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RECENT MOVEMENTS OF THE EARTH'S SURFACE OF THE CARPATHIAN MOUNTAIN SYSTEM ACCORDING TO GNSS DATA

The purpose of the research is differentiation of recent geodynamic processes within the Carpathian Mountains on the basis of freely available GNSS data. Methodology. The methodology included GNSS data collection, processing and analysis. An algorithm for processing was proposed, which consisted of 5 main stages: transformation of data into an internal format, verification of time series for compliance with requirements, determination of horizontal velocities, division of the GNSS network into triangles, and determination of deformation parameters. Results. This study presents a comprehensive analysis of recent geodynamic processes based on GNSS data freely available from the Nevada Geological Survey. Taking into account the requirements for time series, 50 GNSS stations were selected and processed. In general, absolute and regional velocities were obtained and analysed during 2000–2023. Regional velocities of horizontal movements were used to calculate the deformation tensor and deformation parameters. The results of the study are consistent and correlate well with the studies of other scientists. The obtained results confirm the presence of active geodynamic processes within the Carpathians. Originality. The proposed approach made it possible to estimate the main deformation parameters (value and direction of deformation axes, total shear and dilation) within the Carpathian Mountains. This makes it possible to analyse and predict recent geodynamic processes in the region. Practical significance. On the basis of the calculated values, maps of the distribution of vectors of absolute and regional horizontal velocities, total shear rates, dilatation rates, and rotation rates were constructed.

Keywords: Carpathian Mountain, GNSS stations, horizontal velocities, strain rates, deformation processes.

Introduction

The Carpathians are a mountain system in central Europe, covering an area of approximately 210,000 km^2. As a geologically young European mountain chain, they serve as the eastern continuation of the Alps. From the Danube Gap near Bratislava (Slovakia), they unfold in a broad, crescent-shaped arc about 1,450 km long to Orsova (Romania), in a part of the Danube River valley called the Iron Gates [Kondracki, 2023]. Additionally, the isolated lower chain of the Apuseni Mountains extends north from the Southern Carpathians, closing the Transylvanian Basin from the west. To the west, the Carpathians adjoin the Pannonian Basin, while to the north and east they are surrounded by several highland systems. In the south, they border the eastern mountains of the Balkan Peninsula across the Danube Plain. The Danube valley also generally forms their border with the Alps. Finally, in the northwest is the older (Variscan) Bohemian Massif, which includes the Western and Eastern Sudetes [Mráz & Ronikier, 2016].

The Carpathian mountain system covers the territory of 8 countries: Ukraine, the Czech Republic, Poland, Slovakia, Romania, Serbia and Austria. According to Márton et al. in 2009, the Carpathians belong to the European mountain system, which was formed during the convergence and collision of the European and African plates. They are the result of the evolution of continents and oceans from the Triassic to the Tertiary period. The continental blocks consist of the inner Thyso-Dacian and Alpine-Carpathian-Pannonian (ALCAPA) blocks, as well as the outer European-Scythian-Mesian continental foreland, which forms the arc-shaped shape of the Carpathians [Sandulescu, 1988; Csontos & Vörös, 2004; Schmid et al., 2008; Ismail-Zadeh et al., 2012]. As noted by Szűcs et al. in 2018, the beginning of the main uplift and the stage of the main deformation in the Eastern Carpathians occurred at the end of the Miocene, after a gentle collision of the eastward advancing Tyso-Dacian blocks with the stable European and Moesian platform. The Carpathian mountain system includes 8 parts (Fig. 1), namely: Outer Western Carpathians, Inner Western Carpathians, Outer Eastern Carpathians, Inner Eastern Carpathians, Southern Carpathians, Western Romanian Carpathians, Transylvanian Plateau, Serbian Carpathians.

The Carpathians are a young mountain system, so they are subject to deformations accompanied by frequent earthquakes. According to Braclawska in 2019, most earthquakes are located in the bending zone between the Eastern and Southern Carpathians. Different studies [Sperner et al., 2004; Matenco et al., 2007; Müller et al., 2010] confirm the existence of the seismically active Vrancea zone in the southeastern

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part of the Carpathians. The mountain system significantly affects the climate, weather conditions, flora and fauna of the region, and the presence of seismically active zones significantly increases scientific interest in the study of the Carpathians.

