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Deep tectonics and seismogenic mechanisms of the seismic source zone of the Jishishan M_s 6.2 earthquake on December 18, 2023, at the northeast margin of the Tibetan Plateau

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Key Points:

- We discuss the underlying factors that led to the Jishishan M_s 6.2 earthquake.
- The occurrence of the Jishishan M_s 6.2 earthquake is related to the inhomogeneity of the deep structure, especially the rapid changes in physical parameters.
- The crustal medium in the Jishishan region may be subject to both regional tectonic stress and local tectonic constraints.

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Abstract: On December 18, 2023, an M_s 6.2 earthquake occurred in Jishishan, Gansu Province, China. This earthquake happened in the eastern region of the Qilian Orogenic Belt, which is situated at the forefront of the NE margin of the Tibetan Plateau (i.e., Qinghai–Tibet Plateau), encompassing a rhombic-shaped area that intersects the Qilian–Qaidam Basin, Alxa Block, Ordos Block, and South China Block. In this study, we analyzed the deep tectonic pattern of the Jishishan earthquake by incorporating data on the crustal thickness, velocity structure, global navigation satellite system (GNSS) strain field, and anisotropy. We discovered that the location of the earthquake was related to changes in the crustal structure. The results showed that the Jishishan M_s 6.2 earthquake occurred in a unique position, with rapid changes in the crustal thickness, V_p/V_s, phase velocity, and S-wave velocity. The epicenter of the earthquake was situated at the transition zone between high and low velocities and was in proximity to a low-velocity region. Additionally, the source area is flanked by two high-velocity anomalies from the east and west. The principal compressive strain orientation near the Lajishan Fault is primarily in the NNE and NE directions, which align with the principal compressive stress direction in this region. In some areas of the Lajishan Fault, the principal compressive strain orientations show the NNW direction, consistent with the direction of the upper crustal fast-wave polarization from local earthquakes and the phase velocity azimuthal anisotropy. These features underscore the relationship between the occurrence of the Jishishan M_s 6.2 earthquake and the deep inhomogeneous structure and deep tectonic characteristics. The NE margin of the Tibetan Plateau was thickened by crustal extension in the process of northeastward expansion, and the middle and lower crustal materials underwent structural deformation and may have been filled with salt-containing fluids during the extension process. The presence of this weak layer makes it easier for strong earthquakes to occur through the release of overlying rigid crustal stresses. However, it is unlikely that an earthquake of comparable or larger magnitude would occur in the short term (e.g., in one year) at the Jishishan east margin fault.

Keywords: Jishishan M_s 6.2 earthquake; crustal structure; anisotropy; stress and strain; seismogenic mechanism; northeast margin of the Tibetan Plateau

1. Jishishan Earthquake and Tectonic Setting

According to the China Earthquake Networks Center, an M_s 6.2 earthquake struck Jishishan County, Linxia Prefecture, Gansu Province, at 23:59 Greenwich Mean Time (GMT) on December 18, 2023, with an epicenter at (35.70°N, 102.79°E) and a depth of 10 km. From the official information made publicly available, it could be confirmed that the earthquake measured an M_s 6.2 (Gao Y et al., 2024; Wang QC et al., 2024). Up to 21:00 h on December 21, a total of 11 $M \geq 3.0$ aftershocks were recorded, with the largest aftershocks being the M 4.1 earthquakes at 00:59 h on December 19 and at 04:02 h on December 21, respectively. According to public reports, as of 20:00 h on December 22, the earthquake had caused significant damage, resulting in 148 fatalities, 979 injuries, and 3 missing persons. Besides the collapsed houses, the earthquake triggered secondary mudflow disasters in the villages of

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Jintian and Caotan, Zhongchuan Township, Minhe County, and Haidong City, Qinghai Province, having a significant social impact.

The M_s 6.2 earthquake in Jishishan County, Gansu Province, occurred in the eastern section of the Qilian Orogenic Belt, which is part of the NE margin of the Tibetan Plateau frontal zone, encompassing a rhombic-shaped area that intersects the Qilian–Qaidam Basin, Alxa Block, Ordos Block, and South China Block (Figure 1). This region has been subject to strong tectonic activity for an extended period because of the collision and extrusion of the Indian and Eurasian Plates, leading to reverse faulting and frequent seismic activity. The eastern section of the Qilian Orogenic Belt comprises the Linxia Basin and the Longzhong Basin, which are dominated by basin development. The active fault closest to the epicenter of the earthquake is the Lajishan Fault, which is located at the western edge of the Linxia Basin. The Lajishan Fault is characterized by Late Pleistocene activities and serves as a large extrusion tectonic zone and tectonic transition zone between the NNW-oriented Reshui–Riyueshan Fault Zone and the NWW-oriented north margin fault of the western Qinling zone. Historically, more than 20 moderately destructive earthquakes of M 5 have occurred at the Lajishan Fault (Yuan DY et al., 2005). According to global positioning system (GPS) data, the vertical movement rate of this fault is 1.0 ± 0.5 mm/a, and it is currently in a stage of continuous uplift, with the possibility of earthquakes of approximately M 6 (Zhou L et al., 2016). The latest postearthquake express concluded that the Jishishan M_s 6.2 earthquake occurred on the Jishishan eastern margin fault, located at the southern tail end of the Lajishan Fault (Yuan DY et al., 2005; Gao Y et al., 2024), and that the seismic mechanism inversion resulted in a predominantly reverse fault (Wang QC et al., 2024).

Seismic activity is closely related to the crustal structure (Wang Q and Gao Y, 2014). Generally, variations in seismic wave velocity can cause obvious changes in rock strength, and regions with notable differences in crustal strength tend to experience more frequent and intense earthquakes (Li DH et al., 2021; Sun Q et al., 2022; Zuo KZ and Zhao CP, 2023). For instance, the M_s 6.9 Menyuan earthquake in Qinghai in January 2022 (Sun AH et al., 2022; Wang Q et al., 2022) and the M_s 6.8 Luding earthquake in Sichuan in September 2022 (Li Y et al., 2023) both occurred in the transition zone between high and low velocities. In this work, we aimed to scrutinize the profound tectonic background of the Jishishan M_s 6.2 earthquake by collecting data on the velocity structure, anisotropy, and geodetic deformation. Furthermore, we analyzed the relationship between crustal structure and the distribution of earthquakes to investigate the deep tectonic background of these natural calamities.

