Seismotectonic deformations of earth crust in Pamir and neighbor areas

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Abstract. We computed seismotectonic deformations (STD) of earth crust in Pamir and neighbor areas. We used ISC (International Seismological Centre, London) catalogue for average STD rate computations, including more than 25000 earthquakes that took place between 1934 and 2016. STD tensor axes’ directions were computed based on hypocenter focal mechanisms of 3049 earthquakes that took place between 1946 and 2018. We have plotted maps showing distribution of STD intensity and number of earthquakes for various ranges of hypocenters depths, and map showing horizontal part of STD tensor. Finally we analyzed different deformation conditions in South Tien-Shan and Pamir.

1. Introduction

Pamir (Figure 1) is a mountain system in Central Asia located between 37 and 39.5 deg. north, 70 and 76 deg. east. The Pamir is a northward-directed prominence of Alpines-Himalaya fold and thrust belt, Pamir turns into Hindu Kush on south-west, into Karakorum (Muztag and Tashkurgantag ridges) on south-south-east and into Kunlun (Tokhtakorum ridge) on south-east. The Pamir is surrounded from the east and west by relatively low and flat relief formations: Tajik depression on the west and Tarim basin on the east. Northern and north-western borders of Pamir conjunct with south-west part of Tien-Shan, the mountain system enveloping northern border of Tarim basin. The border between Pamir and Tien-Shan is marked out quite clear: in eastern part of conjunction it is along Kyzylsu-Kashgar river, in the middle – along Alay valley (between Alay ridge of Tien-Shan and Transalay ridge of Pamir) and then westwards along Kyzylsuu-Sukhrob-Vakhsh river canyons and valleys. There is Fergana valley to the north from Alay ridge separating South-West and North-West Tien-Shan.

Like neighbor mountain systems, the Pamir was formed during collision of Hindustan continent with Eurasia. Punjab prominence of Hindustan continent defined shape and arc structure of Pamir: tectonic division of Pamir [1] is defined by (1) the Exterior Pamir Arc (Vakhsh-Transalay and Darvaz-Karakul faults) outlining Northern Pamir and lasting from Tajik depression to Kunlun; and (2) the Interior Pamir Arc (Tanymas and Rushan-Pshtar faults) separating internal South Pamir from external North Pamir and lasting from Hindukush to Karakoram. The Shape of western parts of these arc is complicated by movements along Panshir (a.k.a. Zebak-Mundzhan a.k.a. Afgan-Southpamir) right lateral strike-slip fault lying to the north from Hindukush ridge. Modern geo-kinematics of the region was studied using GPS technology [2]. The maximal horizontal shortening of earth surface was observed in Pamir-Tien-Shan conjunction zone with direction of shortening changing from sub-meridional in eastern part to north-west azimuth in western part. The Tajik depression undergoes strong sub-latitudinal shortening. Eastern part of Pamir undergoes significant sub-latitudinal lengthening [2].
Figure 1. The main geographical and tectonic elements of Pamir region and epicentre location of earthquakes from ISC catalogue [3] (grey dots – \( M \leq 6 \), green star – \( 6 \leq M \leq 7 \), cyan stars – \( M \geq 7 \)). Red lines – structural faults [1].
2. Source data and methods
To analyze seismic activity and estimate seismotectonic deformations (STD) intensity we have used ICS (International Seismological Centre, London) catalog [3] that includes more than 25000 earthquakes included (Figure 1). Seismicity is concentrated along sides of Ferghana valley, along Tien-Shan-Pamir (the Exterior Pamir Arc) and Tien-Shan-Tarim conjunction zones. Another seismicity concentration zone with maximal amount of strong earthquakes is the Pamir-Hindu-Kush area – south-west part of Pamir and neighbor territory of North Hindu Kush, where the Interior Pamir Arc intersects with Pandshir fault. Eastern part of Pamir may be considered as an aseismic area.

To compute STD tensor we used several databases on earthquake focal mechanisms, total 3049 events (Figure 2B). Some of these data sources have been described in [4].

![Figure 2.](image)

**Figure 2.** (A) Statistical characteristics of the catalogue of focal mechanisms. (B) The epicenter location and focal mechanisms of earthquakes. Different colors of the mechanisms mean different data sources. Inset shows (a, b) azimuth distribution of compression (blue) and tension (red) axes, and (c) distribution of these axes’ plunge angle.

