Recent Tectonic Stress Field in Northwest Yunnan Province

Wenjie Fan¹, Xiuyi Yao ², *, and Xiaofeng Cui ³

¹Yunnan Earthquake Agency, Kunming 650224, Yunnan, China
²Yunnan University of Finance and Economics, Kunming 650224, Yunnan, China
³National Institute of Natural Hazards, Beijing 100085, Beijing, China

* Corresponding author: ZZ2114@ynufe.edu.cn

Abstract. Based on the collected focal mechanism solutions of M≥3.0 earthquakes in Northwest Yunnan from 2000 to 2018, we used Michael's linear inversion method to perform stress tensor inversion, and attempted to analyze the temporal and spatial evolution characteristics of the tectonic stress field in Northwest Yunnan. The results show that the types of focal mechanism solutions of earthquakes in Northwest Yunnan are complex, mainly strike-slip faulting earthquakes (46%), followed by normal faulting earthquakes (27%). The direction of maximum principal stress in the study area is NNW near NS direction, and the direction of minimum principal stress is ENE direction. It shows that the study area is subjected to horizontal compression from NNW near NS direction. According to the variation of the stress tensor variance over time, M≥5.0 earthquakes in the study area mainly occurred when the stress tensor variance was lower than 0.2. Most earthquakes occur when the variance of the stress tensor decreases, that is, when the focal mechanism solutions tend to be consistent. And these earthquakes mostly occur in the low value area of the variance and its edge.

1. Introduction

The study of the tectonic stress field is an important subject in the study of geodynamics. The research of the fine structure of the tectonic stress field and its continuous dynamic change image is the current development trend of the stress field (Franck et al., 2005; Bohnhoff et al., 2006; Hardebeck et al., 2006). The basic state of the regional modern tectonic stress field is the premise of analyzing the dynamic adjustment and change of the stress field. Northwest Yunnan (25.5°-28°N, 98.5°—101°E) is located in the southeast corner of the Qinghai-Tibet Plateau. It is the front edge of the Himalayas-Burma arc wedged northeast and the edge zone where the Eurasia plate and the Indian Ocean plate converge, subtract and interact. There are very complex geological structure and dynamic environment in Northwest Yunnan. Therefore, the study of the neotectonic movement in this area and its adjacent areas, especially the active structure and its mechanical mechanism since the Quaternary, has always been an issue of great concern to many scholars. Many scholars have used the abundant seismic observation data in Yunnan to study the tectonic stress field in Yunnan. They found that the modern tectonic stress field in Northwest Yunnan and its adjacent areas is characterized by horizontal action and the maximum principal compressive stress direction is NNW near NS(Xiang et al., 1986; Xie et al., 1994; Guo et al., 2014; Luo et al., 2014).

In previous studies, there are few studies about the small-scale tectonic stress state in Northwest Yunnan, and most of them focus on the large-scale tectonic stress field in Yunnan and even Sichuan-Yunnan area. At the same time, the research on the temporal and spatial changes of the stress field and the relationship with the occurrence of earthquakes is still insufficient. Therefore, it is very necessary to
study the temporal and spatial evolution characteristics of the recent tectonic stress field in Northwest Yunnan in detail, which can be useful help for exploring the relationship between tectonic stress field and earthquake gestation. To this end, based on the focal mechanism solution data of small and medium earthquakes, we used Michael's linear inversion method to perform inversion calculations, and conducted preliminary research and analysis on the temporal and spatial characteristics of the tectonic stress field in the study area.

2. Materials and Methods

We collected the focal mechanism solutions of 205 earthquakes with \( M \geq 3.0 \) in Northwest Yunnan from January 1, 2000 to December 31, 2018. The data mainly comes from calculation results of the small aperture network of the western Yunnan experimental field of China Earthquake Administration and Xu et al. (2013). According to the principle that the direction of shear stress is consistent with the direction of fault sliding, Michael (1984, 1987, 1991) proposed an algorithm of stress tensors inversion that converts nonlinear problems into linear, which improves the calculation efficiency of inversion stress tensors. Wiemer et al. (2001) integrated Michael's algorithm into the visualization ZMAP software package. We used the collected focal mechanism solution data to calculate the optimal stress tensor and regional grid inversion calculations by Michael's linear inversion method. We obtained the stress field inversion results to study the temporal and spatial evolution characteristics of the tectonic stress field in Northwest Yunnan and the spatial distribution characteristics of the stress tensor variance, further studied the relationship between the temporal and spatial changes of the stress tensor variance and seismic activity.