There are many methods of geodynamic research of the territory, for example: laser scanning, radar interferometry, remote sensing, geochemical analysis of soils and rocks, etc. Recently, studies using GNSS methods are gaining more and more popularity, they make it possible to study spatial movements, while guaranteeing a fairly high accuracy of measurements. There are many examples of studies of the Carpathians and their parts using GNSS methods.

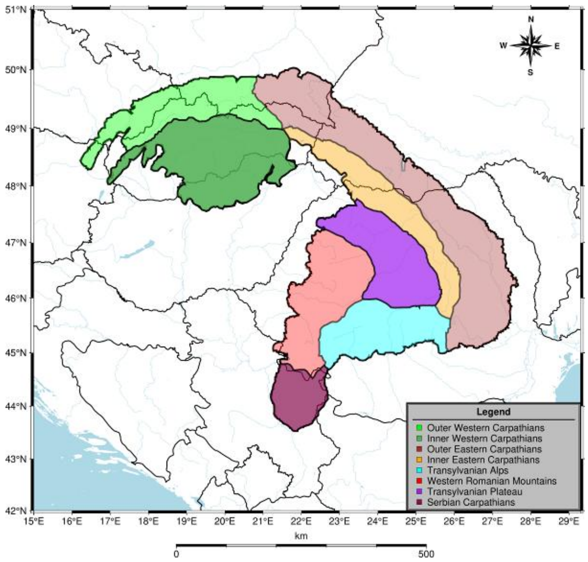

Fig. 1. The diagram of the Carpathian mountain system.

One of the first studies of the Carpathian region based on GNSS data was conducted by Caporali et al. in 2009. The authors investigate kinematics in the Alpine-Carpathian-Dinaric and Balkan region inferred from a new multi-network GPS combination solution. Seven different European networks with a total of 466 stations were considered in the study. It was found that in Transylvania, which is part of the Carpathian arc, the crust is being compressed at a rate of approximately 2.3 mm/year (in ITRF2005) over a distance of 220 km, while in the region of Wallachia and Mezia, located south of the Carpathians, the upper crust is being stretched at a rate of 3.2 mm/year (in ITRF2005) over a distance of 440 km.

Caporali et al. in 2008 investigated the kinematics of Central Europe (including the Carpathians) based on GPS data. In total, data from 95 stations of the CERGOP-2/Environment Project conducted in 2005 were analysed. In the Carpathians, insignificant horizontal velocities were found, indicating the absence of significant intraplate deformations.

A continuation of the described studies is given in [Zurutuza et al., 2019a, 2019b], where the authors analysed the current geokinematics of Central Europe, in particular the Carpathians, based on the Central European GNSS Research Network (CEGRN). They used data from 1229 stations collected over more than 20 years to estimate the rates of horizontal and vertical movements of the earth’s surface. In the profile from Ukraine to Romania through the Carpathians, complex deformation processes were detected, indicating active tectonic processes in this region, which requires further research. Zurutuza et al., 2019b found slight compression in the Carpathians with an east-west velocity decrease of approximately 1 mm/year (ETRF2000), indicating active compressional deformation.

Bednárik et al. in 2016 focused on the study of surface deformation of the Tatras in the Western Carpathians, using GNSS data. The authors identify the problem of presenting complex strain tensor data and propose a new approach, which consists in encoding the three main strain values into color channels (red, green, blue). This allows you to create a color map of the surface strain rate field, where each color represents information about the shape of the strain tensor at a particular point. This research opens up new possibilities for the analysis and understanding of geological processes in mountainous regions and may have important implications for various fields, including geology, geodesy, construction and public safety.

Tretyak & Brusak in 2020 on the territory of the Carpatho-Balkan region makes it possible to confirm the difference in the movements of separate parts of the mountain system. After processing 173 GNSS-stations, the authors constructed vectors of horizontal velocities (in IGS14) and transform to the regional coordinate system. The authors found that the Transylvanian Basin and the Romanian Carpathians have a characteristic south-west direction, and regional velocities range from 0–5 mm/year.

Roštínský et al. in 2020 are exploring the territory of the eastern Bohemian Massif, as well as part of the Western Carpathians. As a result, more than 70 stations were processed, a homogeneous network was created, and the values of recemt regional velocities of horizontal and vertical movement in the Western Carpathians were obtained, which range from from +0.5 to –2 mm/year (in ITRF2008), respectively.

