Acta Geologica Sinica (English Edition), 2021, 95(supp.1): 22–24

A Reappraisal of the 2005 Kashmir Earthquake in the Northwestern Himalaya Syntaxis

BAI Ling[1, 2, *], SU Hui[2] and ZHOU Yuanze[2]

[1] *Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China*
[2] *University of Chinese Academy of Sciences, Beijing 10086, China*

Citation: Bai et al., 2021. A Reappraisal of the 2005 Kashmir Earthquake in the Northwestern Himalaya Syntaxis. Acta Geologica Sinica (English Edition), 95(supp. 1): 22–24.

The collision of the Indian and Eurasian plates caused a massive surface uplift and formed the Himalayas. Throughout the 2500-km long Himalaya mountain range, significant earthquake hazards have occurred either on the interface between the plates, above the interface at the Himalayan wedge, or below the interface within the subducting Indian plate (Bai et al., 2019; Bilham et al., 2019; Shi et al., 2020). Future destructive earthquakes will continue to be major sources of seismic hazard to millions of people in the region. It is thus important to examine the properties of large earthquakes that have occurred along the Himalayan orogenic belt. Here we revisit the source parameters of the 2005 Mw7.6 Kashmir earthquake and its aftershock sequence that have occurred at the western Himalaya syntaxis. The major tectonic feature for source area of the 2005 Kashmir earthquake is the rapid shift of the Himalayan orogenic belt from southeast to southwest direction.

Introduction to the 2005 Kashmir earthquake

On October 8, 2005 at 3:50 am GMT time (8:50 am local time), a Mw7.6 earthquake occurred in Kashmir, western Himalayan syntaxis (Fig. 1). This earthquake occurred at the densely-populated northern Pakistan close to the Kohistan Arc and Peshawar Basin, caused more than 87000 fatalities, a fivefold number of injuries and nearly four million people homeless (Powali et al., 2020). Since last century, more than 20 earthquakes of Mw ≥ 7.0 have occurred on the Himalayan orogenic belt (Bilham et al., 2019) (inset in the Fig. 1). This was the most catastrophic earthquake among them.

According to the International Seismological Centre (ISC) catalog, there were more than 1000 aftershocks with magnitudes greater than 3.5 within two years after the mainshock. Though local seismic stations are rare, many of these earthquakes were well-recorded by regional and teleseismic stations. In addition, there were developments in seismic velocity models, data processing methodologies, such as the multiple event location algorithm. These advances have made it worthwhile to revisit the source parameters of the 2005 Kashmir earthquake sequence.

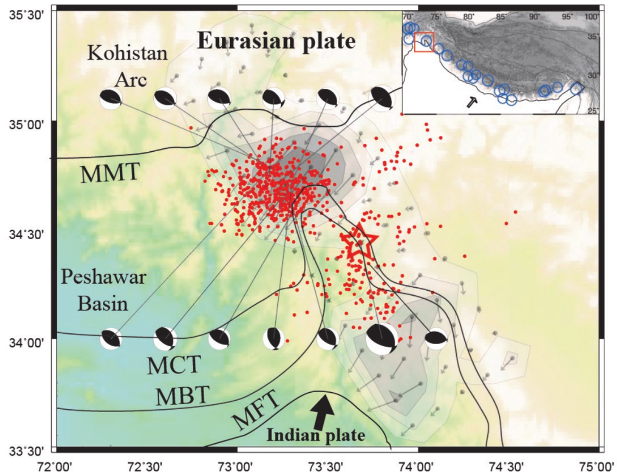

Fig. 1. Tectonic map of the study area.
The red star is the 2015 Kashmir mainshock and red dots are aftershocks relocated in this study. Beach balls are focal mechanisms of the mainshock obtained from this study and those of the aftershocks of Mw ≥ 4.8 taken from the global centroid moment tensor (gCMT) catalog. The gray patches are coseismic rupture area. Black lines are the major faults. Thick arrow is the direction of Indian plate movement with respect to the Eurasian plate (Ischuk et al., 2013). The inset in the upper-right corner show the study area (red rectangle) and historic earthquakes of Mw ≥ 7.0 occurred since 1900.

