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Fault geometry of 2015, Mw7.2 Murghab, Tajikistan earthquake controls rupture propagation: Insights from InSAR and seismological data

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ABSTRACT

Combining space-based geodetic and array seismology observations can provide detailed information about earthquake ruptures in remote regions. Here we use Landsat-8 imagery and ALOS-2 and Sentinel-1 radar interferometry data combined with data from the European seismology network to describe the source of the December 7, 2015, Mw7.2 Murghab (Tajikistan) earthquake. The earthquake reactivated a ∼79 km-long section of the Sarez–Karakul Fault, a NE oriented sinistral, trans-tensional fault in northern Pamir. Pixel offset data delineate the geometry of the surface break and line of sight ground shifts from two descending and three ascending interferograms constrain the fault dip and slip solution. Two right-stepping, NE-striking segments connected by a more easterly oriented segment, sub-vertical or steeply dipping to the west were involved. The solution shows two main patches of slip with up to 3.5 m of left lateral slip on the southern and central fault segments. The northern segment has a left-lateral and normal oblique slip of up to a meter. Back-projection of high-frequency seismic waves recorded by the European network, processed using the Multitaper-MUSIC approach, focuses sharply along the surface break. The time progression of the high-frequency radiators shows that, after a 10 second initiation phase at slow speed, the rupture progresses in 2 phases at super-shear velocity (∼4.3–5 km/s) separated by a 3 second interval of slower propagation corresponding to the passage through the restraining bend. The intensity of the high-frequency radiation reaches maxima during the initial and middle phases of slow propagation and is reduced by ∼50% during the super-shear phases of the propagation. These findings are consistent with studies of other strike-slip earthquakes in continental domain, showing the importance of fault geometric complexities in controlling the speed of fault propagation and related spatiotemporal pattern of the high-frequency radiation.

1. Introduction

The earthquake occurred on December 7, 2015 on the Sarez–Karakul Fault (SKF), in the Gorno–Badakshan Autonomous Region of Eastern Tajikistan. Its moment magnitude (Mw) is 7.2 and its centroid moment tensor and distribution of aftershocks indicate left-lateral, strike-slip movement on a NE oriented, nearly vertical fault (USGS, 2015). The earthquake has a similar magnitude and mechanism as the Sarez–Pamir earthquake, which stroke the region on 18 February 1911 (Kulikova et al., 2016). The 1911 earthquake triggered a massive landslide, building a 600 m high dam known as the Usoi Dam on the Murghab River, which resulted in the formation of Sarez Lake (Schuster and Alford, 2004; Ambraseys and Bilham, 2012). No damage to Usoi Dam was reported following the 2015 event but the seismic hazard in the region makes it a sensible target of study. Important questions to be addressed touch on the significance of the 2015 event within the current tectonic regime of the Pamir Mountains, the characterization of its rupture and direction of propagation and the possible implications for the dam stability (ISDR, 2000).

In this paper we use satellite optical and radar interferometry (InSAR) data jointly with seismological data to describe the source of the 2015 earthquake. In the following sections we summarize the tectonic setting of the region, describe the geometry of the fault rupture, and present the static slip solution obtained by inversion of InSAR data. The second part of the paper presents the

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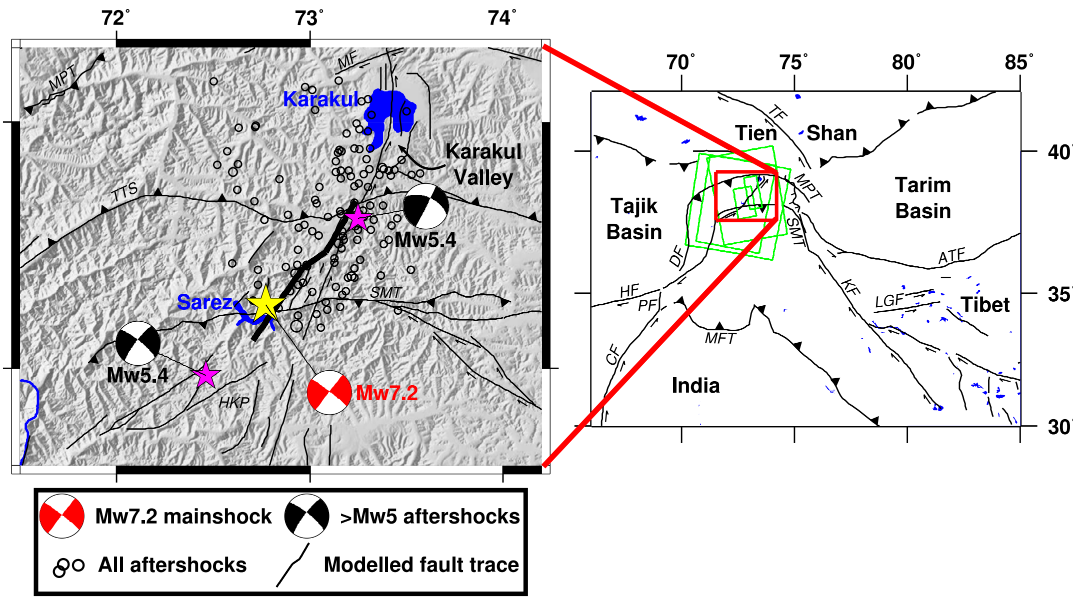

