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Seismogenic fault and tectonic significance of 1996 Karakoram Pass earthquake (Ms 7.1) based on InSAR

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Abstract

Due to hard observation condition of the western Tibet region, the slip behaviors of the Ms7.1 Karakoram Pass earthquake occurred in Hetian, Xinjiang on November 19, 1996 remains unclear. Using ERS 1/2 SAR data and InSAR technique, we obtain the co-seismic deformation of the earthquake. The north and south deformation areas show asymmetric pattern, with the maximum LOS displacement of the southern part approximately 24.6 cm, and the maximum LOS displacement in the northern part approximately -18.5 cm. Nonlinear and linear inversion algorithms are used to determine the geometric parameters and slip distribution of the earthquake fault. Our results show that the co-seismic displacement is dominated by deformation fields are clearly visible sinistral strike-slip accompanied by a small amount of normal slip component. The co-seismic slip occurred between 0 and 18 km at depth. The maximum slip is ~ 81 cm, occurring at a depth of 8.5 ± 0.5 km at (35.36°N 78.03°E), indicating a shallow event with a moment magnitude of Mw 6.5. The seismogenic fault is a secondary fault in the Karakoram fault zone with strike 96° , dip 84° , and rake -24° . This earthquake shows that the Karakoram fault zone undergoes a complex tectonic deformation process, with central part of the fault zone showing minor tensional deformation behaviors.

Keywords: Karakoram Pass earthquake, InSAR, Co-seismic deformation, Seismogenic fault, Slip distribution

Introduction

On November 19, 1996, at 18:44 CST, an earthquake with a surface-wave magnitude of 7.1 (M_s) occurred in the Karakoram Pass region, just southwest of Hetian, Xinjiang (hereinafter referred to as the Karakoram Pass earthquake). This strong earthquake, which resulted in multiple slope collapses and landslides, was the first strong earthquake to occur in this region since the formation of a seismic gap region ($M \geq 4$) in October 1980 (Luo et al. 2003), indicating active crustal movement in the northwest part of the Qinghai-Tibetan Plateau. Various institutions have provided focal mechanism solutions for this event, all of which show that this earthquake was mainly a strike-slip rupture event. However, because this earthquake occurred in an area where the coverage of the seismic network is very limited, the seismogenic

structures provided by the different institutions varied significantly (Table 1). Ge (1997) provided a focal mechanism solution based on the GCMT, where it was proposed that the seismogenic fault should be a secondary transverse fault related to the Karakoram fault. Luo et al. (2003) proposed that the Linjitang fault in the Karakoram fault zone was a seismogenic fault.

The Karakoram Pass earthquake occurred in an uninhabited region (elevation > 5 km) characterized by harsh environment and dangerous roads, where conducting field geological surveys and traditional deformation measurements is extremely difficult. As a result, very few studies have focused on the seismogenic structure and deformation caused by this earthquake. More importantly, an in-depth analysis of the tectonic implications of this event is still lacking. An increasing number of scholars regard interferometric synthetic aperture radar (InSAR) technology as an important tool for studying seismic deformation in remote areas. InSAR has been successfully used for seismic studies in the

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Table 1 Focal mechanism solutions for the Karakoram Pass earthquake provided by various institutions

Institution	Epicenter (°) Latitude, longitude	Magnitude	Depth (km)	Nodal plane 1 (°) Strike, dip, rake	Nodal plane 2 (°) Strike, dip, rake
GCMT	35.45, 77.86	M_w 6.8	15.0	180, 71, 170	273, 81, 19
USGS	35.345, 78.133	M_w 6.8	33.0	90, 87, − 7	180, 83, − 177
Gao et al. (2005)	35.26, 78.21	M_s 7.1	16.0	10, 70, 174	106, 80, 6
This paper	35.36, 78.03	M_w 6.5	8.3	96, 84, − 24	None