The territory of the Ukrainian Carpathians is explored by Doskich in 2021. The author describes the process of detecting deformations of the earth’s crust using GNSS technologies. As a result, the data of 46 stations were analyzed and processed, vectors of absolute horizontal movements were constructed, the velocities of which is approximately 25–26 mm/year (in ITRF2008), and the deformations of the earth’s crust were calculated using the triangle method.

Porkoláb et al. in 2023 is focused on the territory of the Circum-Pannonian region and includes the Carpathian mountain chain. The horizontal velocities obtained by the author in the IGS14 and transformed into ETRF2000 give an opportunity to note that the movement of separate parts of the Carpathian mountain system occurs at different velocity. The movement of the southern, southwestern part is characterized by the movement of the Transylvanian Basin (3 mm/year) and the Romanian Mountains (up to 1.5 mm/year). At the same time, the Western Carpathians in Slovakia have a very low regional velocity of movement, which varies between 0.1–0.5 mm/year.

Since the analysis of literature sources confirms the presence of active modern geodynamic processes in different parts of the Carpathians, for a comprehensive understanding of the situation, it was decided to analyze recent geodynamic processes within the entire Carpathian mountain system.This work is a continuation of the research started by the authors in 2023 and partially presented in Savchyn & Bilashuk, 2023.

Data

The initial data for the research consists of the coordinates and time series of permanent GNSS stations located within the Carpathian region (IGS14 24-hour final solutions in tenv3 format), available freely on the website of the Nevada Geodetic Laboratory [Blewitt et al., 2018]. In selecting GNSS stations for this study, we adhered to enhanced requirements proposed by Altamimi et al. in 2017, which include:

- The time series of daily solutions from permanent GNSS stations should span more than 3 years.
- Permanent GNSS stations should not be influenced by post-seismic deformations [Altamimi et al., 2016].
- Permanent GNSS stations should be located at a distance of at least 100 km from the boundaries of Bird, 2003, outside the deformation zones of Argus & Gordon, 1996 and Kreemer, Blewitt & Klein, 2014, and far from GIA (Glacial Isostatic Adjustment) regions.
- The time series of daily solutions from permanent GNSS stations should not contain outliers or gross errors exceeding the 3σ threshold (99.7 % confidence).
- Residual error values after processing the time series of daily solutions from permanent GNSS stations should not exceed 1 mm/year.

As a result, 50 permanent GNSS stations were selected for the research, their locations, and statistics are provided in Fig. 2. The small number of selected permanent GNSS stations is due to the difficulty of installing and maintaining stations in mountainous areas, given the complex terrain and logistical challenges. Analyzing Fig. 2, ***a***, it can be noted that there is a relatively high density of permanent GNSS stations in the northwestern part of the Carpathians. However, stations are entirely absent in the Ukrainian and Serbian Carpathians. Only the central part of the mountain system can be considered dense and homogeneous. The formed network has a density of 1 station per 4200 km^2. The average distance between neighboring GNSS stations is 150 km, with a minimum distance of 20 km and a maximum distance not exceeding 300 km.