Relocations of the 2005 Kashmir earthquake and its aftershocks

We relocated the mainshock and aftershocks using a multiscale double-difference earthquake relocation method (multiDD) (Bai et al., 2015, 2019), which we developed from the hypoDD method (Waldhauser and Ellsworth, 2000). The hypoDD method assumes a flat Earth model and is appropriate for local-scale calculations. We developed the multiDD method to include arrival times of other phases recorded by local, regional and teleseismic networks by taken the sphericity of the Earth into account. It minimize residuals between observed and theoretical travel time differences for pairs of earthquakes observed at the same station to reduce errors made by velocity models in locating earthquakes.

We used arrival time data from reviewed ISC catalog for the mainshock and 800 aftershocks of Mw ≥ 4.0 within two-year time period. A vast number of new phase readings have been made on permanent and temporary

* Corresponding author. E-mail: bailing@itpcas.ac.cn

© 2021 Geological Society of China
http://www.geojournals.cn/dzxbcn/ch/index.aspx
https://onlinelibrary.wiley.com/journal/17556724

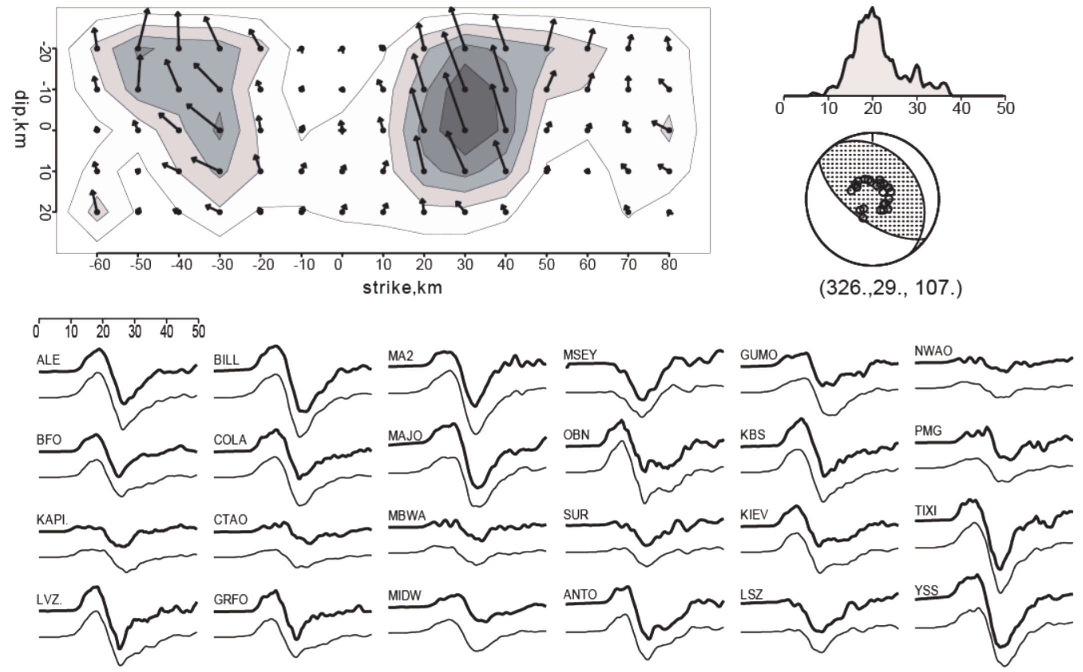

Fig. 2. Waveform inversion for the 2005 Kashmir earthquake.
Upper panels are the rupture process, total duration, and focal mechanism. The lower panels are waveforms of (thick lines) raw data and (thin lines) synthetics.

seismic stations in the reviewed ISC catalog. We used 28000 phase readings, which formed 66000 differential travel time data in the multiDD relocation. For the local structure, we used a velocity model comprised of a uniform mantle (Vp = 8.00 km/s) and a three-layer crust (Vp_1 = 6.00 km/s, H_1 = 24 km; Vp_2 = 6.30 km/s, H_2 = 36 km; Vp_3 = 6.60 km/s, H_3 = 50.0 km) based on the CRUST1.0 model (Laske et al., 2013).

Finally 676 earthquakes are relocated, including the mainshock and 675 aftershocks (Fig. 1). The weighted L1 and L2 norm residuals decreased from 0.84 s and 1.13 s before relocation to 0.41 s and 0.54 s after relocations, respectively, demonstrating that the earthquakes are better relocated (Fig. 1). The seismic activity started with the Kashmir mainshock at the location of (73.6796ºE, 34.4429ºN). Many of the aftershocks are concentrated to the NW of the mainshock while some aftershocks are located to the SE of the mainshock, forming an along-strike distribution.

