GEODYNAMICS & TECTONOPHYSICS

PUBLISHED BY THE INSTITUTE OF THE EARTH'S CRUST
SIBERIAN BRANCH OF RUSSIAN ACADEMY OF SCIENCES

2019 VOLUME 10 ISSUE 1 PAGES 43–51 ISSN 2078-502X

https://doi.org/10.5800/GT-2019-10-1-0403

Tectonophysics

A TEST OF THE OBLIQUE-RIFTING MODEL FOR TRANSFER ZONE DEFORMATION IN THE NORTHERN FEN-WEI RIFT: IMPLICATIONS FROM THE 1989 M 6.1 DATONG-YANGGAO EARTHQUAKE SWARM

Yan-Qun Zhuo[1], Yanshuang Guo[1], S. A. Bornyakov[2], Jin Ma[1]

[1] *State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China*
[2] *Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia*

Abstract: Tectonophysical experiments show that the evolution of the Fen-Wei Rift is controlled by oblique rifting. A key characteristic of the model in our study is that the western and eastern borders of the transfer zone between the adjacent NEE-striking extensional basins tend to form right-lateral strike-slip faults with slight normal slip as a result of the interaction between the adjacent NEE-striking extensional basins under oblique rifting. The current deformation of the Fen-Wei Rift can be clarified by testing this predicted deformation characteristic. Our analysis of the relocation and focal mechanism solutions of the 1989 M 6.1 Datong-Yanggao earthquake swarm, which was the largest earthquake that occurred in the Fen-Wei Rift in the last 200 years, suggests that the transfer zone between the Yangyuan and Hunyuan basins is bounded by the NNE-striking right-lateral strike-slip faults with slight normal slip at its eastern and western edges. This consistency between the model and the current tectonic activity in the study area indicates that oblique rifting still plays an important role in the current deformation of the northern Fen-Wei Rift.

Key words: Oblique rifting model; current tectonic activity; transfer zone; focal mechanism solution; earthquake relocation

RESEARCH ARTICLE

Received: November 7, 2018
Revised: December 10, 2018
Accepted: January 12, 2019

For citation: *Zhuo Y.-Q., Guo Y., Bornyakov S.A., Ma J.*, 2019. A test of the oblique-rifting model for transfer zone deformation in the northern Fen-Wei Rift: Implications from the 1989 M 6.1 Datong-Yanggao earthquake swarm. *Geodynamics & Tectonophysics* 10 (1), 43–51. doi: 10.5800/GT-2019-10-1-0403.

Сравнение модели косого рифтинга и деформаций трансферной зоны, расположенной в северном сегменте рифта Фен-Вей: последствия роя землетрясений 1989 года в районе Датун- Янггао (Китай)

Ян-Цюнь Чжо[1], Яншуан Го[1], С. А. Борняков[2], Цзинь Ма[1]

[1] *Государственная лаборатория динамики землетрясений, Институт геологии, Администрация по землетрясениям Китая, Пекин, Китай*
[2] *Институт земной коры СО РАН, Иркутск, Россия*

Аннотация: Эволюция рифта Фен-Вей происходит под влиянием косого рифтинга, как показывают тектонофизические эксперименты. В данном исследовании основная особенность модели состоит в том, что западные и восточные границы трансферной зоны между соседними впадинами СВВ простирания, образовавшимися вследствие растяжения, имеют тенденцию к образованию правосторонних сдвигов с незначительной сбросовой компонентой как результат взаимодействия между указанными впадинами под влиянием косого рифтинга. Современная деформация рифта Фен-Вей может быть установлена путем проверки характеристики, предсказанной экспериментально. Нами были проанализированы решения по смещениям и механизмам очага землетрясения M=6.1 1989 года в районе Датун-Янггао – сильнейшего землетрясения в рифте Фен-Вей за последние 200 лет. Анализ показал, что трансферная зона между бассейнами Яньюань и Хуньюань ограничена сдвигами ССВ простирания с незначительной сбросовой компонентой на восточной и западной окраинах данной зоны. Установленное в нашем исследовании соответствие между изученной моделью и современной тектонической активностью в изучаемом районе подтверждает, что косой рифтинг по-прежнему играет важную роль в современных деформациях северной части рифта Фен-Вей.

Ключевые слова: модель косого рифтинга; современная тектоническая активность; трансферная зона; решения механизмов очагов землетрясений; перемещение землетрясений

1. Introduction

Tectonophysical experiments play an important role in the analysis of the mechanisms of rift formation and evolution [*Aanyu, Koehn, 2011; Agostini et al., 2009; Bellahsen, Daniel, 2005; Chang, Zhong, 1977; Chang et al., 1975; Chemenda et al., 2002; Clifton et al., 2000; Corti, 2008, 2012; McClay et al., 2002; McClay, White, 1995; Smith, Durney, 1992; Tron, Brun, 1991; Withjack, Jamison, 1986*]. However, since the time scales in the tectonophysical experiments are quite large, it is necessary to test whether the mechanisms derived from the tectonophysical models are consistent with the actual mechanisms that control the current deformation of the rift. On the other hand, studying the present deformation mechanism of rifting is of great significance for understanding the seismogenic structures as well as oil and gas exploration within the rift area. Therefore, testing the results of tectonophysical experiments by using the available current tectonic deformation data can help to understand the current tectonic deformation mechanism.