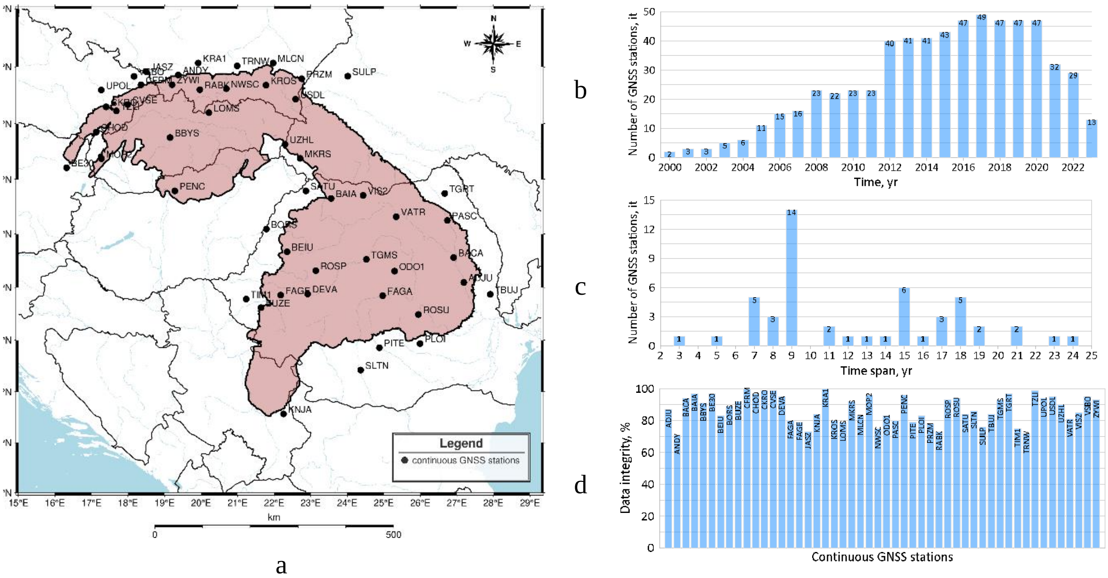

Fig. 2. Continuous GNSS station network of Carpathian Mountain and characteristics (a) of station availability (b), station time span (c) and station data integrity (d).

Until 2020, there was an increase in the number of permanent GNSS stations (especially rapid since 2011), which is associated with the development and direct implementation of GNSS technologies (see Fig. 2, *b*). The sharp decline in the number of stations from 2021 onwards is evidently due to global issues related to the SARS-CoV-2 pandemic.

The heterogeneity of observations over time is identified (see Fig. 2, *c*). For example, 4 permanent GNSS stations (BBYS, PENC, SULP and ZYWI) have a measurement duration of more than 20 years, while there are 2 permanent GNSS stations (BE30 and TZLI) whose measurement duration is less than 6 years. The main group of measurements is characterized by a measurement duration of 9–15 years.

The data integrity of the selected permanent GNSS stations is also different (Fig. 2, *d*) and varies in the range of 70–100 %. The lowest values of data integrity are characterized by permanent GNSS stations: ANDY, JASZ, RABK and TRNW (70–75 %), while the highest integrity is BAIA, BE30, CFRM, CHOD, CKRO, CVSE, DEVA, KRA1, MOP2, PENC, TGRT, TZLI, USDL and VSBO (95–100 %).

Methodology

There are many different methods available for estimating deformations based on data from permanent GNSS stations, the most popular are the least squares collocation method [Caporali, 2003; Caporali, Martin & Massironi, 2003], tensor analysis [Cronin & Resor, 2021] and the finite element method [Alizadeh-Khameneh, Eshagh & Jensen, 2018; Fazilova & Sichugova, 2021]. In this study, we propose a method that combines the division of a plane into triangles using the Delaunay triangulation algorithm [Delaunay in 1934] and tensor analysis [Cronin & Resor, 2021] to estimate deformations.The structure of the proposed algorithm is shown in Fig. 3.

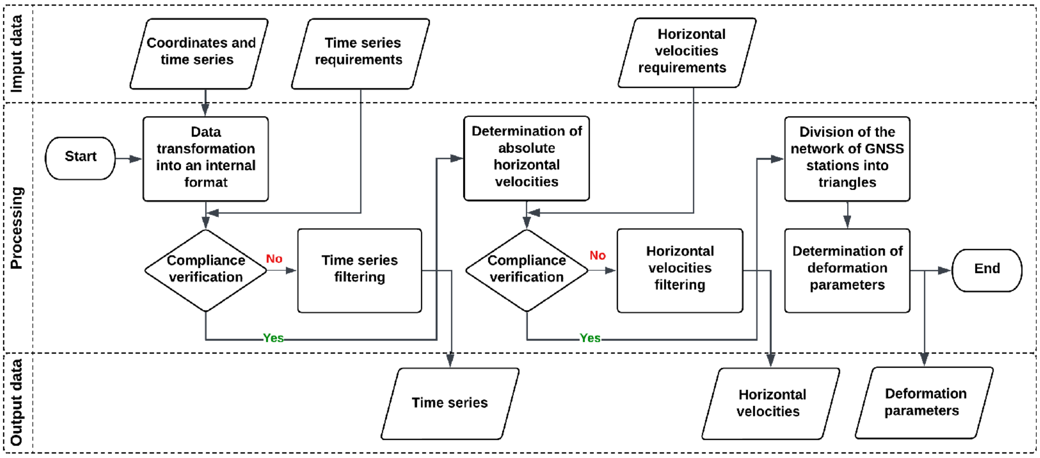

Fig. 3. Algorithm for determining deformation parameters based on GNSS measurement data.

