Regional tectonic stress field evolution based on multi-source stress data—a case study in the Jinzhou area, North China Craton

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Abstract. Regional tectonic stress fields are key crustal stress elements that drive tectonic movements and associated with the evolution of regional tectonics, as well as the formation, preservation, and development of geological resources. The evolution of the regional tectonic stress field of the Jinzhou area, which is located in the eastern block of the North China Craton (NCC), may provide a deeper understanding of the tectonics of western Liaoning and the NCC. In this work, borehole image logging technology and focal mechanism solutions were used to invert the paleo and present regional tectonic stress fields. Four groups of tensile fractures in the southern Jinzhou area were identified via the borehole televiewer, and the azimuths of these fractions were NNW-SSE, NWW-SEE, nearly W-E, and NE-SW in sequence. Focal mechanism solutions showed that the stress states of the area were normal fault and strike-slip, thereby revealing that the southern Jinzhou area is undergoing NEE-SWW-oriented compression and nearly N-S-oriented extension in accordance with the strike-slip mechanism. From the Early Cretaceous to the present, the direction of the regional extensional stress in the southern Jinzhou area has evolved in a counterclockwise and sequential manner from NNW-SSE to NWW-SEE, W-E, NE-SW, and near-N-S; moreover, the regional tectonic mechanism has transitioned from extension to extension-strike-slip to strike-slip.

1. Introduction
Regional tectonic stress fields are key crustal stress elements that drive tectonic movements and associated with the evolution of regional tectonics, as well as the formation, preservation, and development of geological resources. The recovery of paleotectonic stress fields is an essential method used to analyze the regional evolution history and construct accurate geological evolution models[1]. Borehole image logging technology, fault slide data, fractures,
hydraulic fracturing, and focal mechanism solutions are commonly employed to reconstruct tectonic stress fields[2-15].

Abundant geological resources and information of the tectonics of the North China Craton (NCC) are preserved in the Jinzhou area to the west of Liaoning Province (Figure 1), which is located in the eastern block of the craton. Mineralization mainly occurred in the Mesozoic, while oil- and gas-bearing layers were mainly deposited during the Cenozoic[16-21]. However, studies on regional tectonic stress fields have yet to be completed[6, 9,18]. Moreover, because these studies are spatially and temporally isolated, a deeper understanding of the evolution of the regional tectonic stress field in western Liaoning cannot be obtained.

Figure 1. Regional geological map of the southern Jinzhou area (1 - ZK22, 2 - ZK30, 3 - ZK38, 4 - ZK17, 5 - ZK27, 6 - ZK35, 7 - ZK24, 8 - ZK40, 9 - ZK21, 10 - ZK33, 11 - ZK41).

This work investigates the development of the regional paleo- and present tectonic stress field on the basis of borehole image logging technology and focal mechanism solutions to establish a method system that could reveal the evolution of the regional tectonic stress field in the Jinzhou area from the Cretaceous to the present. The results of this study may provide a reliable reference with which to obtain a better understanding of the tectonic characteristics of the NCC and western Liaoning.

2. Methodology

2.1. Borehole image logging technology

The data and images presented in this paper were obtained from borehole televiewers established in boreholes in the southern Jinzhou area, which are located 35 km from the downtown area (Figure 1). Data processing was conducted using the software WellCAD, which is capable of processing and interpreting live data. Patterns, depths, dip directions, and fracture dips were directly observed. The tensile fractures were then identified, and their dip directions were obtained. The tensile fractures corresponded to Mode I fractures that propagate normal to the minimum principal stress $\sigma_3$ in the plane containing $\sigma_1$ and $\sigma_2$ as a
result of true tension ($\sigma_3 < 0$)\cite{1-8}. Furthermore, tensile fractures with opposite azimuths were treated as one group because these fractures could be generated in an identical extensional tectonic event.

2.2. Focal mechanism solutions
One hundred and thirty-four focal mechanism solutions with Ms of over 3.0 within 200 km of the Jinzhou area were collected to analyze the tectonic stress field by using the MATLAB script StressInverse, which is based on iterative joint inversion. The final results are presented in the form of $P$, $B$ (N), and $T$ axes and approximate directions of $\sigma_1$, $\sigma_2$, and $\sigma_3$. The stress shape factor $R$ can also be obtained while calculating the focal mechanism solutions.

