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Comparative analysis of crustal strain deformation obtained from GNSS data with geological measures

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SUMMARY

The creation and development of local GNSS networks, as well as the long-term filling of databases with high-precision coordinate solutions and estimates of the displacement velocities of GNSS stations, made possible to conduct geodynamic studies at the local level. Based on homogenous time series of GNSS stations in the IGb08 reference frame for the period from 1997, December 7 to 2017, January 28 acquired at the GNSS Data Analysis Centre of the MAO NASU were used to obtain crustal strain deformations on the territory of Ukraine. The main parameters of the Earth's surface deformation are the strain ellipses and rotation. The axis of the ellipse is the deformation parameter characterizing the manifestation of compression and/or extension of the Earth's surface. The rotation parameter demonstrates the translational-rotational movements of individual geoblocks that can be caused by their reaction (response) to the uneven rotation of the Earth. On the basis of the lineament zones, areas with dominant deformation processes were identified. The results with the heterogeneity to the Moho surface and longitudinal seismic wave velocities were compared.

Introduction

At the present stage of science progress in the world Global Navigation Satellite Systems (GNSS) are used for a wide range of scientific tasks, in particular, in geodesy, geodynamics, cartography, cadaster, meteorology, etc. This method does not depend on many external factors, such as weather conditions, and provides a high level accuracy of satellite observations at permanent GNSS stations. GNSS observations accumulated over a long period of time and the precise coordinates make possible to obtain high-precision coordinate time series. The velocity vectors for each GNSS station can be determined using the homogeneous time series. Such results for a long period of time can be useful for geodynamic research (Caporali et al., 2019), post-seismic deformation after earthquake (Barut et al., 2016), mining subsidence (Lian et al., 2020), local dam deformation (Savchyn and Pronyshyn, 2020), etc. The creation and development of local GNSS stations made it possible to calculate the parameters of the Earth's surface deformation to conduct geodynamic studies on the local level.

The "deformation" is a difference between an initial and a final state. In the measuring of geology, strain is the distortion of Earth's crust and can be seen in rocks under stresses long ago or measured with GNSS as it happens nowadays. Segments of the crust change their shape—they are strained—but they also move as a block ("translation") and spin as a block ("rotation"). Strain, translation and rotation comprise a "deformation". The axis of the strain ellipse is the deformation parameter characterizing the manifestation of compression and/or extension of Earth's surface. Values of extension and compression are represented by semi-major and semi-minor axes of the strain ellipse, respectively. The rotation parameter demonstrates the translational-rotational movements of individual geoblocks that can be caused by their reaction (response) to the uneven rotation of the Earth. Strain is a dimensionless number to express strain rate as some number "per year". More detailed information about the algorithm of strain rates calculation can be found in (Shen at al., 2015).

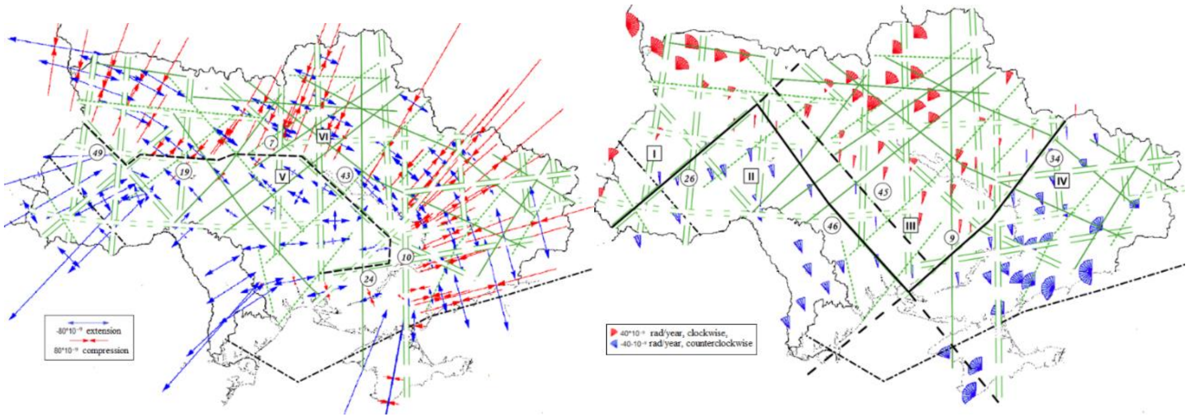
Homogenous time series of GNSS stations in the IGb08 reference frame for the period from 1997, December 7 to 2017, January 28 were received at the GNSS Data Analysis Centre of the Main Astronomical Observatory of Ukraine (Khoda, 2020). After studying of these time series of 166 coordinate sets with observation periods more than three years were defined. Stations that had observations shorter than three years were rejected. After that, homogeneous coordinates time series and the velocities values from 108 GNSS stations were used to obtain crustal strain deformations on the territory of Ukraine (Ishchenko, 2018). The crustal strain was determined using the GeoStrain software (Goudarzi et al., 2015).