The Fen-Wei Rift marks the boundary between the Ordos and North China Plain blocks and is constrained by the South China and Yinshan-Yanshan blocks in North China [*Deng et al., 2003; Zhang et al., 2003*] (Fig. 1). This S-shaped structure consists of the southern and northern extension segments and the central right-lateral shear segment [*Xu, Ma, 1992; Xu et al., 1993*]. Each segment of the Fen-Wei Rift is composed of the NEE-striking extensional basins and transfer zones between the adjacent NEE-striking extensional basins. The Fen-Wei Rift was a reactivated NNE-striking compressive belt formed in the late Mesozoic, which began to develop as a rift in Eocene, according to [*Deng et al., 1973; Liu, 1985; Zhang et al., 1983*]. Three models were proposed to explain the origin of the Fen-Wei Rift: (1) the oblique rifting model attributed the alternative arrangement of the NEE- and NNE-striking segments of the Fen-Wei Rift to the NW extension between the Ordos and North China Plain blocks [*Chang, Zhong, 1977; Chang et al., 1975*]. Furthermore, a segmented oblique rifting model was proposed to further explain the differences of basin distributions, transfer zones and the

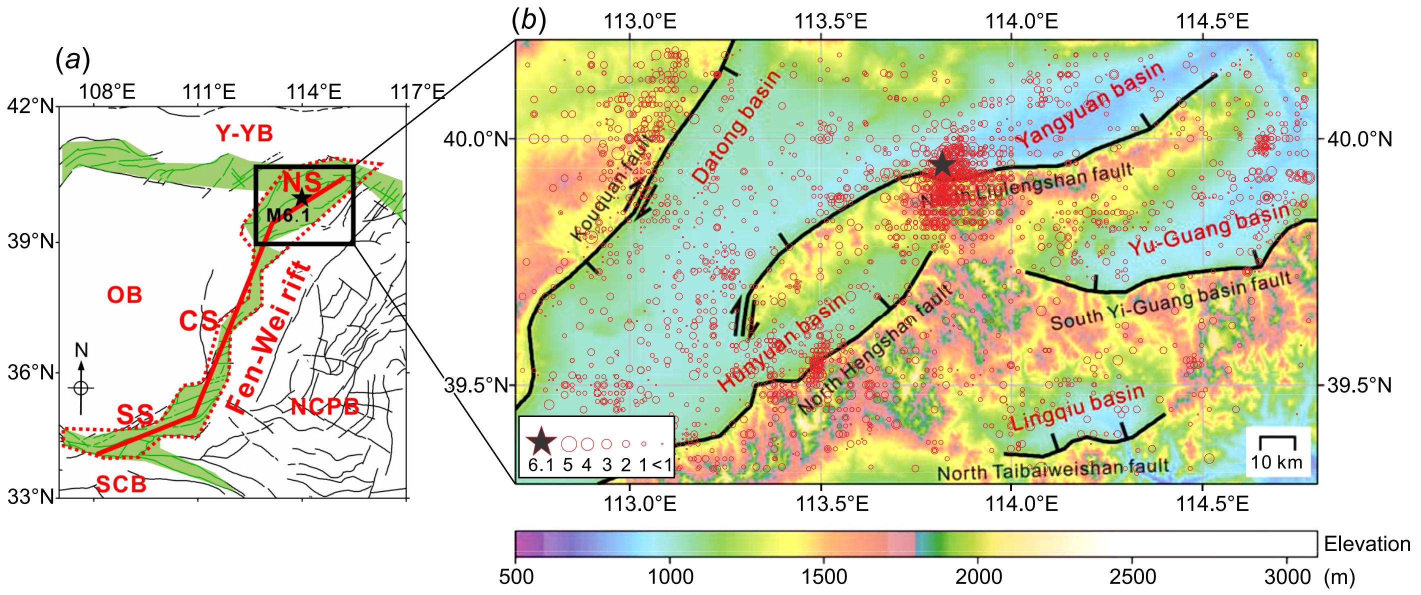

Fig. 1. Tectonic setting of the Fen-Wei Rift, and seismic activity in its northern segment.

(*a*) – the area within the red dashed curves represents the Fen-Wei Rift. The red zigzag line denotes the basic segmentation of the Fen-Wei Rift. The black star represents the epicenter of the 1989 M 6.1 Datong-Yanggao earthquake. The black rectangular area is shown in Fig. 1 (b) and Fig. 2 in detail. The dark green bands denote the boundaries of the four active blocks in China [*Deng et al., 2003*; *Zhang et al., 2003*]. Y-YB, the Yinshan-Yanshan active block; OB, the Ordos active block; NCPB, the North China Plain active block; SCB, the South China active block; NS, the northern segment; CS, the central segment; SS, the southern segment. (*b*) – the seismic activity in the northern Fen-Wei Rift from 1966 to November 2018. The red circles of different sizes represent different magnitudes. The data are provided by China Earthquake Data Center (http://data.earthquake.cn).

Рис. 1. Тектоническая обстановка рифта Фен-Вей и сейсмическая активность в его северном сегменте.

(*a*) – красная пунктирная линия оконтуривает разлом Фен-Вей. Красным зигзагом обозначены основные части разлома Фен-Вей. Звездочка черного цвета – эпицентр землетрясения М=6.1 в Датун-Янггао 1989 года. Зона, оконтуренная черной линией, показана детально на рис. 1 (*b*) и рис. 2. Темно-зеленые широкие линии – границы четырех активных блоков в Китае [*Deng et al., 2003*; *Zhang et al., 2003*]. Y-YB – активный блок Иньшань-Яньшань; OB – активный блок Ордос; NCPB – активный блок Северо-Китайской равнины; SCB – Южно-Китайский активный блок; NS – северный сегмент; CS – центральный сегмент; SS – южный сегмент. (*b*) – сейсмическая активность северной части разлома Фен-Вей в период с 1966 г. по ноябрь 2018 г. Красные кружки разных размеров – землетрясения разных магнитуд. Данные предоставлены Китайским центром сейсмических данных (http://data.earthquake.cn).

chronology of the basins within the three segments of the rift [*Zhuo et al., 2016*]. (2) The block rotation model held that the Fen-Wei Rift is derived from the counterclockwise rotation of the North China Plain block relative to the Ordos block. Specifically, the block rotation was considered to result in the right-lateral shear of the central segment, which induces the extension of the southern and northern segments [*Xu, Ma, 1992; Xu et al., 1993*], or to cause the decreasing extension and clockwise rotation in the extension direction from the southern to northern segments [*Zhang et al., 1998*]. (3) The lateral heterogeneous crustal rheology model ascribed the extension of the Fen-Wei Rift to the gravitational potential energy arising from the preexisting crustal weak zone [*He et al., 2003, 2004*].