2. Crustal Thickness and V_p/V_s Values in the Jishishan Region

Crustal thickness and Poisson's ratio are two important parameters describing the crustal structure and material composition. They provide valuable insights into the geoevolutionary process of the crust and help in studying the seismic environment. In a study by Wang Q et al. (2016), three-component broadband seismic data from the China Seismological Network were used to calculate the receiver function. The seismic records were selected based on certain criteria, such as M > 5, an epicentral distance between 30° and 90°, and clear seismic phases. Using these data, we obtained the crustal thickness and V_p/V_s ratio of the NE margin of the Tibetan Plateau. In another study by Wang XC et al. (2017), the crustal thickness and wave velocity ratio of the NE margin of the Tibetan Plateau were obtained by using data from the temporary seismic network of ChinArray (Phase Ⅱ) and the temporary

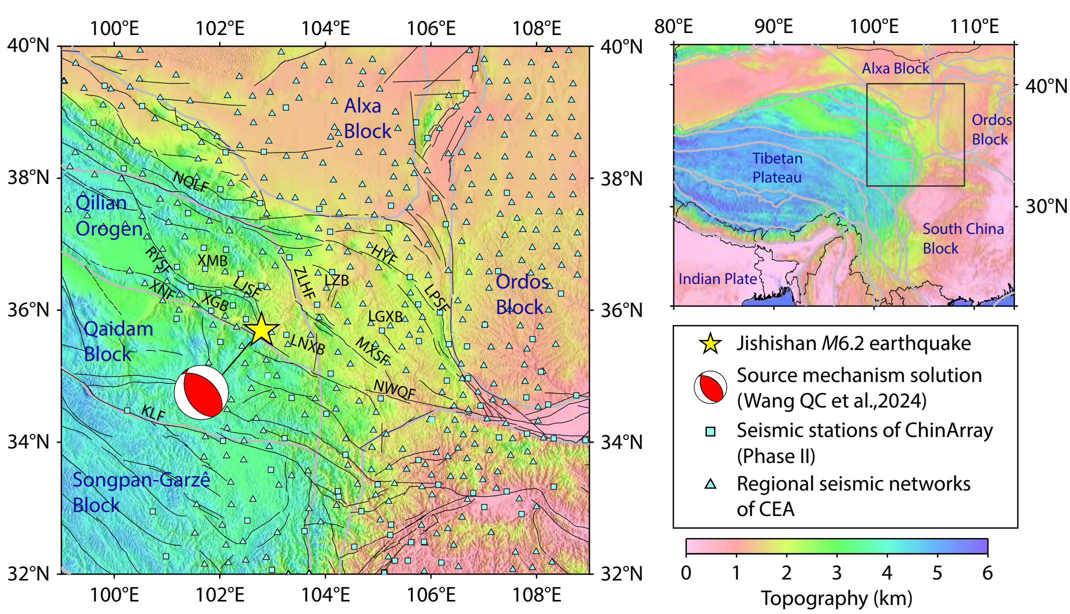

Figure 1. Tectonic background of the NE margin of the Qinghai–Tibet Plateau and the Jishishan earthquake. The fault information is from the Seismic Active Fault Survey Data Center (https://www.activefault-datacenter.cn/). NQLF: North Qilian Fault; HYF: Haiyuan Fault; LPSF: Liupanshan Fault; RYSF: Riyueshan Fault; LJSF: Lajishan Fault; ZLHF: Zhuanglianghe Fault; MXSF: Maxianshan Fault; XNF: Xunhua–Nanshan Fault; NWQF: north margin fault of the western Qinling; KLF: Kunlun Fault; LZB: Lanzhou Basin; LGXB: Longxi Basin; LNXB: Linxia Basin; XGB: Xunhua–Guide Basin; XMB: Xining–Minhe Basin; CEA: China Earthquake Administration.

network deployed in the Ordos Block. To analyze the relationship between the location of the Jishishan M_s 6.2 earthquake and the deep structure in this study, we redrew the images of crustal thickness and the distribution of the V_p/V_s ratio in the Jishishan region based on the results of the aforementioned two data sources (Figure 2).

According to Figure 2a, the crustal thickness in the study area ranges from 30 to 70 km and shows a clear zoning pattern. The NE margin of the Tibetan Plateau has a thicker crust than the peripheral region. The crustal thickness correlates with the topographic relief, exhibiting a gradient-deepening trend from east to west. The Jishishan region has a crustal thickness range of 48–53 km, which corresponds to the findings of Zhang XK et al. (2008) based on the seismic reflection and refraction profile of Maerkang–Luqu–Gulang. Wu LX et al. (2011) also observed a trend of increasing crustal thickness from NE to SW at the NE margin of the Tibetan Plateau, and the Jishishan area is located in the gradient change region (Wang X et al., 2020). Additionally, the results of gravity anomalies illustrate that the gravity anomalies at the NE margin of the Tibetan Plateau are negative, with relatively high anomalies in the Ordos Block, followed by those in the Alxa Block, and extremely low anomalies in Tibet, reflecting the outward-expanding nature of the Tibetan Plateau. Related studies have shown that gravity anomalies are closely related to ruptures and large earthquakes and that large earthquakes mostly occur in the gravity anomaly gradient zone (Wu Y and Gao Y, 2019); the Lajishan region is located exactly within the high-gravity anomaly gradient zone. We propose that when the Qinghai–Tibet Block extruded the Alxa and Ordos Blocks to the NE, it encountered obstructions from these two blocks, resulting in continuous crustal shortening and thickening, and triggering earthquakes caused by stress accumulation at the NE margin of the rhombic-shaped region. Previous studies (Shen XZ et al., 2015, 2020) of the lithosphere and crustal structures have documented this viewpoint.

