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Crustal Deformation Revealed by GPS in Greater Caucasus, Azerbaijan

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Introduction and Background

Azerbaijan is located in the zone of active collision between two continental lithospheric plates: the African and Eurasian plates. The plates' tectonic reconstructions show that the collision between the Arabian and Eurasian plates has been in progress during the last 10–30 Ma . The velocity of the northward motion of the Arabian Plate relative to the Eurasian Plate is more or less constant since the onset of the collision and approximately equal to 20 mm per annum. According to these reconstructions, the Arabian Plate moved away from its initial position by 200–600 km to the place previously occupied by the continental Eurasian lithosphere. This continuing "invasion" of the Arabian Plate into the Eurasian Plate determines the lithospheric shortening along the Main Caucasian Thrust (MCT), which extends in the meridional direction, and horizontal displacement of the lithosphere. Being responsible for crustal deformations, these regional tectonic processes cause earthquakes, which are historically documented throughout the entire Caucasus. This work is dedicated to the investigation of the rate of crustal deformations in Azerbaijan based on the GPS measurements and its relationship with seismicity and mud volcanism.

Results of GPS observations

The GPS network in Azerbaijan was deployed by the combined efforts of the Institute of Geology of the Azerbaijan National Academy of Sciences and Massachusetts Institute of Technology in 1998–2012. In most sites, the measurements were carried out 3–6 times. The network geometry and location of the measurement sites were selected according to the neotectonic structure of the region in such a way as to fully characterize the relative displacements of its individual elements and general deformation of the crust. As of now, 22 GPS sites of periodic observations and three permanently operating CGPS stations (Baku, Sheki and Neftchala) function in Azerbaijan.

The GPS data processing with an estimation of the errors was carried out with the use of the GAMIT/GLOBK software designed at the Massachusetts Institute of Technology.

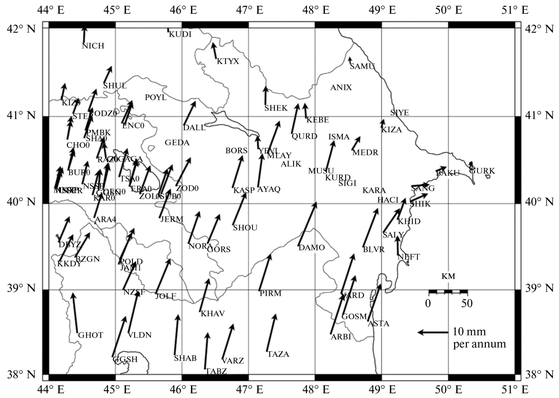


Figure 1.The map of GPS site velocities in the studied region. The data on the velocities of GPS sites located in Azerbaijan are borrowed from (Nilforoushan et al., 2003; Masson et al., 2006; Reilinger et al., 2006).

Concerning the coordinate system used in the GPS measurements, we note the following point. Initially, the measured data were processed in the International Terrestrial Reference System 2000 (ITRF 2000) with the use of 49 stations of the International GNSS geodynamic survey (IGS). In other words, instead of calculating the velocity vectors relative to a single GPS site, we referred the vectors to their whole set, which is temporally more stable compared to each particular GPS site. The random walk noise of 1 mm per annum was also taken into consideration when calculating the velocity errors for each site. For easier interpretation, the velocities are eventually shown in the fixed Eurasian coordinates. As a result of the calculations, for each site we determined the displacement velocity of each component averaged over the entire observation period. Thus, the initial data used for the analysis of the deformation rates represent the field of velocity vectors derived from the GPS measurements for the period 1998 to 2012. The table presents the coordinates and velocities of the horizontal displacements of GPS sites in Azerbaijan and adjacent regions.

Figure 1 shows the map of GPS site velocities for Azerbaijan and adjacent regions, which was used for calculating two dimensional deformations. The arrows in the figure indicate the directions of the velocity vectors, and their lengths characterize the magnitudes of the velocities in accordance with the scale given in the right bottom corner of the map.