The NNE-striking right-lateral strike-slip border faults of the transfer zones between the adjacent NEE-striking extensional basins were emphasized in the oblique rifting models [*Chang, Zhong, 1977; Chang et al., 1975; Zhuo et al., 2016*]. The formation of the transfer zones was attributed to the interactions between the adjacent NEE-striking extensional basins [*Zhuo et al., 2016*]. Furthermore, geological surveys show that at least eight paleoearthquakes of M>7 occurred along the Fen-Wei Rift, the majority of which were associated with the motions of the NNE-striking right-lateral strike-slip border faults of the transfer zones in the rift area [*Huan et al., 2003; Xie et al., 2004; Xu, Deng, 1990; Xu et al., 1992*]. This implies that studying the current deformation mechanism of the transfer zones may shed some light on the seismogenic structures of strong earthquakes in the Fen-Wei Rift.

Although the experimental results showed in accord with the main structure architecture of the Fen-Wei Rift, the validity of the deformation of the transfer zones derived from the oblique-rifting models remains to be tested with respect to the current tectonic activities of the rift. As the current seismic activity is an

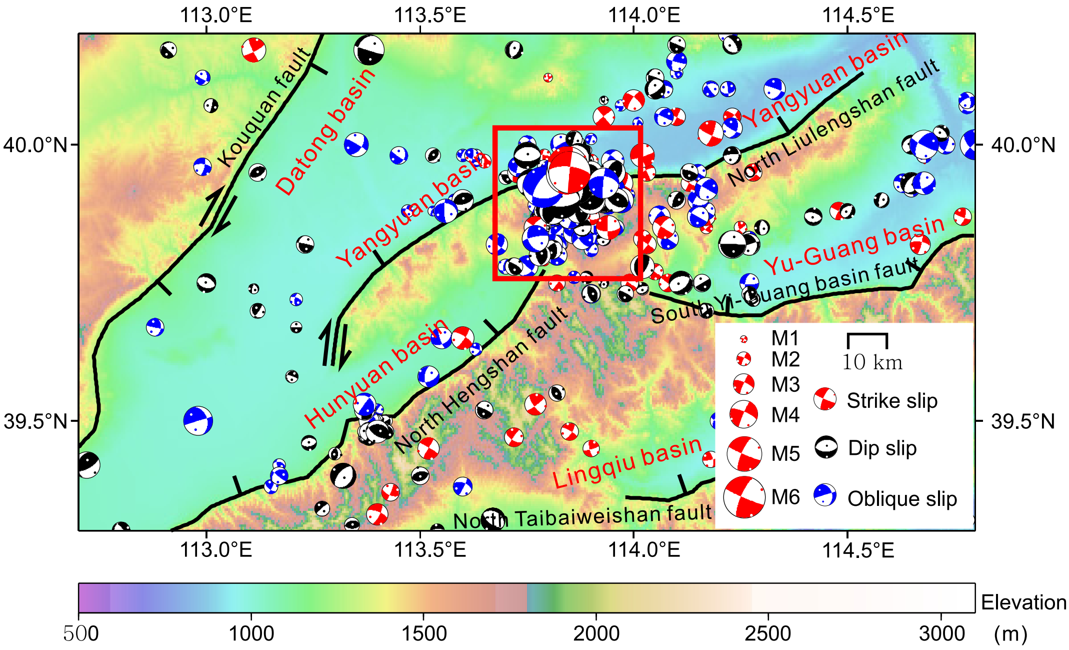

Fig. 2. Architecture of the transfer zone between the Yangyuan and Hunyuan basins. Tectonic setting of a part of the northern segment of the Fen-Wei Rift. The area in the red box is shown in Fig. 4 in detail. The focal mechanism solution and relocation of earthquakes are from previous studies [*Wang et al., 2012; Xu, 1992; Zhao et al., 1992*]. The digital elevation model data are from CIAT-CSI SRTM [*Jarvis et al., 2008*].

Рис. 2. Структура трансферной зоны, расположенной между впадинами Яньюань и Хуньюань. Тектоническая обстановка части северного сегмента рифта Фен-Вей. Зона, оконтуренная красной линией, показана детально на рис. 4. Решения механизмов очагов землетрясений и перемещений землетрясений по [*Wang et al., 2012; Xu, 1992; Zhao et al., 1992*]. Данные цифровой модели рельефа по CIAT-CSI SRTM [*Jarvis et al., 2008*].

important aspect representing the current tectonic activity, deformation on the transfer zones described in the oblique-rifting models can be tested using the data of the current seismic activity. The 1989 M 6.1 Datong-Yanggao earthquake swarm, which is the only earthquake of M≥6 within the Fen-Wei Rift in the last 200 years, occurred at the eastern border of the transfer zone between the Yangyuan and Hunyuan basins (referred to as the Y-H transfer zone hereafter, Figs. 1 and 2) in the northern Fen-Wei Rift. In this study, we refer to the relocation and focal mechanism solution data of this earthquake swarm [*Wang et al., 2012*] to test if the oblique-rifting models are consistent with the current deformation of the Y-H transfer zone. Therefore, whether the eastern and western border faults of the Y-H transfer zone are NNE-striking right-lateral strike-slip faults with slight normal slip is the key issue for this verification.