Within the study area, the V_p/V_s ratios ranged from 1.60 to 1.90. Notably, the rhombic-shaped area situated at the NE margin of the Tibetan Plateau has lower ratios (<1.76) and is surrounded by high V_p/V_s values. The V_p/V_s values in the rhombic-shaped area show a trend of high and low values, with no clear zoning. Related studies have shown that V_p/V_s values (or Poisson's ratio γ) are related to the type of rock published by the laboratory (Christensen, 1996). For common rock types, V_p/V_s is particularly sensitive to rock composition. Generally, $V_p/V_s < 1.75$ is defined as a low Poisson's ratio, which corresponds to more felsic compositions, and $V_p/V_s > 1.81$ is defined as a high Poisson's ratio, corresponding to more mafic compositions. Combined with the results of this research, low V_p/V_s values in the Jishishan region seem to correlate with the average felsic crustal component. The magnetotelluric results showed (Jin S et al., 2012) multiple sets of electrical gradient zones of varying sizes in the Central Qilian Block, reflecting the fact that its crust is the most fragmented and tectonically complex. Comparatively, the epicenter of the Jishishan M_s 6.2 earthquake is located in the transition zone of rapid change in the wave velocity ratio, and a localized high anomaly zone of V_p/V_s occurs in this region. This finding may indicate that small amounts of other rock components are preserved in the deeper crust, which illustrates the relative complexity of the crust in this region.

3. S-wave Velocity Structure in the Jishishan Region

In a recent study, broadband data were collected from 366 stations at the NE margin of the Tibetan Plateau region. These stations included the temporary seismic array established by the Institute of Geology of the China Earthquake Administration (2011), the ChinArray (PhaseII) (2014), and permanent stations of the China Seismological Network. The S-wave velocity structure in the crust of the eastern Tibetan Plateau was inverted (Zhao PP et al., 2021) by utilizing the ambient noise data-processing method proposed by Yao HJ et al. (2006). To investigate the deep seismic

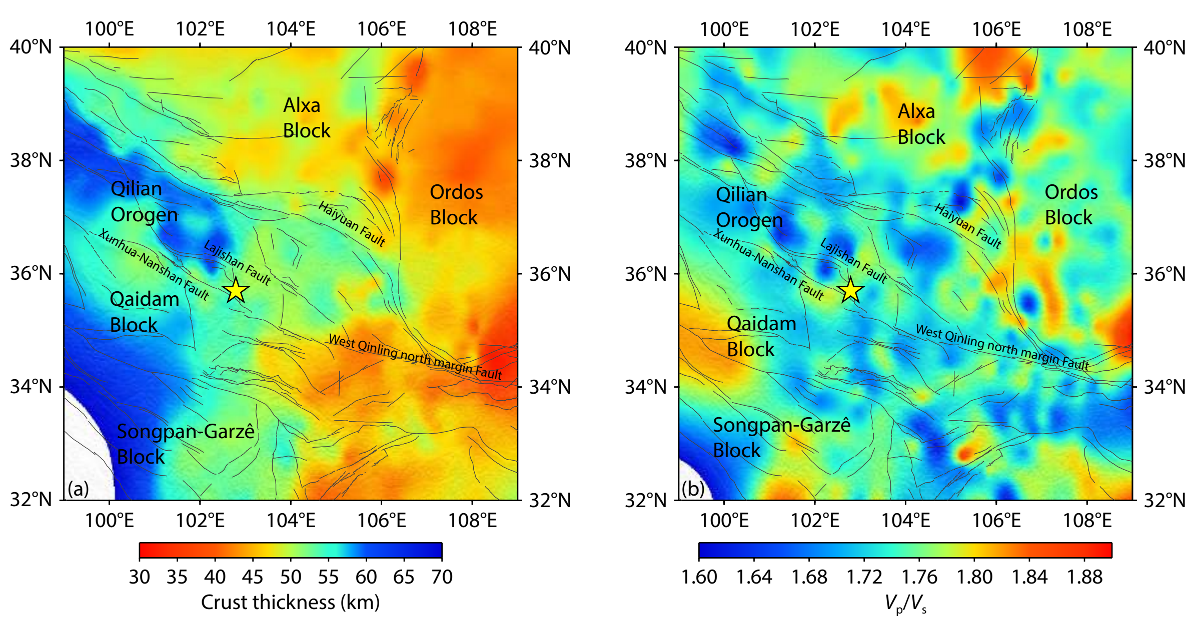

Figure 2. Crustal thickness (a) and V_p/V_s distribution (b) in the Jishishan region. The yellow pentagram indicates the mainshock of the Jishishan M_s 6.2 earthquake on December 18, 2023.

structure of the Jishishan earthquake in Gansu, the deep structure of the Jishishan earthquake source area was locally enlarged and redrawn, and an image of the S-wave velocity distribution in the source area was obtained (Figure 3).

This study revealed significant variations in the S-wave velocities within the source region of the Jishishan M_s 6.2 earthquake, both horizontally and vertically. At a depth of 5–10 km (Figures 3a–3b), the epicenter of the earthquake is at the interface of high and low velocities and is in proximity to a low-velocity region. Two high-velocity anomalies flank the seismic source area from both the east and west side, and their presence is consistent with the phase velocity results obtained from the ambient noise imaging (Figure 5). At a depth of 15–20 km (Figures 3c–3d), the velocity change is not as apparent as that of the shallower layers. However, the earthquake source area is still located at the interface of the high and low velocity of the S-wave. The vertical profiles (Figures 3e–3f) show obvious features of S-wave velocity lateral inhomogeneity. The low-velocity region can clearly be seen above the source of the Jishishan M_s 6.2 earthquake, and the high-velocity region can be seen below. Comparatively, a band of low-velocity anomalies extends throughout the region at a depth of 20–30 km, which is a common occurrence in many seismic zones with strong earthquakes (Li YH et al., 2014; Wang Q et al., 2022; Li Y et al., 2023).