On the Figure 1-a red arrows indicate extension, while blue arrows – compression of the area of study. On territories can be clearly defined that extension of Earth's surface along both axes of the strain ellipse are dominated on south and southwestern part. The territory of the mixed type – extension/compression along each axis are dominated on north, northeastern and north northwestern parts of Ukraine.

On the Figure 1-b red marks define clockwise, blue – counterclockwise rotation. Two identical blocks with some geological processes, separated by the block with the opposite rotation can be clearly identified. The rotation parameters are clearly traced in the form of four morphostructures (geoblocks) – these are northwest and northeast rotating clockwise opposite southwest and southeast.
The purpose of this article is to identify correlations and possible relationships between the latest movements of Earth's crust, which are as close as possible in the time interval and precede modern movements of Earth's surface, with deformation parameters obtained from GNSS observations.

The initial task is to find possible manifestations of lineament zones for the detrminating boundaries of geoblocks (strain rates patterns). The following comparative analysis of the strain rates patterns was performed in comparison with a Moho, profiles and seismic waves.

Lineament and strain rates patterns. At the first stage of the comparative analysis, the authors decided to use a more flexible system of lineament zones (Verkhovtsev, 2008) to determine the boundaries of transitions of different types of deformation instead of a clearer and unambiguous fault system in Earth's crust. Lineaments have a certain autonomy and independence of manifestation, it does not always and not everywhere coincide with the structures known from geological and geophysical data, often exceed the faults in dimension, including them in the form of fragments in the lineament network. Lineaments in quantitative terms are more numerous than known faults, they are characterized by transit distribution, which is expressed in the through, sometimes independent of the location of rock complexes spatial arrangement. Figure 1 shows diagrams of the parameters of the deformation of the Earth's crust, identified in certain groups based on lineament zones.



a) *b)*

Figure 1 *Diagrams of the parameters of the deformation of the Earth's crust identified in certain groups based on lineament zones.*
a) strain ellipses (blue arrows – extension, red – compression) ,b) rotation (red marks – clockwise, blue – counterclockwise).Frame elements of lineament zones: 1 – trans-regional, 2 – regional of 2nd orderMorphotypes of lineaments: 3 – discharges, 4 – throws. The numbers in the circles are the numbers of lineament (the author's numbering has been saved (Verkhovtsev 2008)): 49 – Sokal'sk-Odesa, 19 – Yavoriv-Vovchansk, 7 – Shchors'k-Mykolaivka, 10 – Kotelev'sk-Nizhnosirogoz'k, 24 – Kakhovka-Berdyansk, 43 – Chernobyl-Mariupol, 26 – Khust-Korets, 46 – Kamin-Kashyrsk-Yalta, 23 – Bashtank's-Telmanivsk, 9 – Druzhbivs'k-Ordzhonikidze and 34 – Magdalinivs'k-Meref'yans'k, 45 – Rakitno-Novoarkhangelsk.Solid line is the boundaries between geoblocks of prevailing counterclockwise rotation (II and IV blocks) and clockwise rotation (I and III blocks) of the Earth's surface. Dashed line is the boundary between the areas of prevailing extension (V) and compression (VI) of the Earth's surface. Dashed line with dots – border of East European Platform.

The newest active linear systems form two dominants (orthogonal 0° ÷ 90°, ± 5° and a diagonal of 40–50° ÷ 310–320°) and two diagonal subordinates (30–35° ÷ 300–305 ° and 65–70° ÷ 335-340°) systems and are represented by rectilinear conjugate and mutually perpendicular segments of the dominant and subordinate directions. In particular, the region of predominant compression of Earth's surface can be separated from the region of its predominant giving extension by the following zones of lineament (from west to east): 49 – Sokal'sk-Odesa, 19 – Yavoriv-Vovchansk, 7 – Shchors'k-Mykolaivka, 43 – Chernobyl-Mariupol, 10 – Kotelev'sk-Nizhnosirogoz'k and 24 – Kakhovka-Berdyansk. In a first approximation the direction of the strain axes of maximum compression is perpendicular to the edges of the areas: from northern directions in northwestern Ukraine to sub-latitudinal and latitudinal in the east of the territory.