2. The 1989 M 6.1 Datong-Yanggao earthquake swarm, and its implications for the current deformation of the Y-H transfer zone

The Yangyuan and Hunyuan NEE-striking extensional basins, which strike NE50°~70°, are bounded on the south by the North Liulengshan and North Hengshan faults, respectively (see Fig. 2). The two faults are of mainly normal slip, according to field studies [*Cheng, Yang, 1996; Deng et al., 1994; Xu, 1998; Xu et al., 1996a, 1996b*]. The western tip of the North Liulengshan fault connects with a right-lateral strike-slip fault that strikes ~NE30° and has an outcropping length of ~12 km (see Fig. 2). The geological survey along the right-lateral strike-slip fault showed that a series of gullies were offset at a mean right-lateral slip rate of ~1.26 mm/a and a normal slip rate of ~0.03 mm/a since the last 12 ka [*Xu et al., 1996a*]. This indicates that the western border fault of the Y-H transfer zone is a right-lateral strike-slip fault with slight normal slip since the last 12 ka.

According to the current focal mechanism solution, the azimuth of the principal tensile stress in the northern segment of the Fen-Wei Rift is NW20°~40° (Fig. 3), which is consistent with the NW15°~40° extension of the southern and northern segments of the Fen-Wei Rift since the late Cenozoic derived from satellite SPOT images [*Zhang et al., 1998*]. This consistency indicates that the regional stress field controlling the deformation in the northern segment of the Fen-Wei Rift has been stable from the late Cenozoic to the present day, and that the deformations of the transfer zones, which

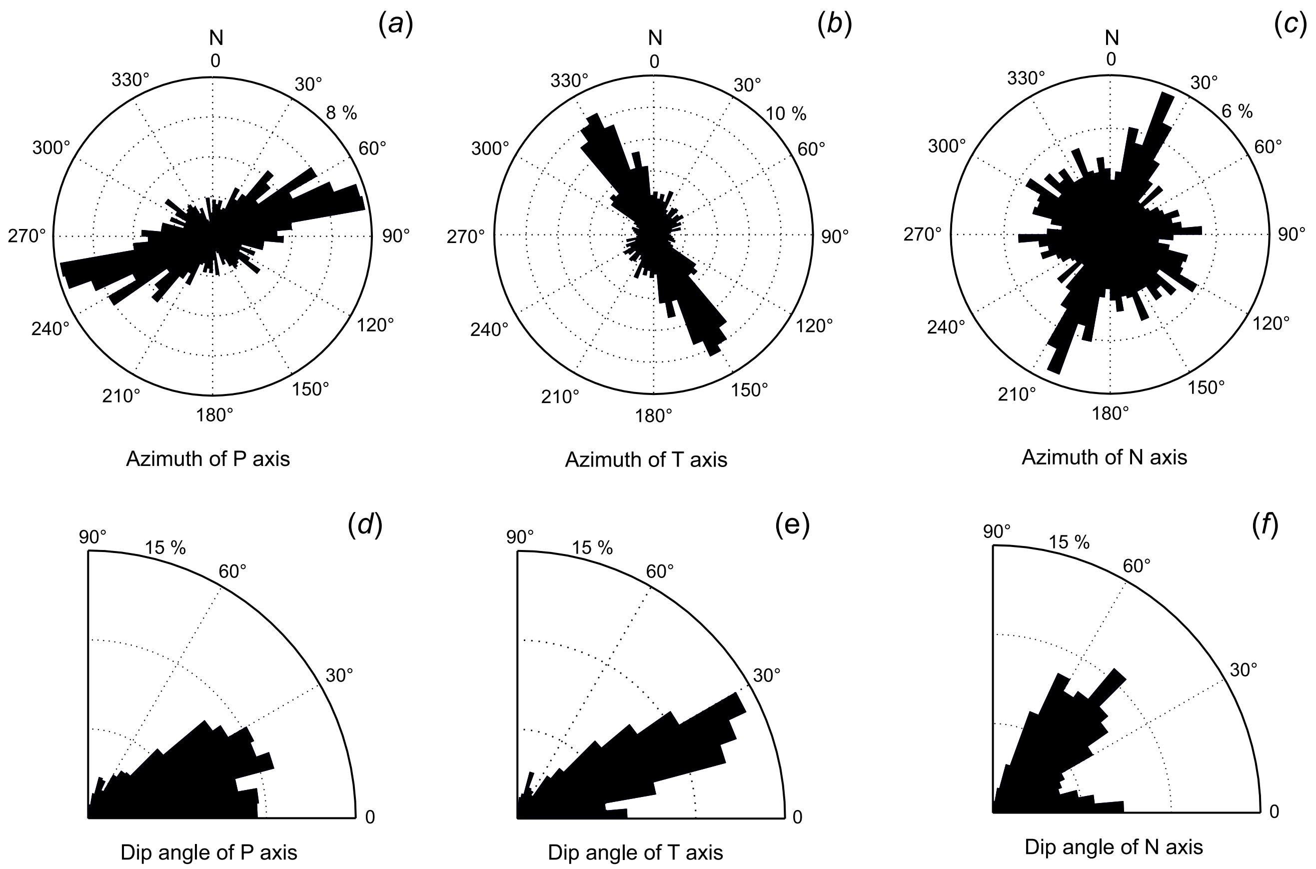

Fig. 3. The principal stress axes for the northern segment of the Fen-Wei Rift derived from the focal mechanism solution data as shown in Fig. 2.

Рис. 3. Оси главных напряжений в северном сегменте рифта Фен-Вей, полученные по решениям механизмов очагов землетрясений (см. рис. 2).

are derived from both the geological survey data and the available seismic data, are comparable.