The proposed algorithm consists of 5 main research stages:

1. *Data transformation into an internal format.* At this stage, a matrix is formed that combines the time series of daily solutions from various permanent GNSS stations.

2. *Compliance verification and time series filtering.* The selection of data from permanent GNSS stations is based on criteria for these stations. Time series from permanent GNSS stations with singular gross errors and outliers are filtered out and not included in the processing.

3. *Determination of absolute horizontal velocities.* Earth's surface deformation processes are influenced by many factors, so a more complex model was chosen for determining horizontal displacement velocities, which additionally considers the seasonality of movements:

$$f(t_i) = y_0 + v(t_i) + \\ + \sum_{f=1}^{2} \left[c_f \cdot \sin(2\pi f t_i) + d_f \cdot \cos(2\pi f t_i) \right] + \\ + \varepsilon_y(t_i) \qquad (1)$$

where, t_i – epoch of observation, v – linear velocity of a permanent GNSS station or GNSS point, y_0 – shift of the time series to the initial epoch, $\varepsilon_y(t_i)$ – noise, c_f and d_f – parameters of periodic motion, $f=1$ or $f=2$ – for the annual and half-yearly period, respectively.

Systems of equations composed on the basis of functional dependence (1) are solved separately for each component by the method of least squares, the components of the velocity vectors of horizontal displacements of permanent GNSS stations are determined, and the accuracy of the determined parameters is also assessed.

For a more precise study and better visualisation of the results, the transition from absolute to regional horizontal velocities was made. Due to the fact that the Carpathians Mountains cover an extremely small part of the Eurasian plate on which they are located, it can be assumed that the parameters of movement of this tectonic plate are the same anywhere in the region under study. For this reason, instead of the classical transition to regional velocities associated with the rotational parameters of tectonic plates, it was decided to use a simpler transition based on the following functional dependence [Tretyak & Vovk, 2012]:

$$v_i^{reg} = v_i^{abs} - \frac{\sum_{i=1}^{n} v_i^{abs}}{n}, \qquad (2)$$

where, v_i^{abs} – the absolute component of the velocity vector of the *i*-th permanent GNSS station in latitude and longitude; $\sum_{i=1}^{n} v_i^{abs}$ – sum of values v_i^{abs} at all permanent GNSS stations; n – number of permanent GNSS stations.

4. Division of the network of GNSS stations into triangles. It is known that the deformation parameters of the earth's surface characterize a certain plane, therefore it is advisable to calculate them for the centers of elementary figures into which this plane is divided. The simplest and, accordingly, the most popular method is the division of the plane into triangles according to the Delaunay algorithm (Delaunay triangulation) [Delaunay in 1934]. An example of the use of such a division is given in Kowalczyk, Bogusz & Figurski (2014) for the study of vertical movements and in Tretyak & Vovk (2012) for the study of horizontal movements. The peculiarity of the algorithm is that the division of the plane into triangles occurs in such a way that the circumscribed circle around any triangle does not include any other node of the network, this condition allows to reduce the number of small angles as much as possible. The algorithm for constructing the Delaunay triangulation is quite simple, as it is based on quick operations of checking whether a point is inside the circle described around the triangle. Using Delaunay triangulation at this stage of our algorithm, the network of permanent GNSS stations is divided into a network of triangles with vertices at these stations.

5. Determination of deformation parameters. This study focuses solely on planar deformations, therefore, three main conditions are imposed on the deformation processes:

a) planar deformations are determined in the horizontal plane;
b) neglecting vertical movements does not significantly affect deformation processes;
c) deformations are uniformly distributed within the triangle.

Tensor analysis is utilized to determine deformation processes, and all calculations are conducted separately for each triangle defined in the previous stage.

Let's consider the definition of deformation parameters using the example of a triangle with vertices $1(x_1, y_1)$, $2(x_2, y_2)$ and $3(x_3, y_3)$, as well as determined velocities of horizontal movements (v_{x_1}, v_{y_1}), (v_{x_2}, v_{y_2}) and (v_{x_3}, v_{y_3}) (Fig. 4).