The deep seismic sounding profile (Wang CY et al., 1995), seismic double-difference tomography (Xia SR et al., 2021), and teleseismic surface wave imaging (Li YH et al., 2017) all revealed the existence of a low-velocity layer in the middle and lower crust beneath the Qilian Orogenic Belt. The results of these studies indicate a significant correlation between the occurrence of earthquakes and the intracrustal low-velocity layer. Additionally, the magnetotelluric results showed the high-resistivity structure of the upper crust and the low-resistivity structure of the middle and lower crust in the source area of the Jishishan M_s 6.2 earthquake (Xin ZH et al., 2021). Xin ZH et al. (2021) suggested that the Japanese-type island arc structure applies to this area, wherein the high-conductivity layer indicates crustal material that is deformed, fractured, and filled with saline fluids. In addition, Xia SB et al. (2019) discovered a connection between the earthquake generation mechanism and the electrical structure in the crust based on the north–south geomagnetic profiles of the eastern section of the Qilian Orogenic Belt and the Alxa Block. They observed that the irregular and discrete high-resistance structure of the upper and middle crust along with the layered low-resistance structure of the lower and middle crust control the occurrence of earthquakes at the NE margin of the Tibetan Plateau. Taken together, these results suggest that the Linxia Basin, to which the earthquake source area belongs, is characterized by a relatively rigid upper crust. This rigid structure is favorable for the accumulation and release of stresses generated by collision and extension. The low-velocity, high-conductivity characteristics of the middle and lower crust may be attributed to the structural deformation and fragmentation of the middle and lower crustal materials on the NE margin of the Tibetan Plateau, along with the filling of salt-bearing fluids in the extension process (Xin ZH et al., 2021). Notably, such a weak layer renders it more accessible for strong earthquakes to occur through stress release from the overlying rigid crust.

4. Global Navigation Satellite System (GNSS) Strain Field and Anisotropy in the Jishishan Region

The research conducted by Wang M and Shen ZK (2020) utilized velocity field data from the Eurasian framework, using multiscale spherical wavelets (Tape et al., 2009; Su XN et al., 2016) to analyze the distribution of the principal compressive strain and maximum shear strain rate at the NE margin of the Tibetan Plateau through the solution method of Li SY et al. (2023). This trend gradually shifts from the NNE–SSW direction in the NW part of the region to

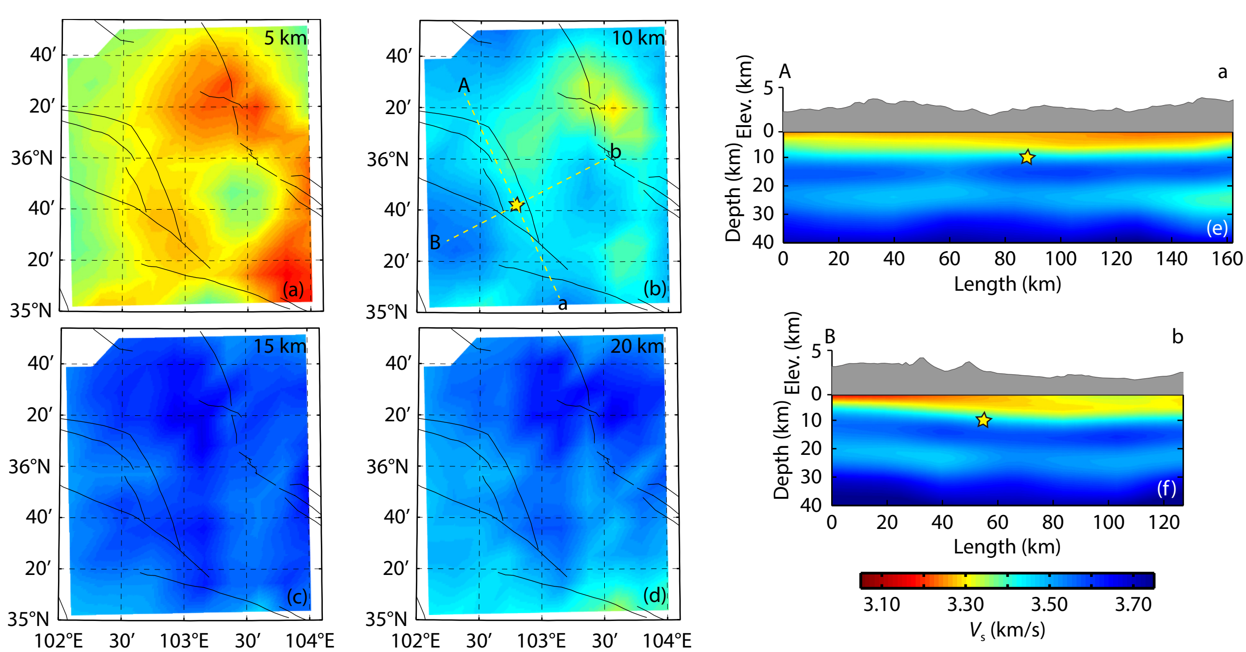

Figure 3. Lateral (a–d) and vertical (e–f) S-wave velocity structures at different depths. The yellow pentagram indicates the mainshock of the Jishishan M_s 6.2 earthquake on December 18, 2023.

the east–west direction in the southern part of the region, which aligns well with the velocity field in the Eurasian reference system. The higher shear strain rates in the region are primarily found along significant slip faults, such as the Kunlun Fault Zone and Haiyuan Fault Zone. Conversely, the Jishishan Mountain area has relatively low shear strain rates.

Wang QC et al. (2024) calculated the source mechanism solutions for the mainshock of the Jishishan M_S 6.2 earthquake. The results of their study indicated that for Section I, the strike was 312°, the dip was 48°, and the slide angle was 76°, whereas for Section II, the strike was 152°, the dip was 44°, and the slide angle was 105° (seismic sphere in Figure 1). Meng W et al. (2022) used historical earthquakes in the region to invert the tectonic stress field in the region based on the seismic source mechanism solution of historical earthquakes at the NE margin of the Tibetan Plateau. The results showed that the maximum principal compressive stress in the Qilian Orogenic Belt is NNE, which is in good agreement with the direction of the maximum principal strain. This result indicates that the growth and deformation of the Tibetan Plateau to the NE is blocked by the hard Alxa and Ordos Blocks and that the plateau exhibits signs of extension adjacent to the NE margin of the Tibetan Plateau.