The relocation of earthquakes from 1966 to 2010 shows that the epicenters (including the 1989 M 6.1 and 1991 M 5.8 earthquakes [*Wang et al., 2012*]) occurred mainly in the NNE-striking zone from the eastern tip of the Hunyuan basin to the central Yangyuan basin and formed a flat oval distribution (see Figs. 2 and 4, *a*). The major axis of the oval distribution of the epicenters strikes at ~NE22.5°, which is in accordance with the distribution in the meizoseismal area obtained by macroscopic earthquake damage observations of the 1989 M 6.1 and 1991 M 5.8 earthquakes in this area [*An et al., 1991; Liu et al., 1992; Wang et al., 1992; Xu et al., 1991*]. Furthermore, we selected the earthquakes within the oval area shown in Fig. 4, *a*, to analyze the distribution of their nodal plane strikes via their focal mechanism solutions. The upper diagram in Fig. 4, *b*, shows that these earthquakes have a dominant nodal plane strike of NE 17.6°–24.7°, which is consistent with the strike of the oval distribution of the epicenters. Thus, the Y-H transfer zone is bounded by a ~NE22.5° striking buried fault at its eastern edge.

To explore the motion of the buried fault, we analyzed the distribution of the rake of slip vectors on the nodal planes as shown in the upper diagram in Fig. 4, *b*. A nodal plane gets a left- or right-lateral strike-slip component when the absolute value of the rake of slip vector on it is less or more than 90°, respectively. However, a nodal plane gets a normal or reversed slip component when the rake of slip vector on it is less or more than zero, respectively. As shown in the bottom diagram in Fig. 4, *b*, most of the rake of slip vectors have absolute values larger than 90°. Moreover, most of the rake of slip vectors are close to ±180°, which indicates that the buried fault has a slight dip-slip component. Therefore, the buried fault is of mainly right-lateral strike-slip with slight normal slip (Fig. 4, *b*). This is also consistent with the focal mechanism solutions of the 1989 Ms 6.1 and 1991 Ms 5.8 earthquakes (Fig. 4, *a*) which both had right-lateral strike-slip with a slight normal slip component [*Wang, Wang, 1992; Wang et al., 1994; Wei et al., 1992; Xu, 1992; Zhao et al., 1992; Zhu et al., 1999; Qiu, Liu, 2005; Feng et al., 2016*]. Thus, the eastern border fault of the Y-H transfer zone is a right-lateral strike-slip fault with a slight normal slip.

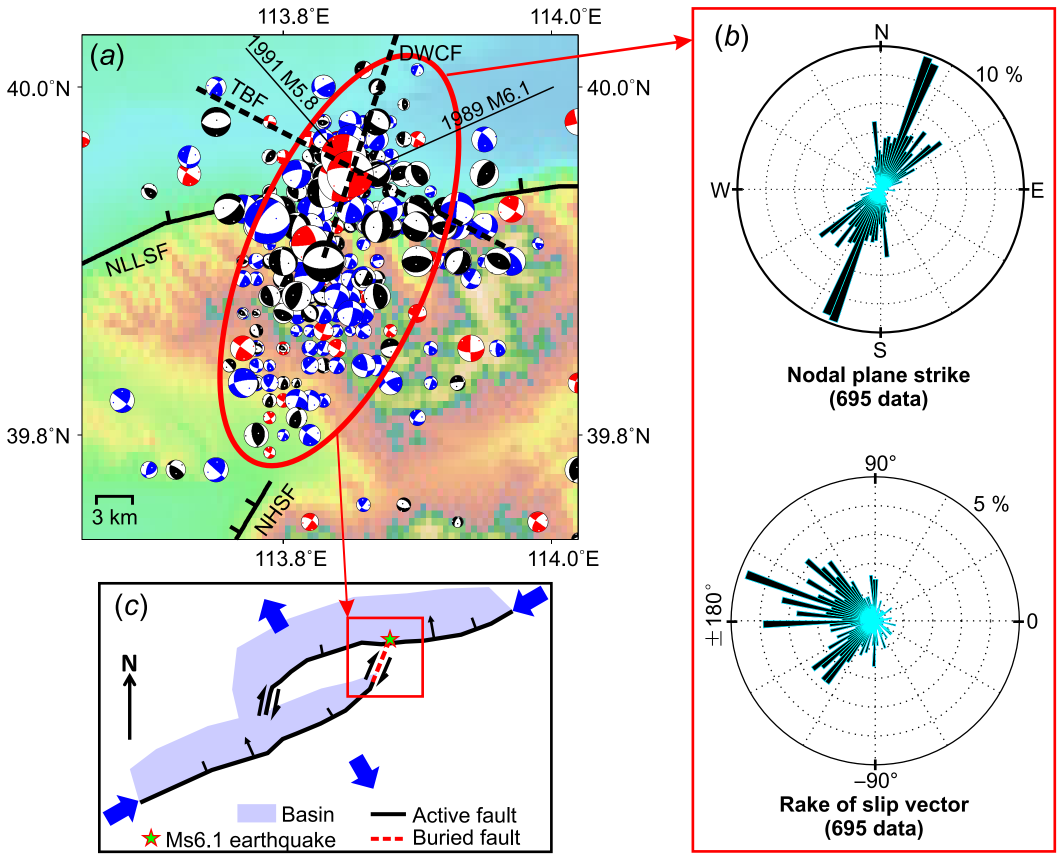

Fig. 4. Deformation of the Y-H transfer zone.

(*a*) – the flat oval distribution of epicenters in the eastern border of the Y-H transfer zone. (*b*) – strikes (upper) and rakes of slip vectors (bottom) of nodal planes derived from the focal mechanism solutions within the red oval in Fig. 4 (a). A nodal plane gets a left- or right-lateral strike-slip component when the absolute value of the rake of slip vector on it is less or more than 90°, respectively. A nodal plane gets a normal or reversed slip component when the rake of slip vector on it is less or more than zero, respectively. (*c*) – sketch diagram of the architecture of the Y-H transfer zone. NHSF, North Hengshan fault; NLLSF, North Liulingshan fault; DWCF, assumed Dawangcun fault (buried fault, according to [*Su, Cheng, 1992*]); TBF, assumed Tuanbao fault (buried fault, according to [*Su, Cheng, 1992*]). See other symbols in Fig. 2.