GCMT Global Centroid Moment Tensor Project, USGS United States Geological Survey

Qinghai-Tibetan Plateau and the surrounding regions (Ji et al. 2017; Zhao et al. 2017; Qiu and Qiao 2017; Wen et al. 2015; Teshebaeva et al. 2014; Sun et al. 2007). Using InSAR and ERS-1/2-SAR (C-band) data provided by the European Space Agency (ESA), the co-seismic surface deformation field of the 1996 Karakoram Pass earthquake was obtained in the present study. Quantitative inversion analysis based on Okada's theory of dislocation was used to determine the seismic fault's geometric parameters and slip distribution (Okada 1985). The aim of the present paper is to investigate the causes and mechanisms of shallow earthquakes in the Karakoram fault zone and to broaden our understanding of the impact of the Karakoram Pass earthquake on the pattern of strong seismic activity in the Qinghai-Tibetan Plateau.

Regional tectonic background

The collision between the Indian and Eurasian plates due to their continuous convergence has led to strong intracontinental deformation in Central Asia, giving rise to intense tectonic activity in the Pamir Plateau and the surrounding regions (Pan et al. 2009; Li et al. 2006). The main bodies of the Karakoram and Kunlun Mountains in the West Kunlun tectonic zone are characterized by continuous uplift. A series of Quaternary tectonic structures have developed in this region, most of which have been especially active since the Late Pleistocene. These tectonic structures determine the distribution of seismic belts and the intensity of modern seismic activity. Among these, the Taxkorgan fault zone, Kongur fault, Kangxiwa fault, Kegang fault, and Karakoram fault are the most representative structures (Chen 2008). The Karakoram fault has an overall length of 510 km. It forms a huge conjugate fault zone with the adjacent left-lateral Altyn Tagh fault, which controls the direction of neo-tectonic movement along the northwest margin of the Qinghai-Tibetan Plateau.

The early-period deep Karakoram ductile shear zones are distributed on the southwest side of the late-period Karakoram fault zone, jointly forming the dextral strike-slip Karakoram fault zone with an overall strike

of N45°W (Searle et al. 1998; Valli et al. 2007). Due to the nearly N–S compressive stress, the cumulative displacement of the Karakoram fault zone has reached at least 280 km, whereas its average long-term slip rate is at least 10 mm/year. (Li et al. 2006, 2008; Matte et al. 1996). Using 2576 GPS velocities of the Indo-Asian continent from 1999 to 2017, Zheng et al. (2017) calculated the dextral strike-slip rate of the Karakoram fault at ~77°E, ~79°E, and ~81°E to be 6.0 ± 1.5 mm/year, 3.8 ± 2.5 mm/year, and 3.2 ± 2.3 mm/year, respectively. In addition, the ~77°E and ~81°E sites had a crustal shortening rate of 5 ± 1.5 mm/year and 0.5 ± 2.5 mm/year, respectively, whereas the ~79°E site had an extension rate of 3.3 ± 2.5 mm/year.

The Ms 7.1 Karakoram Pass earthquake struck in the Mesozoic continental-margin basin in the Karakoram fault zone (Fig. 1). This was the strongest earthquake to occur in this fault zone since 1976. The Mesozoic continental-margin basin of the Karakoram fault zone was uplifted during the Neogene. It formed into NW-oriented compression-shear faults and tight linear folds after multiple periods of tectonic movement (Pan et al. 2013). The Linjitang fault in the basin forms the boundary between the anticlinal fold belt of the South Kunlun Mountains and the Linjitang depression. The Ageledaban fault is a normal crustal fault, which has displayed strong activity in the Late Paleozoic, Mesozoic, and Cenozoic (Luo et al. 2003). The earthquake epicenter was at the location of China's maximum gravity value. Its measured Bouguer anomaly was approximately − 500 mGal and the measured isostatic gravity was − 180 mGal (Xu et al. 2014). Based on geodetic leveling data acquired from 1955 to 1995, the uplift rate in the epicenter area before the Karakoram Pass earthquake was 4–5 mm/year (Wang et al. 2009).

InSAR co-seismic deformation field acquisition

SAR data acquisition and processing

The number of SAR images available for the Karakoram Pass earthquake is very limited. A total of 4 images were downloaded from the ERS 1/2 data catalog published by

the ESA. Table 2 and Fig. 2 show detailed image pairing data.

