Research Article

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Cenozoic paleostress field of tectonic evolution in Qaidam Basin, northern Tibet

<https://doi.org/10.1515/geo-2020-0262>

received April 17, 2019; accepted May 18, 2021

Abstract: This article analyzes the stress fields in the Qaidam Basin since the entire Cenozoic using finite element numerical simulations. The stress fields are investigated by analyzing tectonic joints and the GPS velocity field in the basin. The relationship between the stress field patterns and the tectonic activity of the basin was discussed. Based on previous research on the uplift of the Tibetan Plateau, five stages of the tectonic evolution of the Qaidam Basin are modeled. The simulation results show that the stress trajectories in the Oligocene and the Pliocene–Quaternary were similar. In the Oligocene, the stress trajectories in the basin changed significantly and were mainly controlled by the compressional stress on the southern boundary in the initial stage. As the compressional stress on the northern boundary of the basin gradually increased, the compressional stress on the southern and northern boundaries had equal effects in the intermediate stage, and the compressional stress on the northern boundary mainly controlled the stress trajectories in the late stage. During the uplift of the Tibetan Plateau, the stress trajectories in the Qaidam Basin experienced an apparent reversal. The stress trajectories of the internal basin rotated clockwise from NE–SW to NW–SE in the Oligocene and which gradually changed to counter-clockwise from NW–SE to NE–SW in the Miocene and

recovered to clockwise from NE–SW to NW–SE in the Pliocene–Quaternary.

Keywords: Qaidam Basin, paleostress, finite element numerical simulation

1 Introduction

This article describes the paleostress trajectories in the Qaidam Basin since the entire Cenozoic, mainly for the following reasons: (1) The research on the uplift of the Tibetan Plateau has been a hotspot at home and abroad in recent years. The Qaidam Basin, which is located in the northern part of the Tibetan Plateau, is the direct result of the formation of distant deformation due to plate convergence and collision during the uplift of the Tibetan Plateau. The uplift of the Tibetan Plateau has directly influenced the tectonic deformation of the Qaidam Basin in the Cenozoic and has resulted in the present tectonic geomorphology of the basin [1–8]. The Cenozoic stress field in the Qaidam Basin is part of the stress field of the Tibetan Plateau, so it can complement research on the stress field during the uplift of the Tibetan Plateau. (2) The Qaidam Basin subsidence is mainly controlled by the Eastern Kunlun fault, the Altyn Tagh strike-slip fault, and the Southern Qilian strike-slip fault. These three active faults are also significant seismic zones in China [9]. According to the statistical data from the United States Geological Survey (USGS), the Qaidam Basin experienced 125 magnitude 5+ earthquakes, 17 magnitude 6+ earthquakes, and 3 magnitude 7+ earthquakes between 1800 and the present. Therefore, understanding the characteristic of the S_{Hmax} in the Qaidam Basin can analyze the activity of active faults.

The tectonic stress was analyzed by measuring joints and striations in the field, but some problems need to be resolved. For example, it is difficult and costly to measure tectonic stress in the field, the different stages of tectonic stress in the basin were modeled by numerical simulations method. However, numerical simulations are also limited by several factors. Numerical models cannot fully

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reproduce the actual geological conditions, and they are digitized mainly using the principles of similarity, selectivity, separability, approximation, and statistical properties. Numerous researchers have used two-dimensional geological models to numerically simulate tectonic stress fields. For example, Bertoluzza and Perotti [10] simulated the stress field patterns in pull-apart basins using the finite element method and discussed the patterns of the S_{Hmax} around strike-slip faults under extensional, shear, and compressional stresses. Munoz-Martin et al. [11] simulated the Tertiary paleostress field in the eastern Tahoe Basin of central Spain using the finite element method. Bada et al. [12] proposed that the results of stress and displacement numerical values depend on load stress and geometric boundary. Because the load stress is an estimated value, and the choice of geometric boundary conditions is subjective. Therefore, it is difficult to calculate the absolute stress and displacement at a certain point. Usually, ignore the absolute size of the numerical values and consider the relative size and direction of the value to analyze the activity strength of the active fracture. Previous analyses of the stress field of the Qaidam Basin have mainly focused on intrabasin tectonic joints, magnetic fabric analysis, focal mechanism solutions, and the analysis of GPS. For example, Peizhen et al. analyzed the current stress field in the Qaidam Basin by the GPS velocity field [13].