Рис. 4. Деформации в трансферной зоне, расположенной между впадинами Яньюань и Хуньюань.

(*а*) – распределение эпицентров землетрясений (плоский овал) на восточной границе трансферной зоны, расположенной между впадинами Яньюань и Хуньюань. (*b*) – простирания (вверху) и векторы сдвига (внизу) нодальных плоскостей, полученных по решениям механизмов очагов землетрясений внутри красного овала, показанного на рис. 4 (*а*). Нодальная плоскость имеет компоненту лево- или правостороннего сдвига, если абсолютное значение вектора сдвига по данной плоскости меньше или больше 90°, соответственно. Нодальная плоскость имеет сбросовую или взбросовую компоненту, если вектор сдвига по данной плоскости меньше или больше нуля, соответственно. (*с*) – схема, показывающая структуру трансферной зоны, расположенной между впадинами Яньюань и Хуньюань. NHSF – разлом Северный Хэншань; NLLSF – разлом Северный Люлиншань; DWCF – предполагаемый разлом Давангкун (погребенный разлом по [*Su, Cheng, 1992*]); TBF – предполагаемый разлом Туанбао (погребенный разлом по [*Su, Cheng, 1992*]). Остальные условные обозначения см. на рис. 2.

The deformations in the Y-H transfer zone are schematically shown in Fig. 4, *c*. The current azimuths of the principal tensile and compressive stress in Fig. 4, *c*, are derived from Fig. 3. Fig. 4, *c*, shows that both of the eastern and western border faults of the Y-H transfer zone are the NNE-striking right-lateral strike-slip faults with slight normal slip in the regional stress field shown in Fig. 3, which is the key characteristic of the transfer zone deformation predicted in the oblique-rifting models [*Chang, Zhong, 1977; Chang et al., 1975; Zhuo et al., 2016*].

3. Discussion and conclusion

Similar to the results of our study, it was found that the 1989 M 6.1 earthquake main shock and aftershock as well as the main shock of the 1991 M 5.8 earthquake ruptured the same NNE-striking right-lateral strike-slip faults with steep dip and slight normal slip, based on the studies of focal mechanism solution and earthquake relocation [*Wang, Wang, 1992; Wang et al., 1994; Wei et al., 1992; Xu, 1992; Zhao et al., 1992; Zhu et al., 1999; Qiu, Liu, 2005; Feng et al., 2016*]. The foreshock of the 1989 M 6.1 earthquake was considered to rupture a NW-striking left-lateral strike-slip fault [*Xu, 1992; Qiu, Liu, 2005; Feng et al., 2016*]. These findings are consistent with the distribution of the meizoseismal area obtained by the macroscopic earthquake damage observations of these earthquakes [*An et al., 1991; Ding et al., 2000; Liu et al., 1992; Wang et al., 1992*]. The field geological survey data suggested that no obvious surface ruptures can be identified associated with these earthquakes although they took place near the junction of the North Liulengshan, Dawangcun and Tuanbao faults [*Su, Cheng, 1992*]. The NNE-striking Dawangcun fault and the NW-striking Tuanbao fault (shown in Fig. 4, *a*) were considered to be the NNE-striking and NW-striking buried faults where the main shock and foreshock of the 1989 M6.1 earthquake occurred, respectively, according to the data of the geological survey and seismicity studies [*Su, Cheng, 1992; Feng et al., 2016*], which support the existence of the NNE-striking right-lateral strike-slip buried fault inferred from our data shown in Fig. 4. Therefore, the deformation of the NNE-striking transfer zone between the adjacent NEE-striking extensional basins predicted by the oblique-rifting models [*Chang, Zhong, 1977; Chang et al., 1975; Zhuo et al., 2016*] is consistent with the current deformation of the Y-H transfer zone. This consistency between the model and the current tectonic activity indicates that oblique rifting still plays an important role in the current deformation of the northern Fen-Wei Rift.

4. Acknowledgement

We sincerely thank Professor S. I. Sherman for constructive discussions. We are grateful to Professor Gui-Ling Diao for supplying the relocation and focal mechanism solutions of 2,322 earthquakes in the Fen-Wei Rift. Many thanks to the two reviewers for their constructive comments, to Olga A. Baksheeva for the improvement of the writing. This work was supported by the National Natural Science Foundation of China (Grant Nos. 41572181, 41211120180 and 41702226) and the Russian Fund for Basic Research (Grant No. 12-05-91161-GFEN-a).

5. References

Aanyu K., Koehn D., 2011. Influence of pre-existing fabrics on fault kinematics and rift geometry of interacting segments: analogue models based on the Albertine Rift (Uganda), Western Branch-East African Rift System. *Journal of African Earth Sciences* 59 (2–3), 168–184. https://doi.org/10.1016/j.jafrearsci.2010.10.003.

Agostini A., Corti G., Zeoli A., Mulugeta G., 2009. Evolution, pattern, and partitioning of deformation during oblique continental rifting: Inferences from lithospheric-scale centrifuge models. *Geochemistry, Geophysics, Geosystems* 10 (11), Q11015. https://doi.org/10.1029/2009GC002676.

An W., Yan H., Wang G., Guo W., 1991. Macroexaminations on the intensity of the earthquake in Datong-Yanggao area. *Earthquake Research in Shanxi*, 18–30.

Bellahsen N., Daniel J.M., 2005. Fault reactivation control on normal fault growth: an experimental study. *Journal of Structural Geology* 27 (4), 769–780. https://doi.org/10.1016/j.jsg.2004.12.003.