Due to the low vegetation coverage in the Qinghai-Tibetan Plateau, the multi-path scattering effect caused by vegetation is minimal in this region. To minimize the loss of coherence due to topographic errors or image distortion, NASA's 30-m SRTM DEM data and the ERS Precise Orbit data provided by Delft University, Netherlands are used to perform two-pass differential interferometry (Massonnet et al. 1995) using the advanced radar image processing software ENVI/SARscape. Figure 3 shows a data processing flow chart.

The robust Goldstein filtering method was used to ensure the clarity of fringes and reduce coherence loss due to noise from the spatial and temporal baselines (Goldstein and Werner. 1998). Due to the presence of large areas of low coherence and incoherence, phase unwrapping based on the minimum cost flow method was used to mask any pixels with coherence below a selected threshold (Ghiglia and Romero 1994; Liu et al. 2018). Because the spatial and temporal baselines of the interferometric image pairs were relatively long, the obtained interferograms still contained some phase noise caused by residual orbital errors, despite the use

Table 2 Information for pairing InSAR images(trace number: 334, frame number: 2889)

Master image (satellite)	Slave image (satellite)	Time baseline (days)	Perpendicular baseline (m)	Doppler centroid diff. (Hz)	Master image incident angle (°)
19960418 (ERS2)	19990513 (ERS2)	1120	46.078	- 5.707	23.122
19960522 (ERS1)	19990513 (ERS2)	1086	467.958	226.517	23.258
19960522 (ERS1)	19980910 (ERS2)	841	- 56.212	202.136	23.258

Fig. 2 InSAR image pair baselines

Fig. 3 InSAR image processing flowchart

of precise ephemeris data. To reduce this effect, polynomial model-based orbital refinement and phase shift correction were applied using multiple ground control points (GCPs) located far from the deformation region

in open and flat areas, such as river valleys. Finally, after clipping and geocoding, we obtain the co-seismic surface deformation field produced by the Karakoram Pass earthquake (Fig. 4).

The location of the Karakoram Pass earthquake is the Depsang basin, where melting alpine snowpack and long-time intervals between paired images directly affect the coherence of the interferograms. High coherence could only be obtained in flat regions, such as basins and valleys (coherence coefficient above 0.5).

InSAR co-seismic deformation

It is evident from the InSAR interferograms in Fig. 4a–c that the fringes from the three deformation fields are clearly visible. Deformation along the (LOS) direction for each fringe period is 2.8 cm, and most deformation is concentrated within an area measuring 18×9 km². The surface deformation caused by the Karakoram Pass earthquake presents two deformation areas (north and south) centered on an E–W strike fault. The strike angle

of this fault is approximately 96°, which is consistent with nodal plane 1 of the focal mechanism solution provided by USGS. In addition, this fault cuts across the Ageledaban fault. However, it is presumed to be a concealed secondary fault (white dashed line in Fig. 4) because its structure is not clearly visible on the surface.

The north and south deformation areas are clearly asymmetric. It is evident from the periodic changes in the deformation fringes shown in Fig. 4 that the fringes on the north side of the concealed fault are tightly spaced without an obvious diversion trend, indicating the earthquake caused large deformation within a very narrow area. In contrast, the fringes on the south side are half-elliptical and diverge along the southeast direction, consistent with sinistral shear trend. Because SAR produces side-looking images, the co-seismic

deformation fields were obtained along the LOS direction. In addition, positive LOS deformation value after geocoding with ENVI/SARscape indicates that the surface was approaching the satellite (e.g., uplift), whereas a negative value indicates that the surface was moving away from the satellite (e.g. subsidence). The three deformation profiles in Fig. 4a–c indicate the area north of the fault was moving away from the satellite during the two imaging periods, on the contrary, the area south of the fault was moving toward the satellite. Consequently, one can conclude that the deformation field reflects sinistral strike-slip fault activity, also shown in Wang and Wright (2012).

The maximum LOS displacement in the southern side is approximately 24.6 cm, and the maximum LOS displacement in the northern side is approximately −18.5 cm. The maximum deformation area is located at the intersection of the concealed fault and the Ageledaban fault.