The GPS site velocities estimated by minimization are shown in the Eurasian coordinate system. The errors of site velocities are typically below 0.6 mm per annum (1σ), which makes it possible to estimate the convergence across the Caucasus mountainous system with relatively high accuracy (i.e., the error makes up 5% of the total conver gence velocity). The velocity field derived from GPS observations clearly demonstrates the NNE crustal surface motions in the territory of Azerbaijan and adjacent regions of the Lesser Caucasus relative to Eurasia. The most remarkable feature of the velocity field is the velocity decrease in the observation sites located orthogonally to the Main Caucasian Thrust (MCT) (i.e., between the KURD and MEDR, BILE and SHIK sites). The GPS sites located along the thrust exhibit the westward decrease of site velocities. The NNE motion of the Earth's surface is interpreted as one of the factors responsible for the accumulation of stresses on this thrust. Besides, there is a trend of horizontal displacement within the Kura depression and Lesser Caucasus, where the velocity increases from the west to the east along the strike of the mountain chain.

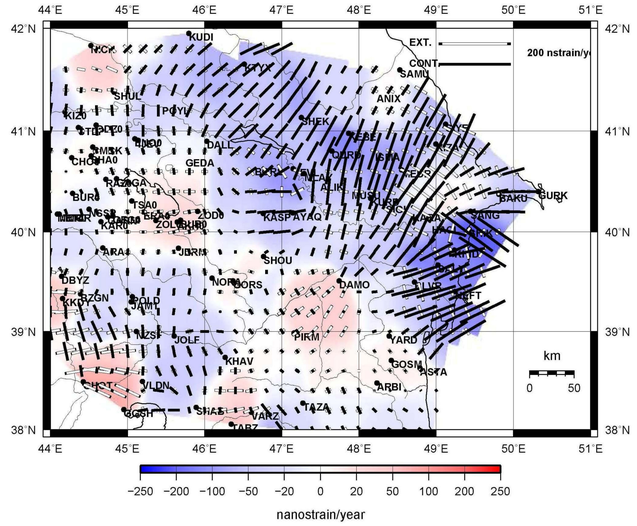


Figure 2. The orientation of the compression/extension axes and the field of dilatation rate according to the GPS data (nanostrain, 10^{-9}).

The strain state in the studied region

Figure 2 shows the distribution of strains in the studied territory calculated by the method of Shen et al. (1996). It can be seen that, although the predominant geodynamical regime is an overall compression, the strain distribution across the Azerbaijan is nonuniform. The compression is observed in the Greater Caucasus, Gobustan, Kura depression, Nakhchyvan Autonomous Republic, and adjacent regions of Iran. The compression axes indicate that crustal shortening in the Greater Caucasus region occurs in the S–NE direction, which is almost meridional in the Shamakhy area (MEDR). The maximum strain rate (about 200 × 10^{-9} per annum) is observed in the area of the SHIK site (Shykhlar), where the compression axis sharply changes its orientation for SE–NW (in the south of the Gobustan and northern part of Nizhnyaya Kura structural zones). In the region of the towns of Salyan, Bilyasuvar, and Neftchala, the compression axis also sharply turns northeast. The zones of the crustal extension are revealed within the Lesser Caucasus in the Gyadabei (GEDA) and Shusha (SHOU) areas and in the zone between the DAMO and PIRM (Iran) GPS sites. In these zones, the dilatation rate amounts to up to 100 × 10^{-9} per annum. Figure 2 shows that, alongside with the areas of compression and extension, the strain field also contains the zones where the strain rates are low (< 5 × 10^{-9} per annum). These zones comprise the Caspian–Guba area (ANIX and SAMU sites) and northern Gobustan (or eastern part of the Zagatala–Govdag structural zone). In these zones, the extension almost entirely compensates the compression.