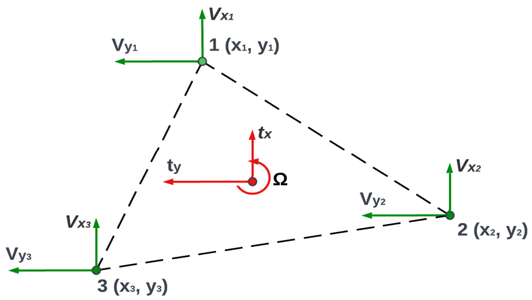

Fig. 4. Scheme of deformations within one triangle.

It is known that deformation processes are the sum of shear deformations, rotation deformations, and shape deformations. Shear deformations mean the parallel movement of the entire triangle relative to the initial system (t_x, t_y). Deformations of rotation characterize the angular speed of rotation of the triangle relative to its center of mass Ω. Shape deformations characterize a change in the shape of a triangle, which can be represented by elements of a two-dimensional deformation tensor $(\varepsilon_{xx}, \varepsilon_{xy} = \varepsilon_{yx}, \varepsilon_{yy})$.

The relationship between the velocities of horizontal movements and deformation processes can be represented as a system of equations [Cronin & Resor, 2021]:

$$\begin{aligned}
v_{x_1} &= (x_1\varepsilon_{xx}) + (y_1\varepsilon_{xy}) - (y_1\Omega) + (t_x) \\
v_{y_1} &= (x_1\varepsilon_{xy}) + (x_1\Omega) + (y_1\varepsilon_{yy}) + (t_y) \\
v_{x_2} &= (x_2\varepsilon_{xx}) + (y_2\varepsilon_{xy}) - (y_2\Omega) + (t_x) \\
v_{y_2} &= (x_2\varepsilon_{xy}) + (x_2\Omega) + (y_2\varepsilon_{yy}) + (t_y) \\
v_{x_3} &= (x_3\varepsilon_{xx}) + (y_3\varepsilon_{xy}) - (y_3\Omega) + (t_x) \\
v_{y_3} &= (x_3\varepsilon_{xy}) + (x_3\Omega) + (y_3\varepsilon_{yy}) + (t_y)
\end{aligned} \qquad (3)$$

In matrix form, the system of equations (3) can be represented as follows:

$$d = G \cdot m$$

or

$$\begin{bmatrix} v_{x_1} \\ v_{y_1} \\ v_{x_2} \\ v_{y_2} \\ v_{x_3} \\ v_{y_3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -y_1 & x_1 & y_1 & 0 \\ 0 & 1 & x_1 & 0 & x_1 & y_1 \\ 1 & 0 & -y_2 & x_2 & y_2 & 0 \\ 0 & 1 & x_2 & 0 & x_2 & y_2 \\ 1 & 0 & -y_3 & x_3 & y_3 & 0 \\ 0 & 1 & x_3 & 0 & x_3 & y_3 \end{bmatrix} \cdot \begin{bmatrix} t_x \\ t_y \\ \omega \\ \varepsilon_{xx} \\ \varepsilon_{xy} \\ \varepsilon_{yy} \end{bmatrix} \quad (4)$$

where d – a data matrix that contains information about the horizontal velocities of the triangle's vertices; m – the strain model matrix, which contains six unknowns; G – the coefficient matrix (named after George Green) that relates d to m using equations (4) [Cronin & Resor, 2021].

The values of the matrix *m* obtained as a result of solving the system of equations (3) and (4) are used to determine the deformation parameters. Within the framework of this work, it was decided to determine: the value and direction of the axes of deformations, general displacement and dilatation. According to Savchyn & Vaskovets (2018), and Savchyn et al. (2020 and 2021) these parameters provide an opportunity to visualize recent geodynamic processes quite accurately.