Fault source modeling

Fault-geometry parameters provide one of the primary bases for understanding co-seismic deformation. Therefore, we invert the InSAR data for estimating the coseismic slip distribution of the Karakoram Pass earthquake in two steps. First, we performed an exhaustive search for the best-fit fault parameters under the assumption of uniform slip on a rectangular fault. Then, we divided the faults into sub-faults and estimated the slip along each fault patch.

To reduce the number of points and consequently improve the computational efficiency, we first attempted to down-sample the InSAR data using the quadtree partitioning method (e.g., Ji et al. 2017). However, this failed to capture the primary deformation pattern with a sufficiently high resolution. We subsequently grid-sampled the near-field area at a dense regular spacing and the far-field area at a sparse regular spacing. The deformation fields (Fig. 4a–c) are downsampled. Finally, we obtained 1315 points for inversion, including 436 from Fig. 4a, 598 from Fig. 4b and 281 from Fig. 4c, and all the three data are combined in one figure (Fig. 5).

Inversion of fault parameters

Okada (1985) showed that the causative fault can be interpreted as one rectangular plane with a uniform slip embedded within a homogeneous, isotropic, elastic half-space. Therefore, using the InSAR surface displacements, we can potentially place constraints on the fault parameters through modeling (Kobayashi 2017).

We use the focal mechanism solution published by USGS as the initial input, the parameters of the fault (latitude, longitude, strike, dip, rake, slip, fault depth, length,

Fig. 5 1315 observed values for inversion of the co-seismic deformation field

and width) were solved iteratively using the Levenberg–Marquardt least squares optimization algorithm (Marquardt 1963). Using repeated iterations allows redundant parameters to be eliminated, thereby ensuring that the cost function converges to a global minimum.

As shown in Table 3, the strike of the fault is approximately east–west (EW) at an angle of 96° and with a dip of 84°. These fault parameters are quite consistent with those provided by USGS for nodal plane 1 in the focal mechanism solution. The model-predicted displacements and the residuals derived from the nonlinear inversion are shown in Additional file 1.

Inversion of slip distribution

When the geometric parameters of the fault are determined, a linear relationship exists between slip (strike–slip and dip–slip components) on the fault plane and surface deformation, as shown in Eq. 1. In this paper, we used the SDM software developed by Wang et al. (2011, 2013) to invert the slip distribution on the fault plane.

$$d_{\text{InSAR}} = Gs + \varepsilon \quad (1)$$

where d_{InSAR} is the observed value at the surface, G is the Green's function, s is the slip on the fault plane, and ε is the measurement error.

Since the fault plane is usually divided into many small patches, s represents the slip on each sub-fault plane. In this paper, we set length and width of the fault to be 38 and 24 km, respectively. The fault plane was subsequently discretized into 912 sub-fault elements, each measuring $1 \times 1 \text{ km}^2$. In addition, to prevent oscillating solutions for the slip distribution, the relationship between slip on the sub-fault element and the InSAR observation must satisfy the following condition:

$$\min \left[\|Gs - d_{\text{InSAR}}\|^2 + \alpha^2 \|Hs\|^2 \right] \rightarrow 0 \quad (2)$$

Table 3 Geometrical parameters of seismogenic fault produced by inversion

Longitude (°E)	Latitude (°N)	Strike (°)	Dip (°)	Rake (°)	Slip (m)	Depth (km)	Length (km)	Width (km)	Magnitude (M_w)
77.806 ± 0.1	35.386 ± 0.1	96 ± 2.6	84 ± 4.2	− 24 ± 7.7	4.6 ± 1.0	17.0 ± 2.0	20.0 ± 2.6	5.8 ± 2.0	6.6 ± 0.3

^a The location (longitude and latitude) of the fault is indicated in the top-left corner

where $\|\cdot\|^2$ is the Euclidean norm, H is the Laplacian constraint that limits fault smoothness, s is the amount of slip in the underground fault plane to be calculated, α is a factor that defines fault smoothness, and $Gs - d_{\text{InSAR}}$ is the residual of a fit to the fault dislocation.