Due to the complex evolution of the stress field in the Qaidam Basin, numerical simulations of the stress field have only been performed along the Altyn Tagh Fault Zone. Few stress field analyses have been performed over the entire basin system. In this study, the Cenozoic stress trajectories for the entire Qaidam Basin were obtained. In addition, the tectonic activities of the Altyn Tagh, Southern Qilian, and Eastern Kunlun faults during different historical periods and their influence on the stress trajectories to gain a full understanding of the evolution of the Cenozoic stress field in the Qaidam Basin were discussed. Moreover, the effects of boundary conditions, selection of the model parameters, and application of the stress load on the simulated results were discussed.

2 Geological background

The Qaidam Basin is a typical petroliferous basin that is located on the northern margin of the Tibetan Plateau (Figure 1) [14–16]. The basin covers an area of approximately $1.2 \times 10^5 \text{ km}^2$ and has elevations of 2,500–3,000 m [17,18]. Sedimentary cover in the Qaidam basin mainly contains a continuous sequence of lacustrine, fluvial,

alluvial, and eolian sediments. The units are as follows: Paleocene to early Eocene (E_{12}) (65–52.5 Ma), middle Eocene (E_{13}) (52.5–42.8 Ma), late Eocene (E_{23}) (42.8–40.5 Ma), late Eocene to Oligocene (40.5–24.6 Ma), early to middle Miocene (N_{12}) (24.6–12 Ma), late Miocene (N_{22}) (12–5.1 Ma), Pliocene (N_{32}) (5.1–2.8 Ma), and late Pliocene to Quaternary (Q) (2.8 Ma – present). The basement lithology of Qaidam Basin is mainly Proterozoic metamorphic rocks [19]. The deformation of major faults and the Cenozoic strata within the basin provides a record of the effect of compression from the uplift of the Tibetan Plateau. The Qaidam Basin block is subjected to compression by several plates, primarily that of the Indian plate, which is oriented NE20°. In addition, the compression from the Kazakhstan and Siberia plates is oriented SE130°. However, the latter two plates have a smaller influence than the Indian plate. Collectively, these forces cause the Qaidam Basin to rotate clockwise from NE to SE. The movement and deformation of major faults surrounding the Qaidam Basin provide a record of the basin–mountain tectonic framework and geodynamic setting. Specifically, three major faults control the evolution of the basin: the Kunlun fault, the Altyn Tagh fault (Figure 2a and b), and the thrust fault zone on the southern margin of the Qilian fault. Elliptical piedmont folds with long axes have developed in front of the Altyn Tagh fault. The direction of the piedmont fold axis was NE–SW (Figure 2c and d). A consensus has been reached on the Cenozoic tectonic activity of the Qaidam Basin. The main driving force is thought to be the collision between the Indian and Asian plates, whose distant effect has caused the tectonic activity of the Qaidam Basin [20–24] (Figure 3). In this study, we analyze the evolution of the Cenozoic stress field in the Qaidam Basin based primarily on the attenuation of the effect of the Tibetan Plateau from south to north, which is divided into five different stages.

3 Cenozoic stress–strain analysis

3.1 Analysis of tectonic joints

Field measurements of joints and stratum attitude were collected mainly using the GPS positioning and orientation sensor of an iPhone. The Field Move Clino app can use the inclinometer of the iPhone to do that work. A total of 78 joints were measured in Wulan County, Wanggaxiu coal mine, Yingxiongling area, and Lenghu Lake (Figure 4). A large number of joints data from previous research were collected [25–27]. The joints data were adjusted to the stratum level using the software StereoStat 1.6.1. The

Figure 1: Simplified tectonic map of the Qaidam region, showing the location of the measurements of joints position. The red star represents the data from this study, and the circular represents the data from other scholar.

joints data were grouped based on a Rose diagram of joints orientations and stratigraphic age from the Mesozoic to Cenozoic era (Table 1). The maximum principal stress was indicated by the acute angle between intersecting conjugate shear joints [28–30], so a rough distribution of the maximum principal stress trajectories in the Cenozoic Qaidam Basin was obtained.

3.2 GPS analysis

Studies of the current crustal movements and the spatial distribution of the stress and strain fields using GPS observation data can provide reliable evidence for validating numerical simulations of the stress and velocity fields of tectonic blocks. The velocity field obtained from the analysis of GPS observation data can accurately explain the movement directions and mean annual velocities of GPS base stations on the ground surface, and velocity field trajectories can reflect the stress trajectories. The analysis of the active tectonic deformation and GPS velocity field in

mainland China by Peizhen and Qi et al. [31,32] indicated that now the direction of the Qaidam activity block, which was consistent with the direction of the Kunlun block in the south, was NE61.45°, and the average activity velocity was lower than that of the Kunlun block (Figure 5).