Rupture process of the 2005 Mw7.6 earthquake

To further determine the source parameters of the 2005 Kashmir earthquake, we carried out waveform inversions using teleseismic direct P wave data (Kikuchi and Kanamori, 1991). Amplitudes are corrected for geometrical spreading using attenuation t^* operator with a value of 1.0 s. For the calculation of synthetic waveforms, we used the CRUST1.0 model for the source side and the IASPI91 model (Kennett and Engdahl, 1991) for the receiver side.

Waveforms are obtained from the Incorporated Research Institutions for Seismology (IRIS) data management center (DMC) for stations at distance ranges of 30° and 95°. We determined the fault plane solution, moment rate function, and source rupture process. Waveforms are band-pass-filtered from 0.01 to 1 Hz and deconvolved from the station response.

The results of the teleseismic wave inversion are shown in Fig. 2. The total durations of the source rupture process is about 20 s. The focal mechanism solution is reliable with a reverse faulting with fault plane solution (strike = 326°, dip = 29°, and slip = 107°). The fault area is about 150 km × 50 km along the strike and dip directions. Ruptures are extended to both of the NW and SE direction from the mainshock, consistent with the rupture revealed from the SAR inversion (Pathier et al., 2006; Wang et al., 2014). The maximum displacement is propagated toward NW from the mainshock at the shallow portion about 10 km.

Discussion and conclusions

The source area is located at the western Himalaya syntax, resulting from the collision of the Indian and Eurasian plates. The structural evolution of the region can be divided into three stages: pieces of landmass separated from Gondwana land and moved toward north; the closure of Tethyan oceans and the collision of the Indian plate with the Eurasian plate; the post-collision and the mountain formation (Yin and Harrison, 2000). Consequently, several major thrust faults are formed and exposed in the source area. From south to north, they are the Main Frontal thrust (MFT, or Salt Range Thrust as the local name), Main Boundary thrust (MBT, or Murree thrust), Main Central thrust (MCT), and Main Mantle thrust (MMT, or Indus suture) (Satyabala et al., 2012; Sippl et al., 2013). They converge beneath the surface of the Earth as the Main Himalayan thrust (MHT), a detachment that separate the subducting Indian plate from the overriding Eurasian plate (Bai et al., 2019).

Thrust earthquakes are more likely to be followed by strong aftershocks, compared with strike-slip and normal faulting earthquakes (Wu et al., 2004). The 2005 Kashmir earthquake is such an example. The seismic activity started with the Mw7.5 mainshock on a NE dipping thrust fault striking in nearly an NW–SE direction. Aftershocks are located to both the NW and the SE from the mainshock. The shift of the main boundary front from MMT to MCT and MBT is an antiformal structure in the hinterland of the northwest Himalaya. The aftershock distribution is almost consistent with the antiformal structure. The NW end of the aftershocks is close to the MMT. MMT is a boundary between the Indian and the Kohistan arc, which may play a barrier for the rupture extention at the NW direction.

When a large earthquake occur the rupture immediately after the earthquake usually cause strong slips on the fault plane. Fig. 1 shows coseismic slip distribution of the mainshock together with the earthquake relocations. The aftershocks are mostly concentrated to the NW from the mainshock, almost consistent with the maximum slip area. To the SE from the mainshock, there were also a clear slip distribution and earthquake distribution. However, the slip is extended further away from the mainshock compared with the aftershock distribution. It is likely that the rupture speed of this earthquake is smaller than the regular value of 3.0 km/s we assumed for the rupture process inversion. The slip and earthquake distributions are almost overlapped and consistent with the local rotation of the MBT and MCT fault system, resulting from the rapid shift of the Himalayan orogenic belt from southeast to southwest direction.

Key words: 2005 Mw7.5 Kashmir earthquake, source parameters, western Himalayan syntaxis

Acknowledgments: This work is supported by the grants of the Wong K.C. Education Foundation (No. GJTD-2019-04), the Second Tibetan Plateau Scientific Expedition and Research Program (No. 2019QZKK07), and the National Nature Science Foundation of China (No. 41988101-0104). We used waveform data from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center.