During the inversion process, the CRUST 1.0 model was used to determine the regional crust stratification structure and calculate Green's function. For the sliding amount of adjacent patches, the stress drop smoothing constraint was applied because a constant stress drop is a more realistic approximation from a physical perspective.

The slip distribution obtained by the inversion is shown in Fig. 7. Gaps between the simulated values were filled using the kriging interpolation method, which is commonly used in geology.

According to the surface deformation distribution characteristics and deformation magnitude of the simulated and observed deformation fields in Fig. 6, the two fields show good consistency with a correlation of 90.1%. This proves that the Okada elastic model can well explain the co-seismic deformation field of the Karakoram Pass earthquake. Quantitative analysis needs to be based on residual error distribution. The residual error values are mainly distributed on both sides of the fault and the edge of the deformation zone, with the values being mostly less than 10 cm and the maximum being 12.1 cm. This shows that the residual error mainly might come from simplification of fault model and unwrapping error caused by excessive deformation gradient.

The co-seismic fault slip distribution shows that the co-seismic displacement is dominated by sinistral strike-slip accompanied by a small normal slip component. The rupture length along the direction of the strike reaches 24 km. The co-seismic slip distribution was concentrated between 0 and 18 km in depth. The maximum slip was 81 cm, which occurred at a depth of 8.5 ± 0.5 km, which shallower than the depth of derived from the uniform slip model (17 km), with projected ground location at lat. 35.36°N and long. 78.03°E. As shown in Fig. 7a, at about 30 km along the fault strike, the eastward displacement of the fault is obviously obstructed by a nearly vertical dip. The co-seismic slip is smaller below 18 km depth, which shows that this was a shallow-focus earthquake. The inverted dislocation model has a corresponding moment magnitude of M_w 6.5 ± 0.11 , which is less than the values

Fig. 6 Inversion of the co-seismic deformation field of the 1996 Karakoram Pass earthquake. **a** simulated values, and **b** residual distribution, and **c** geological surface trace

provided by the three seismological analyses (shown in Table 1). This might be related to the very long temporal baselines in the interferograms and the sparseness of the deformation field.

Discussion

Uncertainty of co-seismic deformation field

InSAR allows the seismology of remote areas with limited seismic networks to be examined. However, the available SAR image data for the Karakoram Pass earthquake are very limited; only 3 sets of interferometric pairs are available that span minimum and maximum time intervals of 841 and 1120 days, respectively. Therefore, the 3 interferometric deformation fields, which were used to invert the co-seismic slip distribution, include post-seismic deformation data for a 2.5 year period after the earthquake. Post-seismic deformation might be caused by residual slip of a seismogenic fault. Therefore, the co-seismic slip distribution should also contain some after-slip. However, because the magnitude of the main shock was not high, after-slip should be relatively small and should not affect the overall distribution of the co-seismic slip. The residual distribution map of the inversion results (Fig. 6b) exhibits fan-shaped over-fitting surrounding the strip-shaped central area in the deformation zone, where the values are mostly less than 10 cm and the maximum being 12.1 cm. The residual error mainly comes from simplification of fault model and unwrapping error caused by excessive deformation gradient. As shown in Fig. 4a'–c', incoherence is the most serious in the mountainous region. Although incoherence caused by the long temporal baseline affect the InSAR results, the InSAR deformation field covers the near-field region of the epicenter well, thus the model-predicted InSAR deformation can account well for the observations in both the near- and the far-fields.

Epicenter location

Due to the scarcity of seismic stations in Asia in 1996 and crustal inhomogeneity in the Qinghai-Tibetan Plateau, the location of the Karakoram Pass earthquake epicenter as determined from seismic data was highly uncertain (Table 1). The largest discrepancy between the GCMT results and those from (Gao et al. 2005) was 38 km. The inversion results presented in this paper show that the location of the co-seismic fault epicenter is 35.36°N and 78.03°E (Figs. 1, 7). This result deviate from the results provided by the three institutions to various degrees, with the smallest discrepancy from the USGS results and the largest discrepancy from Gao et al. (2005) results being 9.4 and 19.8 km, respectively. These deviations might be attributed to three factors: the epicenter location obtained through seismological inversion was the location of the initial rupture; each institution used a different velocity structure for inversion; the Qinghai-Tibetan Plateau is characterized by crustal heterogeneity (Weston et al. 2012).