4 Numerical simulation of the Cenozoic stress field in the Qaidam Basin

4.1 Model construction and parameter selection

The numerical simulation analysis was conducted mainly using a finite element analysis tool, ABAQUS 6.14 Student Edition, which was developed by SIMULIA. The basin model was divided into two parts: the cover and the basement. A 2D model was constructed for each part using

Figure 2: Photograph of tectonic geomorphology on the Qaidam Basin: (a) the Kunlun fault, (b) the Kunlun fault and the Altyn Tagh fault, (c) and (d) elliptical piedmont folds with long axes.

identical boundary conditions by 3D modeling structures of the Qaidam Basin which was proposed by Jianming et al. [19]. The main difference between the cover and basement of the basin was lithology and fracture development. The former lithology is dominated by sedimentary rocks – low stiffness and easy to deform. The latter is dominated mainly by metamorphic rocks – high stiffness and not easy to deform. The fault extended from the basement to the cover, and the main controlling area of fracture development was the basement. To analyze the particularity of cover and base, the cover to be a homogeneous elastic plate and the basement to be an elastic plate with six faults [19] were assumed. Since the stress state of the model being static was discussed, the relative slip between fractures could be ignored. The mechanical parameters of the model are chosen based on the geotechnical test [33] (Table 2). Triangular elements (CPS3) are chosen as the finite mesh elements for the cover model, which is divided into 534 elements and 336 nodes. The finite mesh elements of the basement model was divided into two parts: triangular elements (CPS3) are used for the basement model and

quadrilateral elements (CPS4R) are used for the surrounding block model. The basement model is divided into 371 elements and 366 nodes.

The stress loading conditions are identical for the cover and basement. The effect of the horizontal compressional stress of the plates on the stress trajectories in the basin was considered. Based on the analysis of the evolution of the Cenozoic stress field in the basin, the stress loading in the basin into the following stress states over three different periods was divided as follows: (1) Paleogene – The southern boundary of the basin began to be affected by compressional stress, and the effect of compression to the south gradually extended toward the northern boundary, where no stress accumulation occurred. The relative load on the southern boundary is 1×10^8 Pa, while no stress is applied to the northern boundary. (2) Neogene – Stress gradually accumulated to the maximum level on the northern boundary of the basin, while compressional stress progressively increased on the southern boundary. The ratios of the compressional stresses on the southern and northern boundaries are

Figure 3: The tectonic evolution of Qinghai-Tibet Plateau: (a) Oligocene, (b) Miocene, and (c) Pliocene–Quaternary [17].

chosen as 1:1, 1:2, and 1:3, and the compressional stress on the northern boundary of the basin was dominant. (3) Quaternary – The compressional stress on the northern boundary was gradually released with tectonic deformation and decreased constantly until the compressional stress on the southern boundary became dominant. The ratio of the compressional stresses on the southern and northern boundaries is chosen as 2:1.

4.2 Simulation results and analysis

Because the actual stress trajectories only reflect the stress trajectories of the basin cover, the simulation results of the stress trajectories in the basin cover were analyzed. The simulated stress trajectories in the basement are used primarily to discuss the influence of the Altyn Tagh, Southern Qilian, and Eastern Kunlun faults (Figure 6).

4.2.1 Analysis of the stress trajectories in the Paleogene

A compressional stress perpendicular to the boundary is applied to the Kunlun fault on the southern margin of the Qaidam Basin. The calculated results show that on the southern margin of the basin, the S_{Hmax} trajectories were generally perpendicular to the Kunlun fault, while on the northwestern margin, the S_{Hmax} trajectories were oriented NE–SW, approximately parallel to the Altyn Tagh fault. On the northeastern margin, the S_{Hmax} trajectories were oriented NW–SE, nearly parallel to the Southern Qilian fault. The orientations of the S_{Hmax} trajectories in the basin generally showed a clockwise rotation.

4.2.2 Analysis of the stress trajectories in the Neogene

The northern boundary of the basin was subjected to gradually increasing compressional stress, which influenced the S_{Hmax} trajectories in the basin by gradually increasing amounts. Different ratios of the compressional load are applied to the southern and northern boundaries of the basin. The compressional load on the northern boundary has the greatest influence on the S_{Hmax} trajectories in the basin when the stress loading ratio of 1:3 is used. Increasing the compressional load on the northern boundary does not change the S_{Hmax} trajectories in the basin. In the following section, we simulate the S_{Hmax} trajectories at loading ratios of 1:1, 1:2, and 1:3 between the southern and northern boundaries.