Chang W.-Y., Chung C.-Y., Yeh H., Cong B.-L., 1975. Preliminary note on the origin and development of rock-fracture and its bearing on earthquakes. *Acta Geologica Sinica*, 17–27.

Chang W., Zhong J., 1977. On the developments of fracture-systems in China. *Scientia Geologica Sinica*, 197–209.

Chemenda A., Déverchère J., Calais E., 2002. Three-dimensional laboratory modelling of rifting: application to the Baikal Rift, Russia. *Tectonophysics* 356 (4), 253–273. https://doi.org/10.1016/S0040-1951(02)00389-X.

Cheng S., Yang G., 1996. Late quaternary segmentation and segmented variations in tectonic geomorphology of southern marginal fault zone of Datong-Yangyuan Basin. *Seismology and Geology* 18, 289–300.

Clifton A.E., Schlische R.W., Withjack M.O., Ackermann R.V., 2000. Influence of rift obliquity on fault-population systematics: results of experimental clay models. *Journal of Structural Geology* 22 (10), 1491–1509. https://doi.org/10.1016/S0191-8141(00)00043-2.

Corti G., 2008. Control of rift obliquity on the evolution and segmentation of the main Ethiopian rift. *Nature Geoscience* 1 (4), 258–262. https://doi.org/10.1038/ngeo160.

Corti G., 2012. Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System. *Tectonophysics* 522–523, 1–33. https://doi.org/10.1016/j.tecto.2011.06.010.

Deng Q., Wang K., Wang Y., Tang H., Wu Y., Ding M., 1973. Overview of the seismogeology and seismicity trend in the graben earthquake zone within Shanxi highland. *Scientia Geologica Sinica*, 37–47.

Deng Q., Yonekura N., Xu X., Yasuhiro S., Wang C., Takeuchi A., Su Z., Wang Y., 1994. Study on the late quaternary kinematics of the northern piedmont fault of the Liuleng mountain. *Seismology and Geology* 16, 339–343.

Deng Q., Zhang P., Ran Y., Yang X., Min W., Chu Q., 2003. Basic characteristics of active tectonics of China. *Science in China Series D: Earth Sciences* 46 (4), 356–372. https://doi.org/10.1360/03yd9032.

Ding X.-W., Ding Y.-L., Guo X.-Q., Guo J.-J., Wang Y.-J., 2000. Macroseismic intensity survey of the Ms5.6 earthquake in Datong-Yanggao, Shanxi of 1999. Earthquake Research in Shanxi, 2–7.

Feng Y.-G., Wang H.-Y., Chen Y.-S., Huang Q.-H., 2016. Blind-fault of Datong earthquake sequence: JHD and Coulomb stress analyses. *Chinese Journal of Geophysics* 59, 568–577.

He J., Cai D., Li Y., Gong Z., 2004. Active extension of the Shanxi rift, north China: does it result from anticlockwise block rotations? *Terra Nova* 16 (1), 38–42. https://doi.org/10.1046/j.1365-3121.2003.00523.x.

He J., Liu M., Li Y., 2003. Is the Shanxi rift of northern China extending? *Geophysical Research Letters* 30 (23), 2213. https://doi.org/10.1029/2003GL018764.

Huan W., Shi Z., Li S., 2003. The new recognizes for epicenter location and seismogenic structure of 1556 M 8.25 large earthquake. *Earthquake Research in China* 19, 20–32.

Jarvis A., Reuter H.I., Nelson A., Guevara E., 2008. Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT). Available from: http://srtm.csi.cgiar.org.

Liu G., 1985. Compressional tectonic zones on the Linfen-Weihegraben margin and its geological significance. In: Symposium of tectonic geology, p. 61–70.

Liu W., An W., Zhao X., 1992. The 1989 Datong-Yanggao earthquake of Ms 6.1. *Earthquake Research in China* 8, 19–27.

McClay K.R., Dooley T., Whitehouse P., Mills M., 2002. 4-D evolution of rift systems: Insights from scaled physical models. *AAPG Bulletin* 86 (6), 935–960.

McClay K.R., White M.J., 1995. Analogue modelling of orthogonal and oblique rifting. *Marine and Petroleum Geology* 12 (2), 137–151. https://doi.org/10.1016/0264-8172(95)92835-K.

Qiu Z., Liu W., 2005. Focal mechanism and seismogenic pattern of Datong-Yanggao, Shanxi, earthquake. *Earthquake Research in Shanxi*, 8–18.

Smith J.V., Durney D.W., 1992. Experimental formation of brittle structural assemblages in oblique divergence. *Tectonophysics* 216 (3–4), 235–253. https://doi.org/10.1016/0040-1951(92)90399-Q.

Su Z., Cheng X., 1992. The geological environment and seismotectonic of the earthquake in Datong-Yanggao area in 1989. *Earthquake Research in Shanxi*, 19–32.

Tron V., Brun J.P., 1991. Experiments on oblique rifting in brittle-ductile systems. *Tectonophysics* 188 (1–2), 71–84. https://doi.org/10.1016/0040-1951(91)90315-J.

Wang G., An W., Lan Q., Fan J., 1992. Macroscopic intensity and seismotectonics of the Mag. 5.8 earthquake in Datong-Yanggao area in 1991. *Earthquake Research in Shanxi*, 41–48.

Wang K.-Y., Ma J., Diao G.-L., Yu R., Wang X.-S., Yan X.-B., 2012. Stress change of Shanxi tectonic belt related to the 2001 Ms 8.1 Kunlun earthquake. *Seismology and Geology* 34, 597–605.

Wang M., Wang P., 1992. The focal mechanism and seismotectonic of the Datong-Yanggao earthquake occurred on 18 October 1989. *Acta Seismologica Sinica* 14, 407–416.