Upon zooming and redrawing the strain results of the Jishishan M_S 6.2 earthquake source region (Figure 4b), we found that although the principal compressive strain direction at the NE margin of the Tibetan Plateau has a strong trend and shows regular changes, differences still exist in the principal compressive strain direction on both sides of the Lajishan Fault. The principal compressive strain direction on the north side of the Lajishan Fault transforms from the NNW–SSE direction to the NE–SW direction, whereas on the south side, it shifts from the NE–SW direction to the east–west direction. In addition, the seismic source area of the Jishishan M_S 6.2 earthquake is located near the region of maximum shear strain rate variation. Although the maximum shear strain rate in the seismic source area is weak, the strain rate of the adjacent north margin fault of the western Qinling to the south of the seismic source area is relatively strong, signifying that the seismic source area is a transition zone of shear strain change. The S-wave splitting results for the upper crust obtained from the near-field seismic records (Figure 4) indicated that the fast-wave polarization direction in the eastern part of the Qilian Orogenic Belt exhibits two dominant directions. The first one is the NE direction, which is consistent with the regional principal compressive stress direction, and the second one is the NW direction, which matches the strike of the regional fault (Li SY et al., 2023). As for the phase velocity azimuthal anisotropy results obtained from ambient noise imaging (Wang Q and Gao Y, 2018), a difference in the direction of fast-wave polarization exists on both sides of the Lajishan Fault Zone (Figure 5). All these phenomena indicate that the anisotropy pattern may be affected by regional fault zones, revealing that the anisotropy of the crust in the Jishishan region may be subject to both regional tectonic stress and local tectonics (fault).

5. Deep Tectonic Structure of the Jishishan M_S 6.2 Earthquake

Studies in petrology and source entity tectonics have revealed that the nonuniformity of rock components and their physical–mechanical properties in the middle and upper crust can lead to earthquakes (Ma ZJ et al., 1990). The epicenter of the Jishishan M_S 6.2 earthquake originated in an area where the thickness of the crust, V_P/V_S values (Figure 2), Bouguer gravity anomaly (Wang X et al., 2020; Zhang ZW et al., 2023), phase velocity (Figure 5), S-wave velocity (Figure 3), and maximum shear strain rate (Figure 4b) all change rapidly. Typically, changes in seismic wave velocity can represent changes in rock strength, and large ruptures or strong crustal deformation tends to be concentrated in places with large contrasts in crustal strength (or seismic wave velocity). Our results revealed that the occurrence of the Jishishan M_S 6.2 earthquake was related to the inhomogeneity of the deep

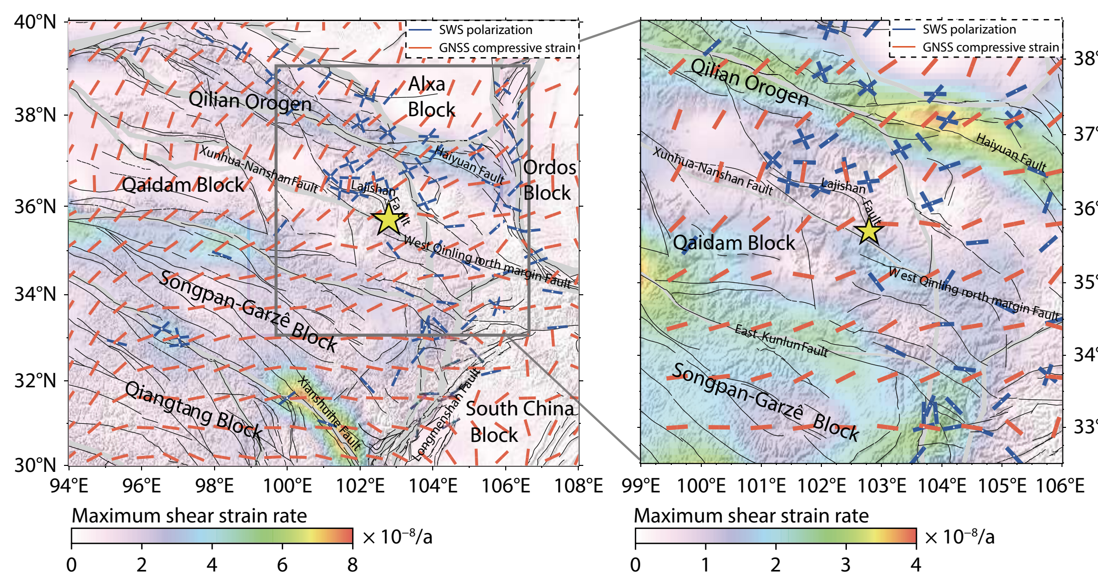

Figure 4. Distribution of the GNSS principal compressive strain at the NE margin of the Tibetan Plateau versus the direction of the shear-wave splitting (SWS) in the upper crust. The yellow pentagram indicates the Jishishan M_S 6.2 earthquake on December 18, 2023.

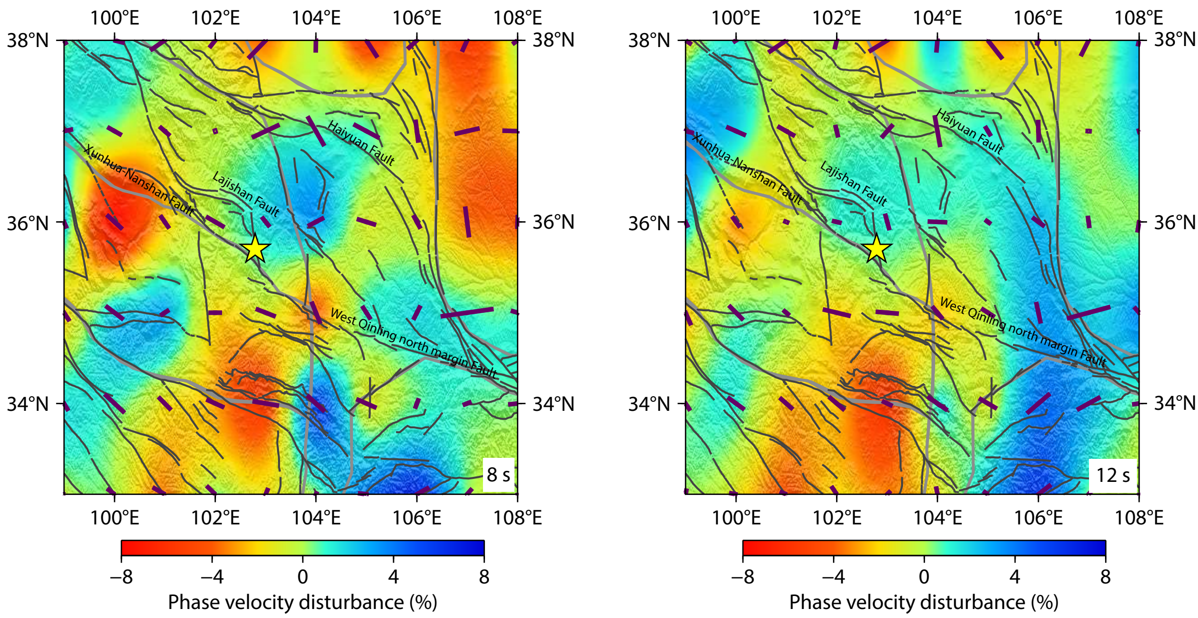

Figure 5. Distribution of phase velocity and azimuthal anisotropy in the source region of the Jishishan earthquake.

structure, especially the rapid changes in physical parameters.