3. Results

3.1. Mechanism

We classified the focal mechanisms (Fig. 1) according to the focal mechanism solution type classification standard of the world stress map (Zoback et al., 1992). Statistics show that the number of strike-slip focal mechanism solutions are the most, with a total of 94(46%). There are 55(27%) normal faulting stress regime including normal faulting stress regime and normal strike-slip faulting stress regime. There are 33(16%) thrust faulting stress regime including thrust faulting stress regime and thrust strike-slip faulting stress regime. Undetermined stress regimes are the least, with 23(11%).

Fig.1 The spatial distribution of focal mechanism solutions. The TF, NF, SS, UD represent thrust faulting stress regime, normal faulting stress regime, strike-slip faulting stress regime, undetermined stress regime respectively. There are Nujiang fault(F1), Lancangjiang fault(F2), Weixi-Qiaohou fault(F3), Longpan-qiaohou fault(F4), Jianchuan-Wenhua fault(F5), Eryuan-Midu fault (F6), Chenhai-Binchuan fault(F7) in Northwest Yunnan.
3.2. Optimal stress tensor inversion

Using the linear inversion algorithm proposed by Michael (1984, 1987, 1991), we performed inversion by 205 focal mechanism solutions. The calculation results include three principal stress orientations and stress ratio $\phi = (S_2 - S_3)/(S_1 - S_3)$. $S_1$, $S_2$, $S_3$ are the maximum, intermediate, and minimum principal stresses respectively (Table 1). Fig. 2 shows the three principal stress directions and their 95% confidence intervals. The colored areas in the figure are the 95% confidence intervals of each principal stress axis orientation.

| Maximum principal stress $S_1$ | Intermediate principal stress $S_2$ | Minimum principal stress $S_3$ |
|--------------------------------|-----------------------------------|-------------------------------|
| Azimuth/(º) | Dip /(º) | Azimuth/(º) | Dip /(º) | Azimuth /(º) | Dip /(º) |
| 168 | 8 | 6 | 82 | 258 | 3 |

Fig. 2   Lower-hemisphere equal-area projection of principle stress axis and their confidence regions.

By combining Table 1 and Fig. 2, the azimuth of the maximum principal stress axis $S_1$ is 168º, which is nearly horizontal, and the minimum principal stress axis $S_3$ is ENE direction, with a small dip angle and nearly horizontal. The stress regime is strike-slip faulting, and the stress ratio is 0.8. The confidence interval range of the maximum principal stress axis, the intermediate principal stress axis and the minimum principal stress axis is relatively small, and they are basically distributed in clusters, indicating that the inversion results have better constraints on the three principal stress axes. The results of the optimal stress tensor inversion show that the Northwest Yunnan is subjected to horizontal compression in the NNW near NS direction and tension in the ENE direction.

3.3. Inversion of regional grid stress tensor

In order to further investigate the reliability of the inversion results, we divided the study area into a grid with a spacing of 0.05º×0.05º and performed the inversion. The number of focal mechanism solutions around the grid node selected during calculation is at least 5. It can be seen from Fig. 3 that the maximum horizontal principal stress orientation of the entire study area is relatively consistent, mainly in the NNW-near NS direction, which is consistent with the optimal stress tensor inversion result. The earthquakes are less distributed in the northern part of the study area, and focal mechanism solutions are complex. Therefore, the maximum horizontal principal stress directions obtained by the inversion are also more disordered in the northern part.
Fig. 3 The distribution of maximum horizontal principal stress orientation in research region.

Fig. 4 shows the stress tensor variance distribution map of the study area obtained after the regional grid inversion, and the earthquakes above $M_5$ in the study period are also marked. The stress tensor variance can be used to characterize the uniformity of the tectonic stress field obtained by the inversion. It is believed that the regional tectonic stress field is non-uniform when the stress tensor variance is greater than 0.2. When the value of the variance is less than 0.1, it means a unified stress tensor can be used to explain the observed focal mechanism solution, indicating that the stress field in the study area is uniform (Lu et al., 1997). The stress tensor variance is more evenly distributed in the southern part of the study area, and the value of stress tensor variance is basically less than 0.1, indicating that the stress field is also uniform. However, in the northern part of the study area, the stress tensor variance is larger, generally greater than 0.2. In addition, it can also be found that earthquakes occur mostly in areas with low stress tensor variance and their edges (Fig. 4), and the stress tensor variance values of these areas are mostly less than 0.2.