3. Stress data

3.1. Fractures from the Cretaceous to the Cenozoic
A total of 193 tensile fractures were identified from all boreholes; in detail, 126, 49, 14, and 4 fractures developed in the Tianqiao granites and diabase, diorite porphyrite, and granitic aplite veins, respectively.

3.2. Focal mechanism solutions
The azimuths of $\sigma_1$, $\sigma_2$, and $\sigma_3$ in this area were ca. 73.91°, 232.34°, and 342.26°, respectively, and the corresponding dips were ca. 15.66°, 73.22°, and 5.86°, respectively. $\sigma_1$ and $\sigma_3$ were nearly horizontal, whereas $\sigma_2$ was nearly vertical (Figure 2).

![Figure 2. Focal mechanism solutions in the southern Jinzhou area. SS, TS, and NS are marked red, NF is marked blue, and TF is marked gray. (a) Distribution of the focal mechanism solutions. (b) Confidence of the principal stress axes.](image)

Focal mechanism solutions were classified according to the principal stress axes by dividing all earthquakes into six types, namely, normal fault (NF), normal strike-slip (NS), strike-slip (SS), thrust strike-slip (TS), thrust fault (TF), and uncertain (U)\cite{22}.  

| Type | Count | Percentage |
|------|-------|------------|
| NF | 16 | 12% |
| NS | 13 | 10% |
The 134 seismic data points were dominated by 91 SS focal mechanism solutions (68%; Table 1). Chaoyang, Yixian, and Fuxin to the north and Panjin to the east were characterized by SS and minor NF and NS focal mechanism solutions (Figure 2a). The Liaodong Peninsula contained all types of focal mechanism solutions, and all TF- and TS-type focal mechanism solutions were distributed in this area only (Figure 2a). The Jinzhou area, together with Chaoyang, Yixian and Fuxin, is located in the Yanshan fold belt; thus, these sites are likely to have identical tectonic settings and focal mechanisms. Therefore, the focal mechanism solution of the southern Jinzhou area should be SS.

4. Discussion

4.1. Regional paleotectonic stress field in the Cretaceous–Cenozoic

According to the tensile fracture counts compiled according to rock type, three groups of preferred fracture directions were evident in the Tianqiao granites, namely, NNW-SSE, NWW-SEE, and nearly W-E. Two groups of preferred dip directions of NWW-SEE and W-E were evident in the diabase, one group with a dip direction of NWW-SEE appeared in the diorite porphyrite, and one group with a dip direction of NE-SW occurred in the granitic aplite veins (Figure 3).

![Figure 3](image_url)

*Figure 3*. Rose diagrams of tensile fractures in different types of rock: (a) Tianqiao granite, (b)
diabase vein, (c) diorite porphyrite vein, and (d) granitic aplite vein.

NNW- and SSE-dipping tensile fractures occurred only in the Tianqiao granites (Figure 3a), thereby implying that the NNW- and SSE-dipping tensile fractures were formed the earliest. NWW- and SEE-dipping tensile fractures were present in all rock types except granitic aplite veins (Figures 3a, b, c), thereby indicating that these fractures are younger than the diabase and diorite porphyrite veins but older than the granitic aplite veins. Therefore, NWW- and SEE-dipping tensile fractures are younger than NNW- and SSE-dipping tensile fractures. The W-, E-, NE- and SW-dipping tensile fractures were younger than the granitic aplite veins because W- and E-dipping tensile fractures were present in all rock types (Figure 3). Similarly, NE-SW tensile fractures (Figures 3a, b, d) were found in all rock types except diorite porphyrite veins. However, defining the order of formation of these tensile fractures on the basis of their presence in various magmatic rocks only is difficult. Two groups of tensile fractures intersect in the Tianqiao granites. In borehole ZK17, two sets of tensile fractures with attitudes of 53.15°∠3.59° (NE) and 254.56°∠59.69° (near W) occurred at depths of 43.11 and 43.152 m, respectively (Figure 4). The W-dipping fractures were transformed and crosscut by the NE-dipping fractures in the borehole images, thereby demonstrating that the W-E fractures are older than the NE- and SW-dipping fractures. In addition, the SEE- and W-dipping fractures intersected in the diabase veins. In borehole ZK17, two sets of tensile fractures with attitudes of 261°∠31.91° (W) and 112.05°∠35.08° (SEE) occurred at a depth of 34.459 m (Figure 4). The SEE-dipping fractures were transformed and crosscut by the W-dipping fracture in the borehole images. Similarly, in borehole ZK17, two sets of tensile fractures with attitudes of 293.34°∠65.11° (NWW) and 257.38°∠53.12° (W) occurred at depths of 41.074 and 41.160 m, respectively (Figure 4). The NWW-dipping fractures were transformed and crosscut by the W-dipping fractures in the borehole images. These results demonstrate that the NWW- and SEE-dipping tensile fractures are older than those with W and E orientations. Thus, fractures with NNW-SSE, NWW-SEE, W-E, and NE-SW orientations were sequentially formed.
Previous studies on Mesozoic–Cenozoic tectonics, magmatic activity, and deposition in Liaoning Province proposed that the tectonic setting of the western Liaoning area includes extension and strike-slip\cite{16-21}. Therefore, the Jinzhou area likely underwent sequential extensions of NNW-SEE, NWW-SEE, W-E, and NE-SW from the Early Cretaceous to the Cenozoic.