Studies have indicated that strong earthquakes occur because of destabilized slipping of faults, and these slipping faults often require a decoupling layer to provide the faults with the overall movement conditions (Zhao LQ et al., 2019). Ma J et al. (1996) proposed that a low-velocity, high-conductivity layer with relatively low strength in the crust could provide such decoupling. The source region of the Jishishan M_s 6.2 earthquake shows significant high- and low-velocity variations, both laterally and vertically (Figure 3), with a low-velocity zone in the middle and lower crust in the vertical section. Geomagnetic results (Xin ZH et al., 2021) also revealed a high-conductivity layer in the lower and middle crust of the source area. The presence, transport, and drag of this low-velocity, high-conductivity layer increases the concentration of stress in the upper brittle crust, making it easier to rupture under the tectonic stress field of lateral compression (Wang CY et al., 2002; Liu G et al., 2020). Therefore, the presence of the low-velocity layer beneath the source area of the Jishishan M_s 6.2 earthquake provides a seismic environment that could lead to strong earthquakes.

Crustal tectonic deformation and seismic activity are intricately linked to the stress state of the crust. Earthquakes occur when a rock mass ruptures along a tectonic plane under the influence of a regional tectonic stress field (Scholz, 2002). The eastern section of the Qilian Orogenic Belt has had a complicated tectonic evolution because of the blockage of the Alax and Ordos Blocks against the NE margin of the Tibetan Plateau (Scholz, 2002). The direction of the principal compressive strain on the two sides of the Lajishan Fault appears to differ, with the main direction being NNE and NE. However, the strain shows the NNW direction locally, which is consistent with the rupture of the eastern edge of the Jishishan Fault. This direction is also consistent with the direction of the upper crustal fast-wave polarization and the direction of the phase velocity azimuthal anisotropy fast wave. We conclude that the joint action of the regional fault and tectonic stress influenced the occurrence of the earthquake.

Gao Y et al. (2024) found little difference between the XKS (teleseismic PKS, SKS, and SKKS phases) fast-wave polarization direction and the APM (absolute plate motion) direction in the source area of the Jishishan earthquake, indicating that the tectonic effect of the earthquake did not come directly from the entire lithosphere but may have come only from the inner crust. Additionally, the Jishishan eastern margin fault is a localized fault with a length of approximately 30–40 km. Therefore, it is difficult to accumulate more energy in a short period of time, which means that it is unlikely that a larger earthquake will occur in the near future.

6. Conclusions

We discussed the underlying factors that led to the Jishishan M_s 6.2 earthquake. This analysis is based on various geophysical results, such as the S-wave velocity structure, crustal thickness, V_p/V_s ratio, GNSS strain field, and anisotropy, along with the results of geologic tectonics, the regional gravity field, and geomagnetic data.

The results of our study indicate that the Jishishan M_s 6.2 earthquake occurred in a region where crustal thickness, V_p/V_s values, phase velocity, and S-wave velocity show rapid lateral changes, indicating a deep, inhomogeneous structure. Additionally, the low-velocity, high-conductivity layer in the lower crust of the source region of the earthquake provides an environment conducive to the occurrence of strong earthquakes.

Further, on the basis of the inversion of GNSS data, we observed changes in the direction of the maximum principal compressive strain and the maximum shear strain rate in the source region of the Jishishan M_s 6.2 earthquake. These results suggest that the crustal medium in the Jishishan region may be subject to both regional tectonic stress and local tectonic constraints. In summary, we conclude that the NE margin of the Tibetan Plateau was blocked by the Alax and Ordos Blocks, resulting in crustal extension and thickening. The middle and lower crustal materials were structurally deformed and fragmented, and they filled with salt-containing fluids in the extension process, making it easier for the overlying rigid crustal stresses to be released and strong earthquakes to occur.

On the basis of the high degree of consistency in anisotropy and the local tectonic characteristics of the earthquake-generating Jishishan east margin fault (Gao Y et al., 2024), it is unlikely that movement of the Jishishan east margin fault is likely to recur in the short term (e.g., within a year) with a comparable or larger magnitude earthquake.

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References

Christensen, N. I. (1996). Poisson's ratio and crustal seismology. *J. Geophys. Res.: Solid Earth*, *101*(B2), 3139–3156. https://doi.org/10.1029/95JB03446

Gao, Y., Li, X. Y., Li, S. Y., Xia, X. Y., Yang, Y. W., and Wang, Q. (2024). Deep and shallow deformation tectonics of Jishishan M_S6.2 earthquake on 18 December 2023 in China. *Earthquake (in Chinese)*, *44*(1), 160–166. https://doi.org/10.12196/j.issn.1000-3274.2024.01.012

Jin, S., Zhang, L. T., Jin, Y. J., Wei, W. B., and Ye, G. F. (2012). Crustal electrical structure along the Hezuo-Dajing profile across the Northeastern Margin of the Tibetan Plateau. *Chin. J. Geophys. (in Chinese)*, *55*(12), 3979–3990. https://doi.org/10.6038/j.issn.0001-5733.2012.12.010

Li, D. H., Ding, Z. F., Zhan, Y., Wu, P. P., Chang, L. J., and Sun, X. Y. (2021). Upper crustal velocity and seismogenic environment of the *M*7.0 Jiuzhaigou earthquake region in Sichuan, China. *Earth Planet. Phys.*, *5*(4), 348–361. https://doi.org/10.26464/epp2021038

Li, S. Y., Gao, Y., and Jin, H. L. (2023). Upper crustal deformation characteristics in the northeastern Tibetan Plateau and its adjacent areas revealed by GNSS and anisotropy data. *Earthq. Sci.*, *36*(4), 297–308. https://doi.org/10.1016/j.eqs.2023.05.003