Fig. 4 The distribution of stress tensor variance and $M \geq 5.0$ earthquakes and in research region.

At the same time, we selected 10 earthquakes as the window length and 5 earthquakes as the step length for sliding calculation to obtain the variation of the stress tensor variance with time (Fig. 5). The results show that $M \geq 5.0$ earthquakes in the study area mainly occurred when the stress tensor variance was lower than 0.2, and most of these earthquakes occurred in the process of gradual decrease of stress.
tensor variance. For example, during the overall decline of stress tensor variance from 2010 to 2014, there were multiple $M \geq 5.0$ earthquakes such as Ninglang $M5.7$ and Eryuan $M5.5$.

Fig.5  The variation of stress tensor variance with time in research region.

4. Conclusions & Discussion
In this study, we collected the focal mechanism solutions of $M \geq 3.0$ earthquakes in Northwest Yunnan from 2000 to 2018 and classified the types of focal mechanism solutions. Based the collected focal mechanism solutions, we performed inversion of optimal stress tensor and regional grid stress tensor to obtain inversion results by Michael's linear inversion method. According to the results of the stress tensor inversion, we attempted to analyze the temporal and spatial characteristics of the tectonic stress field in Northwest Yunnan.

The stress regimes of focal mechanism solutions of earthquakes in Northwest Yunnan are complex, mainly strike-slip faulting stress regime (46%), followed by normal faulting stress regime (27%), and reverse faulting stress regime accounts for only 16%. Wan (2020) found by simulating stress system that the strike-slip stress system can produce normal faulting, normal strike-slip faulting, reverse faulting, reverse strike-slip faulting and strike-slip faulting of focal mechanism solutions. In Northwest Yunnan, various types of complex focal mechanisms have emerged under the strike-slip stress system of horizontal squeezing from the NNW near NS direction. The faulted basins distributed in Northwest Yunnan are pull-off basins formed since the Tertiary. The boundary faults that control the development of the basin are mostly shear extensional or normal faulting, such as the Longpan-Qiaohou fault and Chenghai-Binchuan fault, etc. (Wu et al., 1985). The pull-apart basin is a faulted basin formed by local extension in the strike-slip fault system. This local extension has contributed to the generation of vertical fault movement, making the study area dominated by strike-slip faulting earthquakes and accompanied by the occurrence of earthquakes of normal faulting and reverse faulting.

The direction of maximum principal stress in the study area is NNW near NS direction, and the direction of minimum principal stress is ENE direction. The inclination angles of the principal compressive stress axis and the principal tensile stress axis are very small, indicating that the study area is squeezed horizontally from the NNW-near NS direction. This means that the regional tectonic stress field compressed by the NNW-near NS direction has always controlled the modern crustal movement and seismic rupture characteristics of the upper crust in this area. The Northwest Yunnan is located in the boundary zone where the Indian plate and the Eurasian plate collide. Due to the pushing force of the Indian plate in the NNE direction, the substances escape eastward along the edge of the Qinghai-Tibet Plateau (Wu et al., 2015), and squeeze northern Yunnan along the southeast direction after encountering obstacles in the Sichuan Basin. This NNW near NS direction horizontal squeezing action also creates the characteristics of fault movement in this area, that is, NE trending faults are left-handed, NNE or near NS trending faults are normal faults, NW trending faults are right-handed, and NE trending left-handed strike-slip faults and NW trending right-handed strike-slip faults constitute a group of conjugate shear ruptures in the region (Xie et al., 1994).

In addition, the results of regional grid stress tensor inversion show that the stress tensor variance in Northwest Yunnan is basically below 0.2, the values are greater than 0.2 in individual areas. The stress tensor variance is at a low value, indicating that the focal mechanism tends to be consistent.
mechanism consistency can be used to characterize the degree of consistency between the released stress field in the source area and the regional stress field. The focal mechanism of small earthquakes in the source area tends to be consistent before moderately strong earthquakes. In essence, it is a process of stress concentration in a certain range of source area under the action of the regional tectonic stress field (Han et al., 2015). According to the variation of the stress tensor variance over time, \( M \geq 5.0 \) earthquakes in the study area mainly occurred when the stress tensor variance was lower than 0.2. And most of these earthquakes occurred in the process of gradual decrease of stress tensor variance, that is, in the process of convergence of the focal mechanism solutions. The locations of these earthquakes are mostly in the low-value area of stress variance and near the edge, which is helpful to research the stress concentration process in the source area and judging the earthquake risk.

