Characteristics of crustal stress field in Tienshan area

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Abstract. Based on 1143 focal mechanisms in Tienshan area from 1900 to 2019, according to the world stress map classification criterion, the main types of focal dislocations are thrust and strike slip; The results of parameter statistics show that the nodal plane of focal mechanism solution is basically consistent with the main tectonic strike in Tienshan area, and the orientation of P axis is perpendicular to the main tectonic strike in Tienshan area, which shows the horizontal nearly NS thrust. The direction of the maximum principal compressive stress is 175.1°, the minimum principal stress direction is 67.8°, the plunge angle of the maximum principal compressive stress axis is 4.3°, the plunge angle of the minimum principal compressive stress axis is 75.8°, the relative stress ratio R is 0.80, and the stress state is compressional, which indicates that the area is in the background of compressional orogeny.

1. Introduction
The Tienshan Mountain System stretches in the hinterland of Central Asia, starting from Turpan Basin in Xinjiang in the East and Fergana basin in Uzbekistan in the West. It is wedge-shaped, with a length of about 2500 km from east to west and a width of 250-350 km (Figure 1). It is the most important and largest orogenic belt formed by the continental convergence in Asia. The latest crustal movement in the Tienshan area is the Himalayan tectonic movement after the collision of India and Eurasia plates 38-40 million years ago. The intracontinental orogeny occurred in the Tienshan orogenic belt due to NS compression, which affected by the rapid uplift and continuous compression of the Tibetan Plateau caused by the strong collision of India and Eurasia plates[1-2]. At the same time, it extends to the foreland basins on the north and south sides of the Tienshan Mountains, and forms multiple rows of reverse fault fold belts at the intersection of the basins, whose compressional folds and faults constitute the main seismogenic structures of the Tienshan Mountains[3-4]. GPS observation results show that the crust deformation of the Tienshan orogenic belt is still highly active, and the overall crustal movement rate in the Tienshan area gradually decreases from south to north. The observation results confirm the impact of the NEE collision between the Indian plate and the Eurasian plate [5-6].

The tectonic stress field plays a very important role in the study of geodynamics, the regional crustal stress field, temporal and spatial variation characteristics provide reliable information for understanding of tectonic deformation, seismic mechanism and the interaction of seismic stress[7]. The inversion of the focal mechanism to obtain the regional tectonic stress field is a more feasible and commonly used approach. Many Chinese scholars have used different methods and data to carry out a large number of studies on the tectonic stress field in the Tienshan Mountains and adjacent areas in China [8-14], inferred that the direction of the principal stress axis in the Tienshan area of Xinjiang is close to NNE or NS. Kufner used seismic data recorded by three temporary networks TIPAGE, FERGHANA and TIPTIMON to invert the focal mechanisms of the earthquakes occurred on Tienshan
outside China\textsuperscript{[15]}. This paper will collect the focal mechanism solutions inverted by different methods of predecessors to form a complete set of focal mechanism database in the Tienshan area, which is convenient for the study of the focal mechanism and stress field in the Tienshan area, and has great significance for understanding the structural deformation, seismogenic mechanism and seismogenic background.

2. Data and Method

The earliest focal mechanism study in the Tienshan area is the 1902 Kashgar earthquake\textsuperscript{[16]}. The earthquake catalog used for focal mechanism solution is composed by three different catalogs: the International Seismological Centre (ISC)\textsuperscript{[17]}, the ISC-GEM Catalogue\textsuperscript{[18]} and the ISC-EHB Bulletin\textsuperscript{[19]}, and the three catalogues are corrected by each other. The focal depths are fixed to the ISC-EHB catalog, only when there is no such earthquake in the above three catalogs, the earthquake catalog used the parameters in the reference literature. The Tienshan area ($38^\circ \sim 46^\circ$N, $66^\circ \sim 92^\circ$E) is selected as the studied region, the time scale ranges from 1900 to 2019, and the focal depths are constrained to shallower than 60km. The focal mechanism solution data used in this work including 251 centroid moment tensors that downloaded from the Global Centroid Moment Tensor (GCMT) database from 1976 to 2019\textsuperscript{[20-21]}, 104 focal mechanism solutions from the Tienshan earthquake catalog and focal mechanisms of the moderate and strong earthquakes edited by Xinjiang Earthquake Administration\textsuperscript{[22]}, and remaining 788 focal mechanisms derived from the results of previous studies\textsuperscript{[9,16,23-40]}. If the there are overlaps between each other, the GCMT solutions are chosen as the optimized results. Finally we collected a total number of 1143 focal mechanism solutions.

The focal mechanism solutions are classified in the Tianshan area according to the division standard of the world stress map\textsuperscript{[41]}. Based on the features of the dip angles $P$, $T$, and $B$ axes, the focal mechanism solutions are divided into 6 types: normal fault, strike-slip with normal component, strike-slip, strike-slip with thrust component, thrust and unknown type. The inversion of the crustal stress field in the Tienshan area uses the linear stress inversion (LSIB) method, and the principle is referred to Michael\textsuperscript{[42,43]}.