References

Bai, L., Klemperer, S.L., Mori, J., Karplus, M.S., Ding, L., Liu, H., Li, G., Song, B., and Dhakal, S., 2019. Lateral variation of the Main Himalayan Thrust controls the rupture length of the 2015 Gorkha earthquake in Nepal. Science Advances, 5: eaav0723.

Bai, L., Li, G., Khan, N.G., Zhao, J, and Ding, L., 2017. Focal depths and mechanisms of shallow earthquakes in the Himalayan-Tibetan region. Gondwana Research, 41: 390–399.

Bai, L., and Zhang, T., 2015. Complex deformation pattern of the Pamir-Hindu Kush region inferred from multi-scale double-difference earthquake relocations. Tectonophysics, 638: 177–184.

Bilham, R., 2019. Himalayan earthquakes: A review of historical seismicity and early 21st century slip potential. Geological Society Special Publications, 483: 423–482.

Ischuk, A., Bendick, R., Rybin, A., Molnar, P., Khan, S.F., Kuzikov, S., Mohadjer S., Saydullaev, U., Ilyasova, Z., Schelochkov, G., and Zubovich, A.V., 2013. Kinematics of the Pamir and Hindu Kush regions from GPS geodesy. Journal of Geophysical Research, 118: 2408–2416.

Laske, G., Masters, G., Ma, Z., and Pasyanos, M., 2013. Update on CRUST1.0–A 1-degree Global Model of Earth's Crust, Geophys. Res. Abstracts, 15, Abstract EGU2013–2658.

Kennett, B., and Engdahl, E., 1991. Traveltimes for global earthquake location and phase identification. Geophysical Journal International, 105(2): 429–465.

Khan, P.K., Moanty, S., and Mohanty, M., 2010. Geodynamic implications for the 8 October 2005 North Pakistan Earthquake. Surveys in Geophysics, 31: 85–106.

Kikuchi, M., and Kanamori, H., 1991. Inversion of complex body waves-III. Bulletin of Seismological Society of America, 81(6): 2335–2350.

Pathier, E., Firlding, E.J., Wright, T.J., Walker, R., Parsons, B.E., and Hensley, S., 2006. Displacement field and slip distribution of the 2005 Kashmir earthquake from SAR imagery. Geophysical Research Letters, 33: L20310.

Powali, D., Sharma, S., Mandal, R., and Mitra, S., 2020. A reappraisal of the 2005 Kashmir (M 7.6) earthquake and its aftershocks: Seismotectonics of NW Himalaya. Tectonophysics, 789: 228501.

Waldhauser, F., and Ellsworth, W.L., 2000. A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California. Bulletin of Seismological Society of America, 90(6): 1353–1368.

Wang, K., and Fialko, Y., 2014. Space geodetic observations and models of postseismic deformation due to the 2005 M7.6 Kashmir (Pakistan) earthquake. Journal of Geophysical Research: Solid Earth, 119(9): 7306–7318.

Wu, Z., Wan, Y., and Zhou, G., 2004. Focal mechanism dependence of a few seismic phenomena and its implications for the physics of earthquakes. Pure Applied Geophysics, 161: 1969–1978.

Satyabala, S.P., Yang, Z., and Bilham, R., 2012. Stick-slip advance of the Kohat Plateau in Pakistan. Nature Geoscience, 5: 147–150.

Sippl, C., Schurr, B., Yuan, X., Mechie, J., Schneider, F., Gadoev, M., Orunbaev, S., Oimahmadov, I., Haberland, C., Abdybachaev, U., Minaev, V., Negmatullaev, S., and Radjabov, N., 2013. Geometry of the Pamir–Hindu Kush intermediate-depth earthquake zone from local seismic data. Journal of Geophysical Research, 118: 1438–1457.

Shi, D., Klemperer, S.L., Shi, J., Wu, Z., and Zhao, W., 2020. Localized foundering of Indian lower crust in the India-Tibet collision zone. Proceedings of the National Academy of Sciences of the United States of America, 117: 24742–24747.

Yin, A., and Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen. Annual Review of Earth and Planetary Sciences, 28: 211–280.

About the first and corresponding author

BAI Ling, female, Ph.D.; professor in geophysics, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. She is now interested in earthquake source physics and deep structure of the Earth, especially for the Himalayan-Tibetan area, E-mail: bailing@itpcas.ac.cn.