Methodology

In order to determine the velocity field of horizontal deformations on the territory of Azerbaijan from the GPS data, we used Shen's method (Shen et al., 1996) and the program of Sagiya et al. (2000).

$$\begin{pmatrix} U \\ V \end{pmatrix} = \begin{bmatrix} 1 & 0 & \Delta x_i & \Delta y_i & 0 & \Delta y_i \\ 0 & 1 & 0 & \Delta x_i & \Delta y_i & -\Delta x_i \end{bmatrix} \begin{bmatrix} u \\ v \\ \dot{\varepsilon}_{xx} \\ \dot{\varepsilon}_{xy} \\ \dot{\varepsilon}_{yy} \\ \omega \end{bmatrix} + \begin{pmatrix} \varepsilon_x^i \\ \varepsilon_y^i \end{pmatrix} \quad (1)$$

$$\varepsilon_x^i = \sigma_x^i \exp(\Delta x_i^2 / 2D^2)$$
$$\varepsilon_y^i = \sigma_y^i \exp(\Delta y_i^2 / 2D^2) \quad (2)$$

$$\Delta = \dot{e}_{xx} + \dot{e}_{yy} \quad (3)$$

The components of the horizontal velocity of the displacement (u, v), the strain rate tensor components (e_{xx},e_{xy},e_{yy}), and rotation velocity (ω) at the arbitrary point with coordinates (x, y) are linked with the displacement velocity (U, V) at the observation point (X, Y) by the above relationships.

$\sigma_{x,y}^{i}$ - original observational error. $(\varepsilon_x^i, \varepsilon_y^i)$ - are the observational errors.

Δ - dilatation rate. D - Distance Decaying Constant

The distribution of earthquake epicenters

Figure 3 shows the distribution of seismic events with M ≥4 that occurred from 1998 to 2012 against the map of the strain rates. The distribution of the epicenters is based on the data of the Republic's Center of Seismological Surveys of the National Academy of Sciences of Azerbaijan, Geophysical Survey of the Russian Academy of Sciences, and open source data of the international seismological centers such as EMSC and IRIS.

As follows from the figure, the epicenters of the strong earthquakes (M ≥ 5) that occurred from 1998 to 2012 are typically confined to the gradient zone of the deformations.

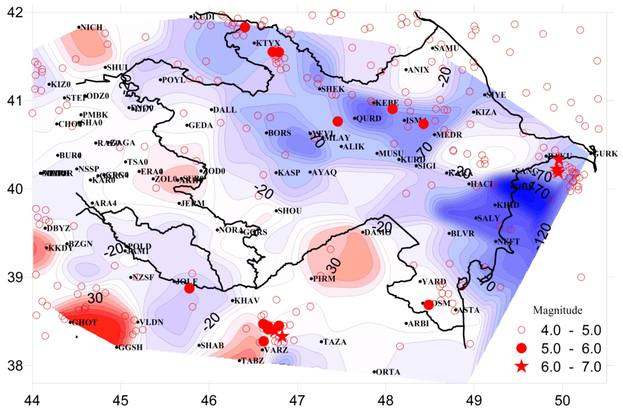


Figure 3.The epicenters of the earthquakes with M ≥ 4 and the distribution of the rates of strain (1998–2012).

The analysis of mud volcanic activity

As is known, Azerbaijan is a classical region of the formation and evolution of mud volcanism. In terms of the number of mud volcanoes, their morphological diversity, activity, and volume of the discharged combustible gas, this region has no analogs in the world. For understanding the mechanisms of the formation and subsequent activity of mud volcanoes, it is important to explore their relationship with geodynamic processes. For this analysis, in Fig. 4 we present the map of the distribution of active (erupting) mud volcanoes combined with the map of the crustal strain rates (Fig. 4). The data on the eruptions of mud volcanoes in Azerbaijan are borrowed from (Aliev et al.,2009). The figures in the map correspond to the following volcanoes and the number of the eruptions (indicated in brackets): 1, Gamandag (5); 2, Karasu Ada (5); 3, Sangi Mugan Ada (5); 4, Agnokhur (5); (5) Gaidzha (5); 6, Shakikhan (west) (5); 7, Durandag (5); 8, Akhtarma Pashaly (6); 9, Chapylmysh (6); 10, Airanteken (6); 11, Goturdag (6); 12, Dashgil (6); 13, Uchtepe (7); 14 Pilpile Buzovna Banka (7); 14, Bozdag Gyuzdek (8); 16, Otmanbozdag (8); 17, Chigildeniz Banka (8); 18, Nardaran Akhtarma (8); 19, Akhtyrma (8); 20, Bakhar (8); 21, Bozdag Gobu (9); 22, Gil Ada (10); 23, Aiaz Akhtarma (10); 24, Toragai (10); 25, Gushchu (12); 26, Keireki (17); 27, Shykhzairli (21); and 28, Lokbatan (23).