(1) Loading ratio of 1:1

The calculated S_{Hmax} trajectories show that on the southern margin of the basin, the S_{Hmax} trajectories to the west of the Eastern Kunlun fault were oriented NE–SW, approximately perpendicular to the Eastern Kunlun fault. The S_{Hmax} trajectories rotated counterclockwise from NE–SW to NW–SE. Due to the influence of the Altyn Tagh and Southern Qilian faults, the S_{Hmax} trajectories on both sides were generally parallel to the boundaries. From the Altyn Tagh fault to the Southern Qilian fault, the S_{Hmax} trajectories showed a clear clockwise rotation from NE–SW to NW–SE.

(2) Loading ratio of 1:2

The calculated S_{Hmax} trajectories show that on the northern margin of the basin, the S_{Hmax} trajectories to the west of the Southern Qilian fault were oriented NNE–SSW, approximately perpendicular to the Southern Qilian fault. The S_{Hmax} trajectories rotated counterclockwise from NNE–SSW to WNW–ESE. Due to the influence of the Eastern Kunlun fault, the S_{Hmax}

Figure 4: Typical joint of outcrops on the field: (a) typical joint in Wulan County, (b) typical joint in Wanggaxiu coal mine, (c) typical joint in Yingxiongling area, (d) typical joint in Lenghu Lake, (e) the striation in Wanggaxiu coal mine, and (f) tectonic deformation in Wulan County.

Table 1: Comprehensive analysis results of structure joints on the Qaidam Basin

Stratigraphic age	The number of joint sets	The direction of S_{Hmax}
N_2^3	1	NNW–SSE
N_2^2	1	NW–SE
N_2^1	4	NNE–SSW, NEE–SWW, NE–SW, NW–SE
J	3	NNE–SSW, N–S, E–W
C	1	E–W

trajectories on this side were parallel to the fault, and they rotated clockwise from NW–SE to nearly EW from west to east. At the Altyn Tagh fault, the S_{Hmax} trajectories were nearly perpendicular to the fault. In general, the S_{Hmax} trajectories in the basin rotated counterclockwise from west to east from NW–SE to NE–SW.

(3) Loading ratio of 1:3

The calculated S_{Hmax} trajectories show that NNE–SSW trending S_{Hmax} trajectories extended further southward at the Southern Qilian fault, and rotated slightly counterclockwise compared with the results with the loading ratio of 1:2. In the other regions, the S_{Hmax} trajectories were generally consistent with those in the previous

Figure 5: The rose diagram analysis of the strikes of joints and velocity profile of GPS on the Qaidam Basin.

Table 2: Material properties of the crustal blocks and the upper mantle lithosphere in China and its surrounding areas

Block	Young modulus E (Pa)	Poisson coefficient ν
Lhasa–Gangdese	5.4×10^{10}	0.27
Tarim	5.4×10^{11}	0.25
Qaidam	3.0×10^{10}	0.27
Upper mantle lithosphere	1.2×10^{12}	0.33

stage, which indicates that the higher the stress applied to the northern margin of the basin is, the greater the influence on the NNE–SSW-trending S_{Hmax} trajectories. However, the simulation results show that with an additional load on the northern boundary, the orientations of the stress trajectories in the basin were similar.

4.2.3 Analysis of the stress trajectories in the Quaternary

During this stage, compressional stresses were applied to the Kunlun fault on the southern margin and to the

Southern Qilian fault on the northern margin of the basin at a loading ratio of 2:1. The calculated S_{Hmax} trajectories show that at the Eastern Kunlun fault, the stress trajectories were generally perpendicular to the boundary. However at the Altyn Tagh and Southern Qilian faults, the stress trajectories were parallel to the boundary, which is similar to the stress trajectories observed for the Paleogene. The data suggest that during the Paleogene and Quaternary, the S_{Hmax} trajectories were mainly influenced by the stress on the southern boundary of the basin.