Statistical characteristics of earthquake catalogs. Most earthquakes from the ISC catalog are weak events of magnitudes $2 \leq M \leq 3$ (Figure 3A, a), which mostly took place after 2000 (Figure 3A, b). The most of them have depth of 0-40 km; also there are some distribution density peaks with depth between 70 and 250 km (Figure 3A, c). The most of earthquakes with known focal mechanisms also have magnitudes of $2 \leq M \leq 3$ (Figure 2A, a). They are unevenly distributed the time; time period between 1980 and 1995 is the most statistically representative (Figure 2A, b); the most of earthquakes have depth between 0 and 40 km (Figure 2A, c).

Statistical characteristics of principal stress axes’ direction (Figure 2B, inset) show certain patterns of deformational processes. For the studied area the azimuth of compression axes changes from north-west to north. This matches well with past researches [5]. 57 % of earthquakes have compression axis plunge less than 30 degrees; as regarding to tension axis, the percentage of such events is 38%.

To estimate depth-wise distribution of earthquakes we have plotted integral projections of hypocenters’ locations to vertical planes with slicing along west-east (Figure 3B) and along north-south (Figure 3C) directions. For each direction. We have made 2 slices. These plots revealed that among the ISC catalogue deep (70-250 km) earthquakes were located within Pamir-Hindu-Kush area and the very most of all other earthquakes had depths in range 0-40 km. According to [6] in Pamir-Hindu-Kush, earthquake hypocenters are located in the upper mantle at depth between 100 and 300 km. This focal area is interpreted as continental lithosphere subduction zone [7-9]. Detail geometry of middle-deep
Pamir-Hindu-Kush earthquakes distribution is given in [10]. The depth of earthquakes with known focal mechanisms varies between 0 and 90 km, but most of them are within the range 0-40 km.

![Figure 3. (A) Statistical characteristics of the ISC catalogue. (B), (C) – integral projections of earthquakes to vertical planes. (B) – slicing along west-east direction, (C) – along north-south direction. Black dots are ICS earthquakes, red dots – focal mechanism catalogs’ earthquakes.](image)

We computed average STD rate per year (intensity) in the studied area in overlapping grid cells of size 1.0° along both latitude and longitude with 0.5° step between cell centers. For every grid cell the STD intensity is computed as a sum of its earthquakes’ scalar seismic moments divided by the product of geometric volume, time span and shear modulus [11, 5]. To calculate scalar seismic moment for given magnitude we used the formula from [12]. We varied depth range for all cells by the manner described below. We also counted number of earthquakes belonging to each grid cell.

Then we determined direction of STD tensor for each possible cell of the same grid. Computation of STD tensor involved the weighted summation of focal mechanism matrices of all earthquakes within the cell with known focal mechanisms. Statistical weight of each event was assigned according to [13]. The result of computation a plot at the centre of each cell. To draw the STD tensor orientation we use STD modes classification with 11 modes introduced by S.L. Yunga. The classification has been described in [4, 14-16].

### 3. Results

To take into account depth-wise distribution of earthquakes (Figure 3B, 3C) we computed STD intensity for various depth ranges: the whole seismic layer 0-250 km (Figure 4A, a), crust earthquakes one 0-40 km (Figure 4A, b) and the layer of deep seismicity 40-250 km (Figure 4A, c). For each layer we plot also a number of earthquakes located within each cell. The computations for whole seismic layer 0-250 km (Figure 4A, a) indicated that the maximum of STD intensity (61.4E-9 per year) lies within and near the Garm polygon (71° East, 39.5° North). The centre of Pamir-Hindu-Kush area (71° East, 36.5 North) has STD intensity of 47.4E-9 per year; a little bit less intensity of 36.9E-9 per year is in Tien-Shan, to the east from Alay ridge. So, STD intensity within Pamir and Tien-Shan conjunction zone has maximum in its eastern and western parts, and local minimum in the middle (Figure 4A, a). While overall maximum of STD intensity is in western part of the conjunction zone, the maximal concentration of seismicity (maximum number of earthquakes per cell) is in eastern part of the zone, within eastern half of Alay valley (Figure 4B, a).
Figure 4. Distribution of (A) decimal logarithm of STD intensity and (B) number of earthquakes in the computation cell for different depths: a – 0-250 km; b – 0-40 km; c – 40-250 km.

The most of the area studied has STD intensity of no more than 2.0E-9 within depth range of 0-40 km per year (Figure 4A, b). STD intensity maxima are in abovementioned parts of Pamir and Tien-Shan conjunction zone; with the value of 384.0E-9 per year in western part and of 232.0E-9 in the east. This is about 10 times more than that in the previous 0-250 km model. Areas like sides of Tajik depression and Ferghana valley, Middle Pamir and North-East Tarim have significantly smaller estimations of STD intensity.