As follows from the figure, a distinct correlation between these two parameters is not observed. Nevertheless, we note the remarkably unusual patterns of activity of two mud volcanoes (Eastern Cheildag and Goturdag) located within the zone of maximum compression revealed in the eastern coastal part of Azerbaijan. These processes result in the heaving out of the clay masses in the Eastern Cheildag Volcano, where they protrude to the surface in the form of a diapir; in the Goturdag Volcano, the clay mass is squeezed out in the same way as toothpaste is squeezed from a tube with its subsequent flowing down the slope. In both situations, the process alternately becomes stronger and weaker. Using the statistical analysis of the markers of the volcanic stresses, these authors estimated the presentday directions of maximum regional horizontal stresses oriented approximately eastward at 30°.

It would be more reasonable to relate the described examples of the unusual activity of the Eastern Cheildag and Goturdag mud volcanoes to the manifestations of active vertical deformation processes, which may result from the action of the horizontal compressive forces.

Thus, the analysis of the relationships between the contemporary deformation processes and mud volcanic activity overall demonstrates the predominance of vertical displacements, which may result from the horizontal compression. As far as the factors responsible for the eruptions of mud volcanoes are concerned, it is most likely that the leading role here is played by the intensity of the gas formation in the interior, while the horizontal strains act as triggers.

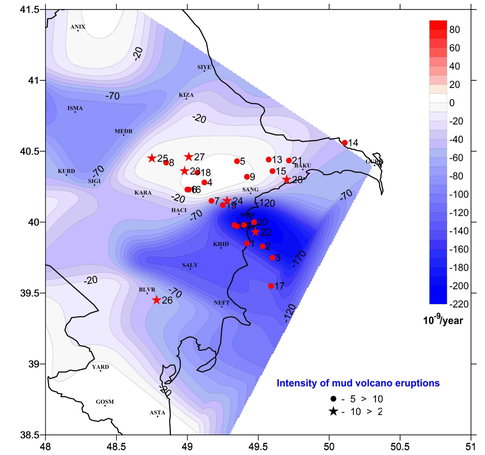


Figure 4. The distribution of the strain rates and active mud volcanoes in Azerbaijan.

Conclusions

The analysis of GPS data for the territory of Azerbaijan and neighboring countries (Iran, Georgia, andArmenia) reveals the heterogeneous patterns of strain field in the region. The increase in the number of GPS stations would promote increasing the degree of detail in the reconstructions of the deformation field and identifying the microplate boundaries. The compression regime is observed in the Greater Caucasus, Gobustan, Kura depression, Nakhchyvan Autonomous Republic, and adjacent areas of Iran.

The compression axes indicate that crust shortening within the Greater Caucasus is oriented in the S–NE direction. The maximum strain rate (approximately 200 x 10^{-9} per annum) is observed at the Shykhlar area (SHIK site), where the compression axis sharply changes its direction for SE–NW.

The zones of extension are confined to the Lesser Caucasus and adjacent areas of Iran. In these zones, the dilatation rate reaches 100 x 10^{-9} per annum. The spatial distribution of the earthquakes with M>=5 indicates that they are largely confined to the gradient zones of the crustal strain field.

The intensity of gas production in the Earth's interior is the predominant factor responsible for the eruptions of mud volcanoes, while horizontal deformations are most likely to play the role of triggers.



Figure 5. Dashgil mudvolcano, Alat settl., Baku

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