5 Discussion

5.1 Influence of basement faults

Based on the previous description of the stress trajectories in the basin cover and basement, the basement faults that had a significant influence on the stress trajectories were obtained. Specifically, the NE–SW-trending faults in the basin absorbed the NNE–SSW-trending compressional stress by stratigraphic uplift. In particular, near the southern margin of the basin, the Eastern Kunlun fault

Figure 6: S_{Hmax} trajectory results for both models. (a) Model I cover, [(b) Model II basement, (a) Oligocene, (b) Miocene, and (c) Pliocene–Quaternary].

absorbed most of the stress; thus, the stress only affected the Altyn Tagh fault on the northwestern margin of the basin. The stress trajectories in the basement were generally consistent with those in the cover, which indicates that the basin-boundary faults had a greater influence on the stress trajectories than the intrabasin faults. Figure 7 shows the absorption of the displacement by the NE–SW-trending faults in the basin. When the basin was mainly influenced by the compressional stress from the southern boundary, the displacements in the basin were similar from south to north in the absence of faults, whereas the displacements were concentrated between the faults adjacent to the southern boundary when faults were present. This implies that the intrabasin faults directly controlled the compression and deformation of the basin.

5.2 Fitting of the simulation results

In the previous section, the simulation results were fitted by joint, fold structures, and GPS data, but actual stress trajectories' value cannot show the stress trajectories in the entire basin. The measured data and the simulation results to determine the reliability of the simulation were fitted. As shown in Figure 8, the S_{Hmax} indicated by the joints and GPS data fits the simulated principal stress trajectories to varying degrees.

The joints data analyzed in this study are mainly derived from Neogene strata. Based on the fitting results, we conclude that on the southwestern side of the basin, the joints in the Miocene Lower Youshashan Formation (N_{21}), which were measured in the Yingxiongling area,

Figure 7: The numerical simulation of displacement results: (a) spatial displacement results for Model Group I (Cover) and (b) spatial displacement results for Model Group II (Basement).

Figure 8: Fitting of the S_{Hmax} trajectory results for Model Group I (Cover).

indicate S_{Hmax} orientations of NE–SW, NNE–SSW, and NNE–SSW. These accurately fit the simulation results obtained with the compressional stress ratio of 1:1 between the northern and southern boundaries. On the northern margin of the basin, the joints in the Miocene Upper Youshashan Formation (N_{22}), which were measured at Lenghu Lake No. 4, indicate a S_{Hmax} orientation of NW–SE, which closely matches the simulation results obtained with the compressional stress ratio of 1:2. On the northern margin of the basin, the joints in the Miocene Shizigou Formation (N_{23}), which was measured at the Erboliang fault, indicate a S_{Hmax} orientation of NNW–SSE, which closely fits the simulation results obtained with the loading ratio of 1:3. However, the joints measured at Lenghu Lake No. 4 on the northern margin of the basin indicate a S_{Hmax} orientation of NW–SE, which does not fit the simulation results.

The simulation results from the Quaternary to represent the modern stress trajectories in the Qaidam Basin were chosen, which closely fit the modern stress trajectories obtained from the analysis of GPS data. Both datasets demonstrate that the S_{Hmax} was nearly perpendicular to the Eastern Kunlun fault; from south to north, the S_{Hmax} rotated clockwise from NNE–SSW to NW–SE. In general, the S_{Hmax} in the basin rotated clockwise. The fitting is poor on the eastern side of the basin, where the simulation results indicate NW–SE S_{Hmax} , while the GPS data indicate E–S S_{Hmax} .

Fold structures are common on the western side of the basin. It has been suggested that the folds developed at the time of deposition of the Neogene Youshashan Formation (N_{2y}). Because the mechanical properties of the folds cannot be determined, the relationship between the simulation results of the maximum principal stress trajectories and the axial planes of the folds was inferred; a small intersection angle indicates a transpressional fold, and an approximately perpendicular intersection indicates a compressional fold. A comparative analysis reveals that the piedmont folds near the Southern

Qilian fault are mainly compressional folds, while those on the northwestern margin of the Qaidam Basin are mainly transpressional folds. This conclusion must be verified by additional studies.