Value and direction of deformation axes. The maximum (larger) value of the strain axis represents tension, and the minimum (smaller) value represents compression, and they are always perpendicular to each other. The magnitude of the vector indicates the intensity of deformation processes. Calculation of values of deformation axes e_1 and e_2, which are actually the maximum and minimum eigenvalues of the two-dimensional strain tensor, as well as determining the orientation of the main (major) axis of the strains is performed using dependencies [Cronin & Resor, 2021]:

$$e_{1,2} = \frac{(\varepsilon_{xx} + \varepsilon_{yy}) \pm \sqrt{4\varepsilon_{xy}^{2} + (\varepsilon_{xx} - \varepsilon_{yy})^{2}}}{2} \quad (5)$$

$$\alpha = \frac{1}{2} tg^{-1} \cdot \frac{\varepsilon_{xx} - \varepsilon_{yy}}{2\varepsilon_{xy}} \quad (6)$$

Total shear characterizes the horizontal heterogeneity of the deformed area and is an indicator of extensional tectonics [Lazos et al., 2021]. The following relationship is used to determine the total shear [Cronin & Resor, 2021]

$$\varepsilon_{shear} = 2\sqrt{\left(\frac{\varepsilon_{xx} - \varepsilon_{yy}}{2}\right)^{2} + \varepsilon_{xy}^{2}} = e_1 - e_2 \quad (7)$$

Dilation characterizes the relative change in surface area, and identifies regions with active shape deformations, relative expansion (increase in area) or compression (decrease in area). A dependence is used to determine dilation [Cronin & Resor, 2021]:

$$\varepsilon_{area} = \varepsilon_{xx} + \varepsilon_{yy} = e_1 + e_2 \quad (8)$$

Note that the sequence of actions described on the example of one triangle in the proposed algorithm was used for calculations in each triangle built according to Delaunay's algorithm at the previous stage. As a result of the calculations, a matrix containing the deformation parameters of the entire studied area was obtained.

Results

Using the selected data and the mathematical apparatus, in accordance with the proposed algorithm, the necessary calculations were performed and interesting results were obtained. After transforming the data and verifying their compliance with the requirements, using dependence (1), the value of the linear velocities of the horizontal movements of the continuous GNSS stations in the Carpathians was determined (in IGS14). On Fig. 5 shows the map of the obtained absolute horizontal velocities distribution.

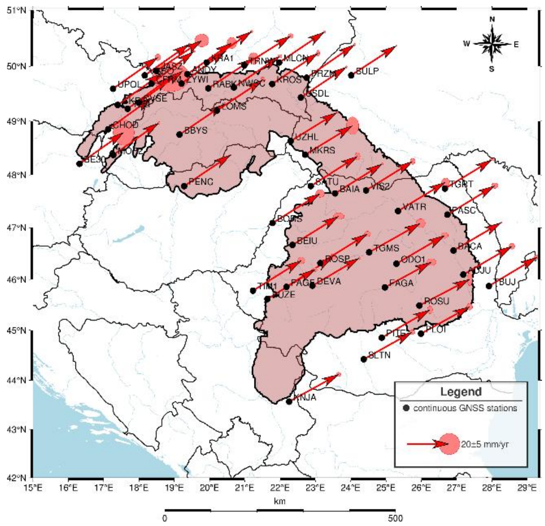

Fig. 5. Distribution of absolute velocity vectors of horizontal movements.

When analysing this map, it can be noted that the vectors of linear velocities of horizontal movements of GNSS stations are directed to the northeast. The values of these vectors range from 25.05 to 28.02 mm/year (in IGS14), they correlate well with previous results presented by Doskich in 2021, in the territory of the

Ukrainian Carpathians, the author determined a velocity of 25–26 mm/year (in ITRF2008).

The average accuracy of determination is at the level of 11 % of the length of the vector (2.87–3.03 mm/year). It is interesting to note that the range of vector values is quite limited. The maximum vector value of 28.02 mm/year was recorded at the TGMS station (Tirgu Mures, Romania), while the minimum value was 25.05 mm/year at the FAGA station (Fegaras, Romania). [Savchyn & Bilashuk, 2023].

Since the absolute velocities of horizontal movements have practically the same direction and a slight difference in magnitude, for further accurate research and better visualization of deformation processes, applying formula (2), the systematic component was excluded and the transition to regional velocities of horizontal movements was made. That is, the absolute component of the velocity vector was calculated, as the average value of the absolute velocities, and excluded from the velocity of each GNSS station.

Fig. 6 presents vectors of regional velocities.