The maximum surface deformation caused by the Karakoram Pass earthquake is located at the intersection between the concealed secondary fault and the Ageledaban fault at the lowest elevation of the epicenter region. However, the inversion results show that there is over-fitting in the alluvial valley. Therefore, one can deduce that some mass slides from the mountains on the north side of the fault were carried by thawing and flow of river water during summer. This mass deposited in the alluvial valley during the temporal baseline of the interferograms. The maximum surface deformation should be closer to

the intersection between the concealed secondary fault and the Ageledaban fault.

The maximum co-seismic slip is located at a depth of 8.5 ± 0.5 km, which is a relatively shallow depth compared with other seismic structures. This shows that focal depths determined by InSAR are generally shallower than those determined through traditional seismological methods (Weston et al. 2012). Moreover, as the depth increases, the discrepancy increases. This is because the focal location determined through InSAR is calculated based on a slip distribution model, which is derived from a surface deformation field. For shallow source earthquakes, InSAR better constrains the spatial characteristics of faults compared to seismological inversion based on long-period body waves or surface wave data (Weston et al. 2012).

Seismogenic fault

After the Karakoram Pass earthquake, the focal mechanism solutions determined from teleseismic body wave data show that this earthquake was primarily a strike-slip rupture event. However, different solutions show large differences in the deformation distribution caused by this earthquake. USGS estimated the epicenter intensity at VIII with the long axis strike oriented east–west. Based on the GCMT focal mechanism solution, Ge (1997) proposed that the seismogenic fault should be a secondary transverse fault related to the Karakoram fault. Luo et al. (2003) proposed that the seismogenic fault was the Linjitang fault (LF) in the Karakoram fault zone, with the maximum epicenter intensity VIII, and the long axis strike was oriented NW, which is consistent with the strike in the seismogenic structure. The simulated deformation map of the Karakoram Pass earthquake obtained based on InSAR technology and SDM method shows that surface deformation caused by this earthquake exhibits a regularly shaped ellipse along the EW direction and asymmetric distributed on both sides of a concealed fault zone. These findings are relatively consistent with the USGS shake map (<https://earthquake.usgs.gov/earthquakes/eventpage/usp0007t7m/executive>).

The co-seismic slip distribution image shows co-seismic displacement being dominated by sinistral strike-slip with a small normal slip component. The co-seismic slip distribution was concentrated at a depth ranging from 0 to 18 km, with the maximum slip reaching 81 cm. The obtained results show that the Ageledaban fault is not a seismogenic fault. Rather, the seismogenic fault is a concealed secondary fault with 96° strike, 84° dip, and -24° rake. Because of the limited amount of data, the geological structure of the concealed fault and its relationship with the surrounding deep tectonic structures should be investigated further.

Based on the inversion results for slip distribution, one can deduce that the fault caused by this earthquake was affected by the Ageledaban fault during the slip process. It is presumed that when the south side of the seismogenic fault slid eastward and made contact with the Ageledaban fault, slip energy was absorbed by the deep Ageledaban fault, and affected by gravity, it produced partial normal dip-slip. This also explains why the fringes on the south side of the fault diverge to the southeast.

Tectonic movement of the epicenter region

Shallow earthquakes are generally related to tectonic activity. Being a subduction passive-continental margin in an orogenic belt, the Karakoram formed as a part of an ancient continent, which was divided by rift basins over different epochs. The Karakoram Mesozoic continental-margin basin was uplifted during the Neogene and formed a series of NW-strike compression-shear faults and linear folds after undergoing multiple episodes of tectonic movement (Luo et al. 2004). Due to the nearly N–S compressional stress, the Karakoram fault zone has dextral strike-slip characteristics, with multiple strike-slip earthquakes occurring in the fault zone (Valli et al. 2007).