5.3 Basin activity

The basin activity in different geological periods was judged by analyzing the magnitude and direction of the maximum principal stress in the basin. According to the numerical simulation results, the area of maximum principal stress concentration can be obtained (red area in Figure 8). During the Cenozoic, the basin was mainly influenced by the compressional stress on the Eastern Kunlun fault due to the effect of the distant collision between the Indian and Eurasian plates and the compressional stress on the Southern Qilian fault due to the blockage of northward movement of the basin by the Qilian block; the basin was influenced by compressional stresses on both the southern and northern boundaries. The tectonic activity in the Qaidam Basin was mainly divided into three stages [20] as follows: (1) During the Paleogene, when the two plates initially collided, the southern boundary of the basin was first subjected to NE-trending compressional stresses. At this stage, the S_{Hmax} trajectories in the basin were approximately perpendicular to the Eastern Kunlun fault. From south to north, the stress trajectories were controlled by the Altyn Tagh and Qilian faults. The stress orientations rotated clockwise to become nearly parallel to the western and northern boundaries of the basin. In general, the S_{Hmax} trajectories in the basin rotated clockwise from NE–SW to E–S. (2) During the Neogene, as the effect of the collision expanded northward, the Qilian fault zone was influenced by SW-trending compressional stresses from the Qilian block, which continually increased. Due to the compressional stresses from both directions, fold structures developed in the piedmont near the Eastern Kunlun and Southern Qilian faults in the western Qaidam Basin. The cover strata in the basin were more prone to deformation and bending than the basement strata. Due to the compressional stress, the magnitude of south–north compression in the cover was greater than that in the basement, which resulted in a slip between the cover and the basement. We simplify this process into three stages with different ratios (1:1, 1:2, and 1:3) of compressional stress on the southern and northern boundaries to discuss the influence of the gradually increasing compressional stress on the northern boundary of the basin

on the S_{Hmax} trajectories in the basin. At the stress ratio of 1:1, the stress trajectories in the basin were significantly influenced by both the southern and northern boundaries and had patterns similar to those in the Paleogene. At the stress ratio of 1:2, the stress trajectories were markedly different from those in the Paleogene and were influenced mainly by the northern boundary. At this stage, the S_{Hmax} trajectories in the basin were nearly perpendicular to the Qilian fault. From north to south, the stress trajectories were controlled by the Altyn Tagh and Eastern Kunlun faults, rotated counterclockwise, and were nearly parallel to the western and southern boundaries of the basin. In general, the stress trajectories in the basin rotated counterclockwise from NE–SW to E–S. The compressional stress on the northern boundary of the basin had the greatest influence on the S_{Hmax} trajectories at the stress ratio of 1:3. (3) During the Quaternary, the Qaidam Basin experienced dramatic fold deformation and was compressed in the south–north direction, and the shrinkage of the basin was converted into lithospheric thickening. The kinetic energy from the compressional stress on the northern boundary was absorbed by the fold structures. The compressional stress on the northern boundary decreased while the stress on the southern boundary continued, so the stress trajectories returned to patterns similar to those in the Paleogene stage. The general stress directions in the basin rotated clockwise from NE–SW to E–S. In this stage, the simulation results were generally consistent with the GPS velocity field in the southern boundary of the model, but the simulation results at the northern boundary were different from the GPS velocity field. We speculated that the northern boundary of a model should be Qilian block because the GPS velocity field in the Qilian block was E–S. The general stress directions in the basin rotated clockwise from NE–SW to E–S by the Qilian and the Altyn Tagh fault.

6 Conclusion

The stress trajectories can be divided into five stages in the Qaidam Basin since the Cenozoic. The simulation results show that the stress trajectories were substantially influenced by the Kunlun fault, Qilian fault, and Altyn Tagh fault. The S_{Hmax} trajectories of the Kunlun fault oriented NE–SW in the Oligocene, Early Miocene, and Pliocene–Quaternary and which oriented NW–SE in the Middle Miocene and Late Miocene. The S_{Hmax} trajectories of the Qilian fault oriented NW–SE in the Oligocene, Early Miocene, and Pliocene–Quaternary and which

oriented NE–SW in Middle Miocene and Late Miocene. The S_{Hmax} trajectories of the Altyn Tagh fault oriented NE–SE in the Oligocene, Early Miocene, and Pliocene–Quaternary and which oriented NW–SE in the Middle Miocene and Late Miocene. The S_{Hmax} trajectories of the internal basin rotated clockwise from NE–SW to NW–SE in the Oligocene, Early Miocene, and Pliocene–Quaternary and which oriented counterclockwise NW–SE to NE–SW in the Middle Miocene and Late Miocene.

Acknowledgments: We are grateful to two anonymous reviewers for their constructive reviews on the manuscript.

Funding information: This study was financially supported by the National Natural Science Foundation of China (No. 41872226), the Basic Scientific Research Fund, Science and Technology Innovation Base of Lanzhou, Institute of Earthquake Forecasting, China Earthquake Administration (2020IESLZ06), the Important Direction Project of Knowledge Innovation in the Resource and Environment Field of the Chinese Academy of Sciences (KZCX2-EW-QN112), and the fund from the Key Laboratory of Petroleum Resources, Gansu Province (No. 135CCJJ20160517).