For areas of left-right rotation of the earth's surface, the articulation line can be carried out by: 26 – Khust-Korets, 46 – Kamin-Kashyrsk-Yalta, 23 – Bashtank's-Telmanivsk, 9 – Druzhbivs'k-Ordzhonikidze and 34 – Magdalinivs'k-Meref'yans'k. It should be noted that the intensity of rotational movements increases from the separation zone to the central parts of morphostructures (potential geoblocks). This may indicate that the cause of their rotation is not the rotation of one of the megablocks, in this case the maximum values should be confined to the contact zone itself. It should also be noted that the junction zones of the regions of prevailing compression-expansion and clockwise and counterclockwise rotations are, as it were, in antiphase to each other.

Thus, a boundaries for four morphostructures (geoblocks) are singled out by lineament zones of north-east and north-west strike for both type of strain rates patterns and can be separated as I and III (areas of clockwise rotation) as well as II and IV (areas of counterclockwise rotation). Approximate boundaries are established with reference to lineament for territories where compression and extension are prevailing and can be separated as V (area of extension) and VI (area of compression) blocks.

Comparison of the Moho layer and seismic waves with strain rates patterns. Comparison of the obtained parameters of the deformation of the Earth's surface from GNSS data with the heterogeneity to the Moho surface was done. Figure 2 is presented a variant of the relief profile of the bottom of the surface, constructed according to the scheme of the deep structure of the lithosphere of the southwestern part of the East European Platform generalization of seismic data with the profiles of deep seismic sounding, including international geotraverses of individual point soundings, as well as data on the thickness of the Earth's surface (Kutas at al., 2018).

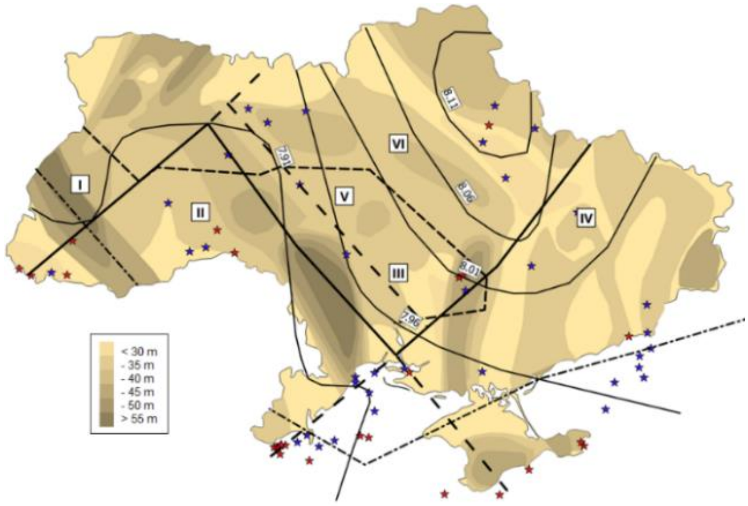


Figure 2 *Scheme of the Moho deps in km and longitudinal seismic wave velocities. Red stars – earthquake epicentres for the last 100 years from the earthquake.usgs.gov database. Blue – local seismicity data for period 2007–2019 years with Mag 3.4–4.9. Solid line is the boundaries between geoblocks of prevailing counterclockwise rotation (II and IV blocks) and clockwise rotation (I and III blocks) of the earth's surface. Dashed line is the boundary between the areas of prevailing extension (V) and compression (VI) of the earth's surface. Dashed line with dots – border of East European Platform.*

The depth of occurrence of Moho discontinuity varies widely – from less than 30 km in the western part of I block to 67 km in the southwestern part of II block. For III and partially for I geoblocks, the average thickness of the Earth's surface has small deviations (40–45 km). It should be noted that for I geoblock along with a thinner crust in the western part, its sharp increase is observed for the northern part of this geoblock. The central part of the III geoblock is characterized by the northwestern strike of Moho, consistent with the strike of the depression, with a sharp decrease in the crust thickness to 35 km. With the transition in the stress of the IV geoblock, the crust thickness increases to 45 and 50 km, respectively.

Additionally, a comparison of the deformation parameters with the longitudinal seismic waves was done. The relationship with the velocities of P (primary) seismic waves at a depth of 50 km were defined in strain rates patterns (Geyko et al., 1998). Namely, for II–IV blocks rotating counterclockwise, lower speeds of seismic waves (7.91 ÷ 8.01 km/s), and for I and III blocks – increased values (7.92 ÷ 8.11 km/s) are characteristic respectively. Fundamentally, such a picture of the velocity distribution is preserved in the upper mantle to depths of 200 km (Tsvetkova et al., 2016). Thus, the relationships in GNSS observations with Moho discontinuity density and seismic waves are observed in analysis.

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