Considering simple number of earthquakes the zone of their maximal concentration contains eastern ends of Ferghana basin, Alay ridge, Alay basin and Transalay ridge (Figure 4B, b). For depths more than 40 km (Figure 4A, c) we clearly observe only one STD intensity maximum (64.0E-9 per year) in the central part of Pamir-Hindu-Kush area. Seismic events concentration maximum is in the same place (Figure 4B, c); the events mostly have depths of more than 75 km, reaching sometimes 250 km (Figure 3A).

The plots of STD intensity distributions versus depth ranges have showed that location of intensity maximum is different for different depth layer considered. The reason is that not only crustal but also deep seismicity takes place in the region at hand.

STD direction map (Figure 5). The orientation of STD tensor at every cell is displayed with a sign showing direction of horizontal deformation components and their fraction (part) in the whole tensor.
The sign consists of two axes, each axis may be a narrow rectangle (horizontal compression) or a pair of spreading arrows (horizontal tension). In most cases compression along one axis is combined with extension along the other one. Length of plotted axes shows fraction (part) of horizontal deformation along the axis in the whole tensor; it does not depend on the above-discussed STD intensity. The orientation of the rectangle and arrows shows the azimuth of compression and tension axes. The signs are colorized differently showing their STD mode defined by fraction of both horizontal compression and horizontal tension in the STD tensor according to classification on inset of Figure 5 [4, 14-16].

Figure 5. STD tensor orientations map. The Garm polygon is contoured with grey rectangle. Inset shows classification of STD modes [4, 14-16].

We used earthquakes data from focal mechanism catalog in processing to get STD tensors. These earthquakes have depths 0-90 km, mostly between 0 and 40 km (Figure 2A, 3B, 3C). This means that STD tensor orientation map (Figure 5) characterizes depth range 0-40 km.
Analysis of STD modes and axes azimuth in different areas is presented in Table 1. Blue color of first column means overall horizontal compression deformation, brown color means horizontal tension. Color of text in second column matches STD mode color in Figure 5.

| Area | STD mode | Compression axis azimuth |
|------|----------|--------------------------|
| South Tien-Shan Tajik depression Garm polygon West end of Tarim basin and neighbor mountains | Transitional mode between vertical shift and horizontal compression, horizontal compression, transpresion. Transitional mode between vertical shift and horizontal compression. Transpresion Transpresion Transition mode between vertical shift and horizontal compression, oblique strike-slip, transpresion. | North to north-west. West, north-west. North-west. North, North-north-east. |
| North Pamir | Horizontal strike-slip | North-north-west. |
| Central and South Pamir | Horizontal strike-slip, oblique strike-slip, transitional mode between horizontal tension and strike-slip, horizontal tension, transitional mode between vertical shift and horizontal tension, transitional mode between vertical shift and horizontal compression. | North-north-west. |

The compression axis lies near-horizontally on most parts of the studied region; its direction changes from northern (in eastern part of the region) to north-western (Turkestan ridge) or even western (Tajik depression). The tension axis is oriented sub-vertical in Tarim, Tajik depression, Turkestan ridge and Garm polygon; in Pamir (both Northern, Central and South) its direction changes to sub-horizontal in Pamir (both Northern, Central and South). The STD mode also varies widely: areas around Pamir (first four rows in Table 1) undergo horizontal compression with some component of horizontal strike-slip while Pamir itself undergoes mostly horizontal and oblique strike-slip having even some spots with large horizontal tension components.

4. Conclusion

We studied stress-strain state of Pamir-Tien-Shan region by computing spatial distribution of seismotectonic deformations (STD). We computed STD intensity on the base of ISC catalog, and on the focal mechanisms data on STD tensor orientation (3049 records). Vertical cross-sections show hypocenter depth distribution along latitude and longitude. For hypocenter depths below 40 km the STD intensity maximum is on eastern and western ends of Pamir and Tien-Shan conjunction zone; for depth more than 40 km it is in central part of Pamir-Hindu-Kush area. Distributions of earthquakes’ amount have their maxima in approximately similar locations. For the region at hand the compression axis direction changes from sub-meridianal in eastern part to north-western and even western in western part; there is a wide variety of STD modes. The areas around Pamir: Tien-Shan-Tarim conjunction area, Alay and Turkestan ridges, Tajik depression and Garm polygon undergo horizontal compression. There is mostly horizontal strike-slip in the central part of Northern Pamir while a horizontal strike-slip exists together with horizontal extension and oblique STD modes in Central and South Pamir. We can conclude that a wide variety of deformation processes’ types is in the region of presented research.

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