Conflict of interest: Authors state no conflict of interest.

References

- [1] Acharyya SK. Collisional emplacement history of the Naga-Andaman ophiolites and the position of the eastern Indian suture. *J Asian Earth Sci.* 2007;29(2–3):229–42.
- [2] Avouac JP, Tapponnier P. Kinematic model of active deformation in central-ASIA. *Geophys Res Lett.* 1993;20(10):895–8.
- [3] Beaumont C, Jamieson RA, Nguyen MH, Lee B. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. *Nature.* 2001;414(6865):738–42.
- [4] Brookfield ME. The himalayan passive margin from precambrian to cretaceous times. *Sediment Geol.* 1993;84(1–4):1–35.
- [5] Hodges KV, Parrish RR, Housh TB, Lux DR, Burchfiel BC, Royden LH, et al. Simultaneous miocene extension and shortening in the himalayan orogen. *Science.* 1992;258(5087):1466–70.
- [6] Holt WE, Ni JF, Wallace TC, Haines AJ. The active tectonics of the eastern himalayan syntaxis and surrounding regions. *J Geophys Res-Solid Earth Plan.* 1991;96(B9):14595–632.
- [7] Zhiqin X, Jingsui Y, Haibing L, Jianxin Z, Lingsen Z, Mei J. The Qinghai-Tibet plateau and continental dynamics: a review on terrain tectonics, collisional orogenesis, and processes and mechanisms for the rise of the plateau. *Geol China.* 2006;02:221–38. (In Chinese).
- [8] Zhiqin X, Jingsui Y, Haibing L, Shaocheng J, Zeming Z, Yan L. On the tectonics of the India-Asia collision. *Acta Geol Sin.* 2011;1:1–33. (In Chinese).
- [9] Lishe W, Wei Z, Xingxing D, Xiaoping L, Zhongping M, Zhongbao S, et al. Isotopic age and genesis of the monzogranitic gneiss at the Huanxingshan in middle Altyn Tagh. *Acta Petrol Sin.* 2015;01:119–32. (In Chinese).
- [10] Bertoluzza L, Perotti CR. A finite-element model of the stress field in strike-slip basins: implications for the Permian tectonics of the Southern Alps (Italy). *Tectonophysics.* 1997;280(1–2):185–97.
- [11] Munoz-Martin A, Cloetingh S, De Vicente G, Andeweg B. Finite-element modelling of Tertiary paleostress fields in the eastern part of the Tajo Basin (central Spain). *Tectonophysics.* 1998;300(1–4):47–62.
- [12] Bada G, Cloetingh S, Gerner P, Horvath F. Sources of recent tectonic stress in the Pannonian region: inferences from finite element modelling. *Geophys J Int.* 1998;134(1):87–101.
- [13] Peizhen Z, Qi W, Zongjin M. GPS velocity field and active crustal blocks of contemporary tectonic deformation in continental China. *Earth Sci Front.* 2002;2:430–41. (In Chinese).
- [14] Fan Z, Deqing S, Cunfeng Y, Xiaojun Z, Songling S, Xianglong N, et al. Meso-Cenozoic tectonic evolution of Qaidam Basin and its relationship with oil and gas accumulation. *Nat Gas Geosci.* 2013;05:940–7. (In Chinese).
- [15] Mingyu L, Xiangnan Y, Qingchun J, Zhenzhen W, Chunnan Z, Xuebin W, et al. Relationship between hydrocarbon accumulation and tectonic evolution in main structural belt of the northern border of Qaidam Basin. *Nat Gas Geosci.* 2012;3:461–8. (In Chinese).
- [16] Liwei S, Shihu F, Yonghe S, Chunyan Y, Qingyang M, Lili G, et al. The tectonic evolution accumulation controlling characteristics of Shizi gou-Ying dong structural belt of western Qaidam Basin. *Earth Sci Front.* 2014;01:261–70. (In Chinese).
- [17] Herb C, Koutsodendris A, Zhang W, Appel E, Fang X, Voigt S, et al. humidity fluctuations in the western Qaidam Basin (NE Tibetan Plateau) revealed by an integrated magnetic-palynological record from lacustrine sediments. *Quat Res.* 2015;84(3):457–66.
- [18] Rieser AB, Neubauer F, Liu Y, Ge X. Sandstone provenance of north-western sectors of the intracontinental Cenozoic Qaidam basin, western China: Tectonic vs climatic control. *Sediment Geol.* 2005;177(1):1–18.
- [19] Jianming G, Xuebing W, Guohui L, Bo W, Hailong F, Shiyang X. Three-dimensional structural model of the Qaidam basin: Implications for crustal shortening and growth of the northeast Tibet. *Open Geosci.* 2017;9:174–85.
- [20] Haibing L, Sui YJ, Zhiqin X, Zhiming S, Tapponnier P, Woerd JVD, et al. The constraint of the Altyn Tagh fault system to the growth and rise of thenorthern Tibetan plateau. *Earth Sci Front.* 2006;04:59–79. (In Chinese).
- [21] Fang X, Zhang W, Meng Q, Gao J, Wang X, King J, et al. High-resolution magneto stratigraphy of the Neogene Huaitoutala section in the eastern Qaidam Basin on the NE Tibetan Plateau, Qinghai Province, China and its implication on tectonic uplift of the NE Tibetan Plateau. *Earth Planet Sci Lett.* 2007;258(1–2):293–306. (In Chinese).
- [22] Li D, Chen Y, Zhou J, Kang H, Hou K. Continuity of the Western Qinling and Qaidam-Qilian blocks: Evidence from Precambrian and Permian-Triassic strata around the Gonghe Basin area, NW China. *Geol J.* 2020;55(5):3601–14. (In Chinese).