The tectonic strain field in the epicenter region (Fig. 8) was calculated using the least square collocation method (Zhang et al. 2004) based on 33 GPS velocity (Fig. 1) values close to the epicenter measured from 1997 to 2015 (Zheng et al. 2017). The results show that this high-strain zone represents post-seismic deformation from the 1996 earthquake, which is consistent with Wang and Wright (2012), and the Karakoram strike-slip fault zone has undergone a complex tectonic deformation process. The continuous northward movement of the Indian plate is causing a continual uplift of the Qinghai-Tibetan Plateau. This is accompanied by coupling deformation and northward migration of the lithospheric upper mantle, causing accumulation of significant residual mass. Meanwhile, due to the constraining role of the rigid Tarim basin, many surface uplifts and depressions have formed in the Karakoram fault zone (Xu et al. 2014). The principal strain rate shows a decreasing trend on both sides of the Karakoram strike-slip fault. In addition, positive and negative surface expansion rates are present. Under the assumption of volume conservation, a negative value indicates vertical expansion or thickening, and a positive value indicates vertical contraction or thinning. It is evident from Fig. 8b that the expansion rate is primarily positive on the north side of the epicenter region and negative on the south side, meaning the north side is experiencing crustal thinning, while the south side is undergoing crustal thickening. This means that the

Karakoram Pass earthquake occurred in a strain gradient zone. In addition, as shown in Fig. 8c, the epicenter is located in a region with the largest value of the maximum shear strain rate field, and the shape of the field in this region is consistent with the strike of the seismogenic fault. Although these results reflect the strain conditions after the 1996 earthquake, they also indicate from the side that left-lateral component of the earthquake may have occurred to offset the accumulated strain energy. This indicates that the Kongur system on the north side of the Karakoram fault zone is extensional, but so is the central part, which might explain the formation of a basin in the middle part of the fault zone.

Conclusion

The Ms7.1 Karakoram Pass earthquake on November 19, 1996 occurred at the northwest of the Qinghai-Tibet Plateau, in an area with harsh natural conditions and very weak monitoring capability of the seismic network. We obtained the co-seismic deformation field of the earthquake by using the ERS1/2 SAR data and InSAR technology. With the deformation field as a constraint, the geometric parameters of seismogenic fault were inverted nonlinearly based on Okada dislocation model, and the slip distribution on the fault plane was inverted linearly using SDM method. The main conclusions are as follows:

1. Most of the deformation caused by this earthquake is concentrated within an area measuring $18 \times 9 \text{ km}^2$, with the maximum LOS shortening in the southern side 24.6 cm. The maximum LOS lengthening in the

northern side is approximately 18.5 cm. The inversion result shows that the location of the co-seismic rupture centroid is (78.03°E, 35.36°N), and the calculated moment magnitude is Mw6.5, which is slightly smaller than the magnitude released by other methodologies.

2. The seismogenic fault is a concealed secondary fault with 96° strike, 84° dip, and -24° rake, which is located in the movement range of the Ageledaban fault. The co-seismic displacement is dominated by sinistral strike-slip accompanied by a small normal slip component. The slip distribution was concentrated between 0 and 18 km in depth. The maximum slip was 81 cm, which occurred at a depth of $8.5 \pm 0.5 \text{ km}$.
3. The Karakoram strike-slip fault zone has undergone a complex tectonic deformation process: the north side of the epicenter region is experiencing crustal thinning, while the south side is undergoing crustal thickening. This indicates that tension also exists in the central part of the Karakoram fault zone.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s40623-019-1089-4>.

Additional file 1. The model-predicted displacements (a) and the residuals (b) derived from the non-linear inversion.

Abbreviations

ERS: European Space Agency; InSAR: Interferometric synthetic aperture radar; CST: China Standard Time; GCMT: Global Centroid Moment Tensor Project; USGS: United States Geological Survey; GPS: Global Positioning System; NASA: National Aeronautics and Space Administration; LOS: Line of sight; AZ: Azimuth; SDM: Steepest descent method.

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Authors' contributions

JQ processed SAR data and analyzed the results. LJ designed this work and supplemented the conclusions. LL completed calculation and mapping of GPS data, and CL provided technical support and useful advice for InSAR processing. All authors read and approved the final manuscript.

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Availability of data and materials

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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