Wang M., Zhang L., Wang P., 1994. Seismogenic fault of the 1991 Datong-Yanggao Ms5.8 earthquake occurred in Shanxi. *Acta Seismologica Sinica* 16, 124–128.

Wei B., Wang K., Yao Z., 1992. The 1989 Datong-Yanggao earthquake: Focal mechanisms and seismotectonic implications. *Earthquake Research in China* 8, 51–59.

Withjack M.O., Jamison W.R., 1986. Deformation produced by oblique rifting. *Tectonophysics* 126 (2–4), 99–124. https://doi.org/10.1016/0040-1951(86)90222-2.

Xie X., Jiang W., Wang H., Feng X., 2004. Holocene activities of the Taigu fault zone, Shanxi province, in relation to the 1303 Hongdong M=8 earthquake. *Acta Seismologica Sinica* 26, 281–293.

Xu J., 1992. A discussion on the fracture direction of the Datong-Yanggao M6.1 eaarthquake group occurred in 1989. *North China Earthquake Sciences* 10, 50–57.

Xu X., 1998. Kinematic features of the northern piedmont faults of Liulengshan and Hengshan range and assessment of their seismic risk. *Research on Active Fault* 6, 74–87.

Xu X., Che Y., Yang Z., You H., Wang Y., Zhu Y., 1991. Discussion on the model of the seismogenic structure for Datong-Yanggao earthquake swarm. *Earthquake Research in China* 7, 77–85.

Xu X., Deng Q., 1990. The features of late quaternary activity of the piedmont fault of Mt. Huoshan, Shanxi province and 1303 Hongdong earthquake (Ms=8). *Seismology and Geology* 12, 21–31.

Xu X., Deng Q., Dong R., Zhang C., Gao W., 1992. Study on strong earthquake activity and risk areas in the Shanxi graben system. *Seismology and Geology* 14, 305–316.

Xu X., Ma X., 1992. Geodynamics of the Shanxi rift system, China. *Tectonophysics* 208 (1–3), 325–340. https://doi.org/10.1016/0040-1951(92)90353-8.

Xu X., Ma X., Deng Q., 1993. Neotectonic activity along the Shanxi rift system, China. *Tectonophysics* 219 (4), 305–325. https://doi.org/10.1016/0040-1951(93)90180-R.

Xu X., Ma X., Deng Q., Liu G., Ma Z., 1996a. Neotectonics, paleoseismology and ground fissures of the Shanxi (Fen-Wei) rift system, China. Geological Publishing House, Beijing, China.

Xu X., Yonekura N., Suzuki Y., Deng Q., Wang Y., Takeuci A., Wang C., 1996b. Geomorphic study on late Quaternary irregular faulting along the northern piedmont of Liulengshan range, Shanxi province, China. *Seismology and Geology* 18, 169–181.

Zhang P., Deng Q., Zhang G., Ma J., Gan W., Min W., Mao F., Wang Q., 2003. Active tectonic blocks and strong earthquakes in the continent of China. *Science in China Series D: Earth Sciences* 46 (2), 13–24. https://doi.org/10.1360/03dz0002.

Zhang Y.Q., Mercier J.L., Vergély P., 1998. Extension in the graben systems around the Ordos (China), and its contribution to the extrusion tectonics of south China with respect to Gobi-Mongolia. *Tectonophysics* 285 (1–2), 41–75. https://doi.org/10.1016/S0040-1951(97)00170-4.

Zhang W., Zhang K., Zhao Y., Cai X., Wang X., Xu G., Wu H., Han B., Zeng X., 1983. The Mesozoic and Cenozoic geotectonic characteristics and dynamical model of the lithosphere in North China fault block region. *Acta Geologica Sinica,* 33–42.

Zhao L., Li Z., Zheng S., 1992. The focal mechanism of the Datong-Yanggao earthquake in October 1989. *Acta Seismologica Sinica* 14, 251–254.

Zhu A.-L., Diao G.-L., Zhang S.-C., Du Y.-C., 1999. Three-dimensional characteristic of focus faults of the two earthquakes at Datong-Yanggao in 1989 and 1991. *Earthquake Research in Shanxi*, 15–20.

Zhuo Y.-Q., Bornyakov S.A., Guo Y.-S., Ma J., Sherman S.I., 2016. Influences of obliquity angle difference on the evolution of Fen-Wei Rift: A study from segmented transtension clay model. *Seismology and Geology* 38, 259–277.

INFORMATION ABOUT AUTHORS | СВЕДЕНИЯ ОБ АВТОРАХ

Yan-Qun Zhuo
PhD of Geophysics, Assistant Professor

State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration
Yard No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China

e-mail: zhuoyq@ies.ac.cn

Ян-Цюнь Чжо
PhD

Государственная центральная лаборатория динамики землетрясений, Институт геологии, Администрация по землетрясениям Китая
No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China

Yanshuang Guo
Assistant Professor

State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration
Yard No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China

e-mail: guoysh@ies.ac.cn

Яншуан Го
Assistant Professor

Государственная центральная лаборатория динамики землетрясений, Институт геологии, Администрация по землетрясениям Китая
No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China

Sergey A. Bornyakov
Candidate of Geology and Mineralogy, Senior Researcher

Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia
128 Lermontov street, Irkutsk 664033, Russia

e-mail: bornyak@crust.irk.ru
https://orcid.org/0000-0002-5119-1092

Сергей Александрович Борняков
канд. геол.-мин. наук, с.н.с.

Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия

Jin Ma
Academician of Chinese Academy of Sciences, Professor

State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration
Yard No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China

e-mail: majin@ies.ac.cn

Цзинь Ма
академик Китайской академии наук, профессор

Государственная центральная лаборатория динамики землетрясений, Институт геологии, Администрация по землетрясениям Китая
No. 1, Hua Yan Li, Chaoyang District, Beijing 100029, China