Li, Y., Tian, J. H., Li, X. Y., Li, S. Y., Wang, Q., and Gao, Y. (2023). Deep tectonic pattern of the Luding M_S6.8 earthquake on 5th September 2022 in Sichuan Province, China. *Chin. J. Geophys. (in Chinese)*, *66*(4), 1385–1396. https://doi.org/10.6038/cjg2023Q0742

Li, Y. H., Xu, X. M., Zhang, E. H., and Gao, J. Y. (2014). Three-dimensional crust structure beneath SE Tibetan Plateau and its seismotectonic implications for the Ludian and Jinggu earthquakes. *Seismol. Geol. (in Chinese)*, *36*(4), 1204–1216. https://doi.org/10.3969/j.issn.0253-4967.2014.04.021

Li, Y. H., Pan, J. T., Wu, Q. J., and Ding, Z. F. (2017). Lithospheric structure beneath the northeastern Tibetan Plateau and the western Sino-Korea Craton revealed by Rayleigh wave tomography. *Geophys. J. Int.*, *210*(2), 570–584. https://doi.org/10.1093/gji/ggx181

Liu, G., Liu, W. Y., Lu, Z., and Zhang, P. (2020). Review of the measurement of rotational component in ground motions: A case study of rotating motion observation in Taiwan, China. *Prog. Geophys. (in Chinese)*, *35*(2), 422–432. https://doi.org/10.6038/pg2020CC0538

Ma, J., Ma, S. L., Liu, L. Q., Deng, Z. H., Ma, W. T., and Liu, T. C. (1996). Geometrical textures of faults, evolution of physical field and instability characteristics. *Acta Seismol. Sin.*, *9*(2), 261–269. https://doi.org/10.1007/BF02651070

Ma, Z. J., Zhang, J. S., Liu, C. D., and Liu, R. X. (1990). Current state of research on continental seismogenic layer—International workshop held in Beijing, April 27–30, 1990. *Seismol. Geol. (in Chinese)*, *12*(3), 262–264.

Meng, W., Guo, X. Y., Li, Y. H., Han, L. B., and Zhang, C. Y. (2022). Tectonic stress field and dynamic characteristics in the northeastern margin of the Tibetan Plateau. *Chin. J. Geophys. (in Chinese)*, *65*(9), 3229–3251. https://doi.org/10.6038/cjg2022P0236

Scholz, C. H. (2002). *The Mechanics of Earthquakes and Faulting* (2nd ed). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511818516

Shen, X. Z., Yuan, X. H., and Ren, J. S. (2015). Anisotropic low-velocity lower crust beneath the northeastern margin of Tibetan Plateau: Evidence for crustal channel flow. *Geochem. Geophys. Geosyst.*, *16*(12), 4223–4236. https://doi.org/10.1002/2015GC005952

Shen, X. Z., Li, Y. K., Gao, R., Chen, X. H., Liu, M., Yuan, X. H., Kind, R., Xiong, X. S., Zhang, Y. P., … Mei, X. P. (2020). Lateral growth of NE Tibetan Plateau restricted by the Asian lithosphere: Results from a dense seismic profile. *Gondwana Res.*, *87*, 238–247. https://doi.org/10.1016/j.gr.2020.06.018

Su, X. N., Meng, G. J., and Wang, Z. (2016). Methodology and application of GPS strain field estimation based on multi-scale spherical wavelet. *Chin. J. Geophys. (in Chinese)*, *59*(5), 1585–1595. https://doi.org/10.6038/cjg20160504

Sun, A. H., Gao, Y., Zhao, G. F., Ren, C., and Liang, S. S. (2022). Seismic structure and *b*-value in the focal area of the 8th January 2022 Menyuan, Qinghai M_S6.9 earthquake. *Chin. J. Geophys. (in Chinese)*, *65*(3), 1175–1183. https://doi.org/10.6038/cjg2022Q0030

Sun, Q., Pei, S. P., Guo, Z., and Chen, Y. S. (2022). Structure-controlled asperity on the generation of large earthquakes. *Rev. Geophys. Planet. Phys. (in Chinese)*, *53*(2), 138–147. https://doi.org/10.19975/j.dqyxx.2021-051

Tape, C., Musé, P., Simons, M., Dong, D. N., and Webb, F. (2009). Multiscale estimation of GPS velocity fields. *Geophys. J. Int.*, *179*(2), 945–971. https://doi.org/10.1111/j.1365-246X.2009.04337.x

Wang, C. Y., Lin, Z. Y., and Chen, X. B. (1995). Comprehensive study of geophysics on geoscience transect from Menyuan, Qinghai Province, to Ningde, Fujian Province, China. *Chin. J. Geophys. (in Chinese)*, *38*(5), 590–598.

Wang, C. Y., Mooney, W. D., Wang, X. L., Wu, J. P., Lou, H., and Wang, F. (2002). A study on 3-D velocity structure of crust and upper mantle in Sichuan–Yunan region, China. *Acta Seimol. Sin. (in Chinese)*, *15*(1), 1–17. https://doi.org/10.1007/s11589-002-0042-x

Wang, M., and Shen, Z. K. (2020). Present-day crustal deformation of continental China derived from GPS and its tectonic implications. *J. Geophys. Res.: Solid Earth*, *125*(2), e2019JB018774. https://doi.org/10.1029/2019JB018774

Wang, Q., and Gao, Y. (2014). Rayleigh wave phase velocity tomography and strong earthquake activity on the southeastern front of the Tibetan Plateau. *Sci. China Earth Sci. (in Chinese)*, *57*(10), 2532–2542. https://doi.org/10.1007/s11430-014-4908-2

Wang, Q., Niu, F. L., Gao, Y., and Chen, Y. T. (2016). Crustal structure and deformation beneath the NE margin of the Tibetan plateau constrained by teleseismic receiver function data. *Geophys. J. Int.*, *204*(1), 167–179. https://doi.org/10.1093/gji/ggv420

Wang, Q., and Gao, Y. (2018). Rayleigh wave phase velocity and azimuthal anisotropy in the northeastern margin of the Tibetan plateau derived from seismic ambient noise. *Chin. J. Geophys. (in Chinese)*, *61*(7), 2760–2775. https://doi.org/10.6038/cjg2018L0509

