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 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.

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
seismic stations in the reviewed ISC catalog. We used 28,000 phase readings, which formed 66,000 differential travel time data in the multiDD relocation. For the local structure, we used a velocity model comprised of a uniform mantle ($V_p = 8.00 \text{ km/s}$) and a three-layer crust ($V_{p1} = 6.00 \text{ km/s}, H_1 = 24 \text{ km}; V_{p2} = 6.30 \text{ km/s}, H_2 = 36 \text{ km}; V_{p3} = 6.60 \text{ km/s}, H_3 = 50.0 \text{ km}$) 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 (73.6796º E, 34.4429º N). 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 $r^*$ 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 IASP91 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 30º and 95º. 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 = 326º, dip = 29º, and slip = 107º). 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 extension 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

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References

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