- [23] Liu Z, Sun Y. Characteristics and formation process of contractional deformation bands in oil-bearing sandstones in the hinge of a fold: a case study of the Youshashan anticline, western Qaidam Basin, China. *J Pet Sci Eng.* 2020;189:106994. (In Chinese).
- [24] Fan Z, Binshan D, Yingru L, Aiping Wang. Strike-slip fault and hydrocarbon accumulation in the Qaidam Basin, China. *Carbonates Evaporites.* 2020;35(28):1–11.
- [25] Shoumai R, Xiaohong G, Yongjiang L, Dewu Q, Chengming Y, NEUBAUER F, et al. The stress field of Late Mesozoic-Cenozoic tectonics in the northern Qaidam basin. Northwest China: Evidences from the analysis of joints data. *Geological Bulletin of China;* 2009;28(07):877–87. (In Chinese).
- [26] Chengming Y, Shoumai R, Liyan T. Effect of Altyn Tagh fault to Southwest Qaidam Basin: evidences from analysis of joints data. *J Jilin Univ (Earth Sci Ed).* 2011;03:724–34. (In Chinese).
- [27] Yuan P, Yinsheng M, Chenglin L, Jiaopeng S, Haiyan C, Kun D, et al. An analysis of late Hercynian–Indosinian Paleotectonic Stress on the Northern Margin of the Qaidam Basin. *Acta Geosci Sin.* 2015;01:51–9. (In Chinese).
- [28] Jingyi H, Jingshan B, Jingxiang J, WanYongge, Rujiang S. Characteristic and Tectonic analysis for joints of coastline Bedrock in Diaoyutai, Western Liaoning. *Sci Technol Eng.* 2014;14:135–41. (In Chinese).
- [29] Bolin C, Lingling C, Yanfei B, Shixin W, Zhengle C, Xuezhi L, et al. A determining on the displacement of the Altun Tagh sinistral strike-slip fault, NW China: new evidence from the tectonic metallogenetic belt in the eastern part of Altun Tagh Mountains. *Acta Petrol Sin.* 2010;11:3387–96.
- [30] Ping C, Xiang F, Chengzhi P, Rui C, Han Z, Xinping Z, et al. Shear test of joint and analysis of morphology characteristic evolution of joint surface. *Chin J Rock Mech Eng.* 2011;03:480–5. (In Chinese).
- [31] Peizhen Z, Qi W, Zongjin M. GPS velocity field and active crustal blocks of contemporary tectonic deformation in continental China. *Earth Sci Front.* 2002;02:430–41. (In Chinese).
- [32] Qi W, Peizhen Z, Zongjin M. GPS database and velocity field of contemporary tectonic deformation in continental China. *Earth Sci Front.* 2002;02:415–29. (In Chinese).
- [33] Yong Z, Rongshan F, Xiong X. Dynamic simulation of lithospheric evolution from the modern China mainland and its surrounding areas. *Chin J geophysics.* 2006;02:415–27. (In Chinese).