Wang, Q., Xiao, Z., Wu, Y., Li, S. Y., and Gao, Y. (2022). The deep tectonic background of the M_S6.9 Menyuan earthquake on January 8, 2022 in Qinghai Province. *Acta Seismol. Sin. (in Chinese)*, *44*(2), 211–222. https://doi.org/10.11939/jass.20220010

Wang, Q. C., Luo, J., Chen H. L., Meng, L. X. (2024). Focal Mechanism for the December 18, 2023, Jishishan M_s 6.2 Earthquake in Gansu Province. *Earthquake* (in Chinese), *44*(1), https://doi.org/10.12196/j.issn.1000-3274.2024.01.015

Wang, X., Jiang, W. L., Zhang, J. F., Wang, D. H., Tian, Y. F., and Shen, W. H. (2020). Deep structure of the gravity field and dynamic characteristics of the northeastern margin of the Tibetan Plateau. *Chin. J. Geophys. (in Chinese)*, *63*(3), 988–1001. https://doi.org/10.6038/cjg2020N0219

Wang, X. C., Li, Y. H., Ding, Z. F., Zhu, L. P., Wang, C. Y., Bao, X. W., and Wu, Y. (2017). Three-dimensional lithospheric *S* wave velocity model of the NE Tibetan Plateau and western North China Craton. *J. Geophys. Res.: Solid Earth*, *122*(8), 6703–6720. https://doi.org/10.1002/2017JB014203

Wu, L. X., Yang, M. Z., Zhao, W. M., Fu, R. S., Zhu, L. B., and Shi, X. J. (2011). Crust thickness inversed from multi-scale decomposition of bouguer gravity anomalies in Northeastern of Qinghai-Tibet Plateau. *J. Geod. Geodyn. (in Chinese)*, *31*(1), 19–23. https://doi.org/10.3969/j.issn.1671-5942.2011.01.005

Wu, Y., and Gao, Y. (2019). Gravity pattern in southeast margin of Tibetan Plateau and its implications to tectonics and large earthquakes. *Earth Planet. Phys.*, *3*(5), 425–434. https://doi.org/10.26464/epp2019044

Xia, S. B., Wang, X. B., Min, G., Hu, Y. B., Li, D. W., Kong, F. T., and Cai, X. L. (2019). Crust and uppermost mantle electrical structure beneath Qilianshan Orogenic Belt and Alxa block in northeastern margin of the Tibetan Plateau. *Chin. J. Geophys. (in Chinese)*, *62*(3), 950–966. https://doi.org/10.6038/cjg2019M0552

Xia, S. R., Shi, L., Li, Y. H., and Guo, L. H. (2021). Velocity structures of the crust and uppermost mantle beneath the northeastern margin of Tibetan plateau revealed by double-difference tomography. *Chin. J. Geophys. (in Chinese)*, *64*(9), 3194–3206, https://doi.org/10.6038/cjg2021O0514

Xin, Z. H., Han, J. T., Gao, R., Guo, X. Y., Liang, H. D., Kang, J. Q., and Liu, L. J. (2021). Electrical structure of the eastern segment of the Qilian orogenic belt revealed by 3-D inversion of magnetotelluric data: New insights into the evolution of the northeastern margin of the Qinghai-Tibet Plateau. *J. Asian Earth Sci.*, *210*, 104707. https://doi.org/10.1016/j.jseaes.2021.104707

Yao, H. J., Van Der Hilst, R. D., and De Hoop, M. V. (2006). Surface-wave array tomography in SE Tibet from ambient seismic noise and two-station analysis—I. Phase velocity maps. *Geophys. J. Int.*, *166*(2), 732–744. https://doi.org/10.1111/j.1365-246X.2006.03028.x

Yuan, D. Y., Zhang, P. Z., Lei, Z. S., Liu, B. C., and Liu, X. L. (2005). A preliminary study on the new activity features of the Lajishan Mountain fault zone in Qinghai Province. *Earthq. Res. Chin. (in Chinese)*, *21*(1), 93–102. https://doi.org/10.3969/j.issn.1001-4683.2005.01.010

Zhang, X. K., Jia, S. X., Zhao, J. R., Zhang, C. K., Yang, J., Wang, F. Y., Zhang, J. S., Liu, B. F., Sun, G. W., and Pan, S. Z. (2008). Crustal structures beneath West Qinling-East Kunlun orogen and its adjacent area—Results of wide-angle seismic reflection and refraction experiment. *Chin. J. Geophys. (in Chinese)*, *51*(2), 439–450. https://doi.org/10.3321/j.issn:0001-5733.2008.02.016

Zhang, Z. W., Gao, G. M., Wang, S. Q., Pan, Y., and Yang, Y. (2023). Study on the transverse variation characteristics of gravity anomalies in the northeastern margin of the Tibetan Plateau and its adjacent areas, based on wavelet multi-scale analysis. *J. Yunnan Univ. Nat. Sci. Ed. (in Chinese)*, *45*(4), 866–874. https://doi.org/10.7540/j.ynu.20220325

Zhao, L. Q., Zhan, Y., Sun, X. Y., Hao, M., Zhu, Y. Q., Chen, X. B., and Yang, H. (2019). The hidden seismogenic structure and dynamic environment of the 21 January Menyuan, Qinghai, M_S6.4 earthquake derived from magnetotelluric imaging. *Chin. J. Geophys. (in Chinese)*, *62*(6), 2088–2100, https://doi.org/10.6038/cjg2019M0204

Zhao, P. P., Chen, J. H., Li, Y., Liu, Q. Y., Chen, Y. F., Guo, B., and Yin, X. Z. (2021). Growth of the northeastern Tibetan Plateau driven by crustal channel flow: Evidence from high-resolution ambient noise imaging. *Geophys. Res. Lett.*, *48*(13), e2021GL093387. https://doi.org/10.1029/2021GL093387

Zhou, L., Wang, Q. L., Li, Z. J., Hao, M., and Song, S. W. (2016). The study of crustal deformation on western end of Lajishan fault based on GPS and leveling data. *J. Geod. Geodyn. (in Chinese)*, *36*(12), 1056–1059. https://doi.org/10.14075/j.jgg.2016.12.005

Zuo, K. Z., and Zhao, C. P. (2023). Seismicity and seismogenic mechanism of the M_S6.0 Luxian earthquake on September 16, 2021. *Earthq. Res. Adv.*, *3*(4), 100253. https://doi.org/10.1016/j.eqrea.2023.100253