Acknowledgments
This work was supported by the Institute of Crustal Dynamics, China Earthquake Administration Research Fund (grant number ZDJ2019-21).

References
[1] Bohnhoff M, Grosser H, Dresen G. (2006) Strain partitioning and stress rotation at the North Anatolian fault zone from aftershock focal mechanisms of the 1999 Izmit Mw = 7.4 earthquake. Geophys. J. Int., 166:373-385.
[2] Franck A, Romero G, Rendon H, et al. (2005) Quaternary fault kinematics and stress tensors along the southern Caribbean from fault-slip data and focal mechanism solutions. Earth-Science Reviews, 69 (2005) :181–233.
[3] Guo X Y, Chen X Z, Wang S W, Wang H X. (2014) Focal mechanism of small and moderate earthquakes and tectonic stress field in Sichuan-Yunnan areas. China Earthquake Engineering Journal, 36(3):559-607.
[4] Hardebeck J L, Michael A J. (2006) Damped regional-scale stress inversion: Methodology and examples for southern California and the Coalinga aftershock sequence. J Geophys. Res., 111 (B11310):1-11.
[5] Han X M, Rong D L. (2015) Consistency of seismogenic stress field of preshocks to the tectonic stress field before eight earthquakes (MW≥6.0) in southern California of United States from 1981 to 2011. Acta Seismologica Sinica, 37(6):948-958.
[6] Lu Z, Wyss M, Pulpan H. (1997) Detail of stress directions in the Alaska subduction zone from fault plane solutions. J. Geophys. Res., 102(B3) :5385-5402.
[7] Luo J, Zhao C P, Zhou L Q. (2014) Characteristics of focal mechanisms and stress field of the Chuan-Dian rhombic block and its adjacent regions. Seismology and Geology, 36(2):405-420.
[8] Michael A J. (1984) Determination of stress from slip data: faults and folds. J Geophys. Res., 89 (B13):11517–11526.
[9] Michael A J. (1987)) Use of focal mechanisms to determine stress: A control study. J Geophys. Res., 92 (B1):357–368.
[10] Michael A J. (1991) Spatial Variations in Stress Within the 1987 Whittier Narrows, California, aftershock Sequence: New techniques and results. J. Geophys. Res., 96(B4) :6303-6319.
[11] Wiemer S, Malone S. (2001) A SOFTWARE PACKAGE TO ANALYZE SEISMICITY: ZMAP. Seismological Research Letters, 72(2):373-382.
[12] Wu Z H, Long C X, Fan T Y, Zhou C J, Feng H, Yang Z Y, Tong Y B. (2015) The arc rotational-shear active tectonic system on the southeastern margin of Tibetan Plateau and its dynamic characteristics and mechanism. Geological Bulletin of China, 34(1):1-31.
[13] Wan Y G. (2020) Simulation on relationship between stress regimes and focal mechanisms of earthquakes. Chinese J. Geophys., 63(6):2281-2296.
[14] Wu D N, Dong Q D. (1985) Basic characteristics and co-formation mechanism of the rifted area in Northwest Yunnan. Modern crustal movement research, 1:118-132.
[15] Xiang H F, Guo S M, Ran Y K, Li X G. (1986) Recent tectonic stress field in the northwest of the Yunnan province. Seismology and Geology, 8(4):15-23.
[16] Xie F R, Liu G X, Liang H Q. (1994) Recent tectonic stress field in the northwest Yunnan province and its adjacent area. Seismology and Geology, 16(4):329-337.
[17] Xu Y. (2013) Decompilation of focal mechanism of small and medium earthquakes above ML3.0 in Yunnan area. Yunnan Science and Technology Press, Kunming.
[18] Zoback M L. (1992) First and second order patterns of stress in the lithosphere: the World Stress Map project. J. Geophys. Res. 97:11703–11728.