3. Statistical characteristics of focal mechanism

According to the stress regime characterization based on the plunge of the focal mechanism solution $P$, $T$, $B$ axis, the statistics of the collected 1143 focal mechanism solutions show that there are 525 focal mechanisms of thrust type, accounting for the largest proportion (45.9\%), mainly distributed on the edge of the orogenic belt; 307 strike-slip earthquakes, accounting for the proportion secondly (26.8\%); 162 earthquakes of normal fault type, accounting for 14.2\%; 149 earthquakes of unknown, accounting for 13\% (Figure 1). The normal and unknown earthquakes are scattered on the edge of the orogenic belt and the intermountain basin. At the contact site between the Tien Shan orogenic belt and the Pamir, six types of focal mechanism solutions exist, indicating that the stress field here is very complex.

We count the normalized frequency at $10^\circ$ intervals from each parameter of the focal mechanism. The results show that the direction of the nodal plane is generally NEE-SWW, which is basically consistent with the overall trend of the Tienshan orogenic belt. Most of the nodal planes are inclined or nearly upright, and there are almost no horizontal nodal planes. The statistical characteristics of the sliding angle show that it has been reverse tilting. The dominant direction of the $P$-axis orientation is the NNW-SSE direction, which is exactly perpendicular to the dominant direction of the nodal plane, that is, perpendicular to the main structural direction of the Tienshan area, mainly horizontal pushing action; the $T$-axis orientation is mainly near the EW direction, and the tilt angle presents two dominant angles-near horizontal and Nearly vertical. The statistical characteristics of the focal mechanism parameters are basically consistent with the focal mechanism type characteristics.
Figure 1. Map of the study area and the distribution of different types of focal mechanism. (a) thrust, (b) strike slip, (c) normal fault, (d) unknown type.
4. Crustal stress field inversion
The Linear Stress Inversion with Bootstrapping (LSIB) method is used to invert the crustal stress field in the Tien Shan area, and the directions of the three stress principal axes are obtained (Figure 3). The maximum principal compressive stress direction $S_1$ of the crustal stress field in the Tienshan area is 175.1°, the minimum principal stress direction $S_3$ is 67.8°, the maximum principal compressive stress axis tilt angle is 4.3°, and the minimum principal compressive stress axis tilt angle is 7.58°. The relative stress magnitude $R = 1 - Pht = (S_1-S_2)/(S_1-S_3)=0.80$, the obtained stress state becomes the thrust state. The inversion results of this stress field indicate that the whole area of the study is still thrust by the NS plate formed by the collision between the Indian plate and the Eurasian plate, which shown the background tectonic stress state of the compacted mountain.

5. Conclusion and discussion
This paper collected and sorted out 1143 focal mechanism solutions in the Tienshan area from 1990 to 2019, and calculates the statistical characteristics of different parameters of focal mechanisms and the inversion of the stress field. The characteristics of the crustal stress field in the Tienshan area are as follows: (1) The earthquake rupture types in the study area are mainly thrust and strike-slip types. The focal mechanism is basically distributed along the contact parts between the Tienshan mountains and the surrounding intermountain basins. The rupture types of individual small earthquakes have a certain degree of randomness. However, the $P$-axis orientation of most earthquakes is roughly perpendicular to the strike of the main fault structures in the Tienshan area, reflecting the influence and control of pre-existing structures on the rupture patterns of small and medium earthquakes; (2) The overall performance of the study area is near-NS-direction horizontal compression, which is conducive to the formation of a background tectonic stress state for the compression orogen. The near-NS-direction force indicates that the area is directly compressed by the thrust influence of the Pamir Plateau and the Tarim Basin from the northward subduction.
As the Tienshan area is generally manifested as vertical shortening of the crust under horizontal compression, oblique shear transformation deformation, and lateral expansion and deformation to the basins on both sides, the active faults are mostly reverse faults and strike-slip faults with rotational characteristics \cite{44}, making thrust and strike-slip earthquakes account for a considerable number. Usually the force generated by plate motion is the dominant factor controlling the stress state of the regional environment, and the interaction between the blocks in the plate and the influence of the spatial non-uniform structure and the non-uniform mechanical properties of the rock cause secondary and local stress changes\cite{45}. The Tarim block forms different focal fault activity modes along its edge. The northern margin of contact with the Tienshan orogenic belt is mostly right-lateral strike-slip, and the west is connected to the Pamir, and is dominated by a large number of thrust earthquakes. The Tarim block is subject to relatively strong peripheral compression, especially at the western end. The collision and compression of the Indian plate against the Eurasian plate is the main reason for the faulty movement of the earthquake source around the Tarim block, which also shows that this collision and compression effect passes through the Tarim block to affects the whole Tienshan area. Due to differences in tectonic environments, regions of different tectonic environments and types have significant differences in their tectonic geometric patterns, crustal deformation characteristics, dislocation modes, and dynamic processes, which lead to different types of earthquakes.

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Figure 3. Results of stress field inversion.
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