Fig. 1. Simplified tectonics map of Central Pamir. 2015 Sarez Lake Mw7.2 mainshock (yellow star), two Mw5.4 aftershocks (magenta stars) plotted with accompanying focal mechanisms from the Incorporated Research Institutions for Seismology (IRIS) (IRIS, 2016), and background seismicity (open dots) data from the International Seismological Centre (ISC) (ISC, 2016). Quaternary faults from (Mohadjer et al., 2016) shown in black. Coseismic fault trace in thick black (this study). Inset map provides location of study area (red box), with major faults (black). Fault abbreviations are Altyn Tagh Fault = ATF, CF = Chaman fault, DF = Darvaz–Karakul fault, HF = Herat fault, HKP = Hindu Kush–Pamir faults, KF = Karakorum fault, LGF = Longmu–Gozha fault, MFT = Main frontal thrust, MPT = Main Pamir thrust, MF = Muji Fault, PF = Paghman fault, SKF = Sarez–Karakul fault system, SMT = Sarez–Murghab thrust system, TF = Talas Ferghana fault, and TTS = Tanymas thrust system. Green frames are locations of five InSAR images from Sentinel-1A and ALOS-2 satellites used in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

seismological data used in a back-projection method to describe the rupture propagation with time. The last section discusses the correspondence between the migration of the source location of high-frequency waves with geometric complexities of the rupture and the implications of these observations.

2. Tectonic setting

The Pamir Mountains developed at the western syntaxis of the Himalaya collision front, north of the Indus–Tsang-Po Tertiary suture zone. They are composed of an assemblage of East–West trending belts squeezed between Paleozoic, Mesozoic, and Tertiary suture zones (Burtman and Molnar, 1993). Since the onset of the collision, north–south shortening is accommodated by a series of thrust systems raising the elevation of the mountains to ∼4500 m, between the Tajik depression to the West and the Tarim Basin to the East (Fig. 1). Seismological (Burtman and Molnar, 1993; Pegler and Das, 1998; Sippl et al., 2013; Schurr et al., 2014) and geological observations (Tapponnier et al., 1981; Coutand et al., 2002) have shown that a large fraction of the India–Asia convergence has been absorbed by southward subduction of the Asian crust along the Main Pamir Thrust to the north and the northward subduction of the Indian plate to the south. The northward migration of the Pamir is accommodated along its eastern front by right-lateral movement on the Kashgar–Yecheng fault system and more internally by the Kongur Shan fault system, a well-developed right-lateral, transtensional fault system that connects to the Tashgorgan Fault and eventually the Karakorum Fault to the south (Robinson et al., 2004, 2015; Chevalier et al., 2011, 2015, 2016). Along its western side, the northward movement of the Pamir is accommodated by left-lateral movement on a north–south shear zone including the Darvaz and the Badakhshan faults connecting to the Chaman and Herat faults to the south (Cowgill, 2010; Mohadjer et al., 2010; Schurr et al., 2014) (Fig. 1). Shallow seismicity of central and northern Pamir indicates that present-day deformation within the range is concentrated in the center and west side of the northern half of the range (Strecker et al., 1995; Sippl et al., 2013; Schurr et al., 2014; Kulikova et al., 2016). Campaign GPS velocities indicate a rather consistent NNW movement of the interior of the Pamir at a rate of ∼13–20 mm/yr with respect to stable Eurasia (Reigber et al., 2001; Mohadjer et al., 2010; Zubovich et al., 2010, 2016; Ischuk et al., 2013) suggesting that the rate of the internal deformation of the range is low compared to the rate of convergence along the Main Pamir Thrust.

The SKF is a ∼NE striking fault that extends from Sarez Lake to Karakul Lake in central northern Pamir and seems to extend towards the SW in a more distributed shear zone south of the Sarez–Murghab Thrust System (Fig. 1) (Sippl et al., 2013). A cluster of shallow seismicity occurs at the intersection of the two fault systems. A NE–SW trend of seismicity highlights the shear zone with focal solutions consistent with sinistral slip on NE oriented planes (Schurr et al., 2014). In the NE part of the Karakul Lake Valley, Strecker et al. (1995) describe the SKF surface morphology as a set of en echelon segments bearing evidence of down-dip and left-lateral movements. However, the source mechanisms of the few small earthquakes along the fault trace, the 2015 Mw7.2 event, and its aftershocks, all indicate sinistral strike slip as opposed to oblique or normal slip (Schurr et al., 2014). Although the main fault of this asymmetric graben runs along the western side of the valley (Komatsu, 2016), south of Karakul Lake the recent faulting activity is observed along the eastern side of the valley with vertical and left-lateral offsets of glacial deposits, small stream channels, and fluvial terraces (Strecker et al., 1995; Schurr et al., 2014; Komatsu, 2016). South of the valley, the fault enters a region of high relief in the direction of Sarez Lake. Observation of the surface morphology in high resolution SPOT and Digital Globe satellite images available on the Google Earth server shows a region of rugged terrain with snow covered peaks, deeply incised valleys, steep and fast eroding slopes and many occurrences of landslides, which obscure potentially active fault scarps in the morphology. As a result, the SKF morphological trace cannot be followed in the