**4.2. Present regional tectonic stress field**

The focal mechanism solutions showed that the azimuths of $\sigma_1$ and $\sigma_3$ were 73.91° and 342.26°, respectively, and that the corresponding dips were nearly 0°. In addition, $\sigma_2$ is nearly vertical (Figure 2b). These findings indicate NEE-SWW compression and NNW-SSE extension, which are consistent with the stress distribution characteristics of the strike-slip tectonic mechanism\cite{23}. Strike-slip stress can result in various types of focal mechanism solutions. When the stress shape factor increases, the NF and NS focal mechanism solutions decrease while the TF and TS solutions increase\cite{23}. The value of the stress shape factor in the study area varied from 0.313 to 0.512 with a peak at 0.4 (Figure 5b); thus, the NF and NS focal mechanism solutions with large dips of the P axis are greater than the TF and TS solutions with large dips of the T axis (Figure 5a). These results are consistent with the characteristics of the strike-slip stress system.
Figure 5. (a) Distribution of the P/T axes and (b) stress shape factors of the focal mechanism solutions.

4.3. Evolution and significance of the regional tectonic stress field

As mentioned earlier, the tectonic setting of western Liaoning is extension in the Cretaceous and strike-slip in the Cenozoic. Thus, the evolution of the regional tectonic stress field in the southern Jinzhou area from the Cretaceous to the present could be divided into five stages by using a combination of borehole image logging technology, structural analysis, hydraulic fracturing, and focal mechanism solutions, as follows (Figure 6).

The first stage, which spanned the Early Cretaceous to ca. 125 Ma, was characterized by NNW-SSE dipping tensile fractures that developed in the Tianqiao granites when the study area underwent NNW-SSE regional extension. The second stage, which occurred at ca. 125 Ma, was characterized by NWW-SEE dipping tensile fractures that developed in the Tianqiao granites, diabase, and diorite porphyritic veins when the area underwent NWW-SEE regional extension. These two tectonic events corresponded to the regional NE-SW stretching normal faults. The third stage, which occurred from 125 Ma to the Late Cretaceous, was characterized by near-W-E dipping tensile fractures that developed in all intrusions when the area underwent near-W-E regional extension. However, this stage only affected deep intrusions, providing few records within the sedimentary strata. The fourth stage, which occurred within the Cenozoic, was characterized by NE-SW dipping tensile fractures that developed in the Tianqiao granites, diabase, and granitic aplite veins when the area underwent NE-SW regional extension to generate a large number of NW-SE stretching normal and strike-slip faults. At present, the area is undergoing NEE-SWW compression and near-N-S extension in the setting of the strike-slip tectonic mechanism.
5. Conclusion

The conclusions of this paper can be drawn as follows.

(1) Four groups of tensile fractures in the southern Jinzhou area were identified via the borehole televiewer. The azimuths of these groups were NNW-SSE, NWW-SEE, nearly W-E and NE-SW in sequence and represent four stages of extensional tectonic events.

(2) Focal mechanism solutions showed that the stress status was NF in shallow areas and transitioned to SS with increasing depth. This finding reveals that the southern Jinzhou area is undergoing NEE-SWW-oriented compression and nearly N-S-oriented extension in accordance with the strike-slip mechanism.

(3) From the Early Cretaceous to the present, the direction of the regional extensional stress in the southern Jinzhou area evolved in a counterclockwise and sequential manner from NNW-SSE to NWW-SEE, W-E, NE-SW, and nearly N-S. Moreover, the regional tectonic mechanism transitioned from extension to extension-strike-slip to strike-slip.

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