile strain. Further analysis of the three observation results from the gravity variation, vertical movement and horizontal strain field revealed that in the areas of Himalayan frontier and Pamirs Plateau of northern Taxkorgan, the crust deformation exhibited a strong extrusion uplifting state, but the gravity field represented an apparent positive variation. These three observation results not only reveal the relative high-value feature with respect to the magnitude but are also in accordance with the inference that the crust of that area represents with respect to ground uplift and the increase in material density under the application of squeezing stress. Therefore, it is inferred that the strain and stress accumulation of the crust in the Qinghai–Tibet Plateau and adjacent areas is probably the important factor leading to gravity variation.

In addition, from the view of earthquake location, the Nepal earthquake was located at the gravity variation high-value area of the Himalayan frontier and the inflection point of the high gradient zone. In the strain field, the earthquake is located at the transition and inflection area [31] of two strain extreme areas of the eastern and western sides. This indicated that the inflection area of both gravity variation and the strain field in the Himalayan frontier area have a

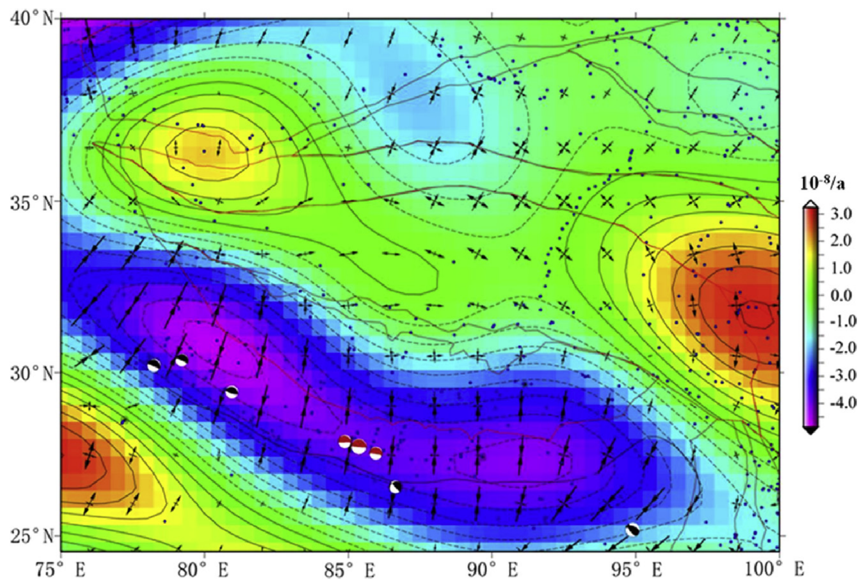

Fig. 4 – Crustal strain field observed by GPS before the Nepal earthquake [31].

better correlation with the earthquake location. The Himalayan frontier is the major deformation zone for the convergence of the India Plate and the Eurasian Plate. It absorbs approximately 30%–40% of the plate convergence rate [32]. This is the primary reason why the crust strain in that area exhibits an apparent compressive strain. However, in the seismogenic areas, due to the locking action of the earthquake fracture, the differential movement on the two sides of the fracture is somehow weakened relative to the adjacent areas. Therefore, the strain field observed by GPS represents a relatively low value and a transition area relative to the adjacent areas and further exhibits a contouring transition with respect to gravity variation.

4. Conclusion

This research utilized gravity data of the Continental Tectonics Environmental Monitoring Network of China from 2010 to 2013, examined the gravity variation of the Tibet area before the Nepal Ms8.1 earthquake, and investigated the gravity variation mechanism in combination with the vertical movement of the crust and the strain field observed by GPS. The major conclusions are as follows.

1) Before this Nepal earthquake, the Himalayan frontier exhibited characteristics of apparent positive variation and high gradient zone and was consistent with the existing recognition of the gravity anomaly and the location of a strong earthquake. This indicates that the gravity variation result provides an important reference value for predicting the location of a strong earthquake.
2) The gravity variation of the Qinghai–Tibet Plateau has an apparent consistency with the vertical movement of the crust and the spatial distribution of the horizontal deformation field in that area. However, the vertical ground movement is not the direct cause leading to gravity variation. It is suggested that the stress and strain accumulation of the crust in the Qinghai–Tibet Plateau and its adjacent areas is probably the important factor that results in the gravity variation.
3) In the Himalayan frontier and the Pamirs Plateau area of northern Taxkorgan, the three observation results of the gravity variation, vertical crust movement and horizontal strain exhibit a relatively high value characteristic with respect to magnitude. In addition, the positive variation characteristic of the gravity field is in accordance with the inference that the ground surface uplifts and materials increase due to the crust-squeezing effect in that area, as well as the northern-pushing dynamics background of the India Plate. Therefore, the gravity variation of the Himalayan frontier is probably a reflection of the seismogenic characteristics of the Nepal earthquake.

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Hongtao Hao, assistant research at Institute of Seismology, China Earthquake Administration. His current research interests focus on surface gravimetric technology and data processing.