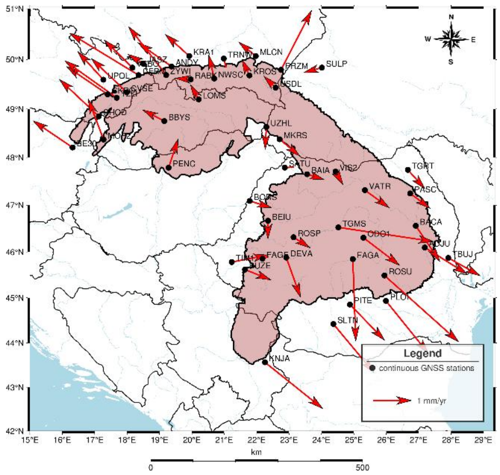

Fig. 6. Distribution of regional velocities vectors of horizontal movements.

After analysing this map, it can be noted that the directions and magnitude of horizontal movements differ significantly in different parts of the Carpathians. For example, the vectors in the northern part are directed to the north, northwest, in contrast, in the south, the directions are diametrically opposite and point to the southeast. It is worth noting the anomalous size and direction of movement of the PRZM station, which clearly stands out against the background of nearby stations. At the same time, the movements in the central part are insignificant, so it can be noted that the process of stretching the mountain system from the north and the south is underway. The values of regional velocities range from 0.11 to 2.47 mm/year (in IGS14 transform to the regional coordinate system). The maximum value of the vector was recorded at the ROSU station of 2.47 mm/year, and the minimum value of 0.11 mm/year at the FAGE station. The obtained results of the directions of movement and the values of regional velocity vectors confirm previous studies and correlate well with the results of the authors of Roštínský et al., 2020 (in ITRF2008), Porkoláb et al., 2023 (in ETRF2000), Tretyak & Brusak, 2020 (in IGS14 transform to the regional coordinate system). Obviously, the different values and directions of the vectors are due to the regional characteristics of individual regions and may be caused by anthropogenic impacts [Brusak & Tretyak, 2021; Tretyak, Korliatovych & Brusak, 2021].

Using the previously determined regional velocities of horizontal movements and applying dependencies (5 and 6), the strain tensor was calculated. The calculation of the strain tensor made it possible to determine the deformation parameters, the total shear was determined by formula (7), and the dilatation was found by applying formula (8).

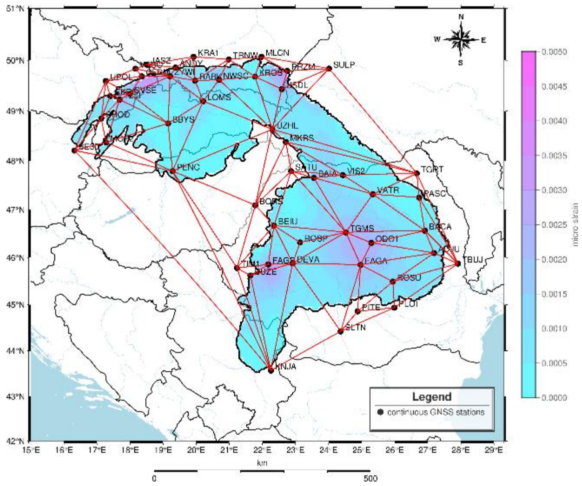

Fig. 7. Distribution of total shear rates velocities.

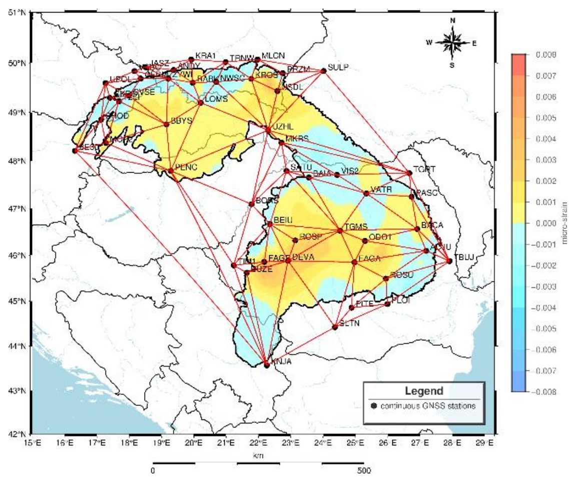

Fig. 8. Distribution of dilatation rates velocities.

Fig. 7 shows that the distribution of the maximum values of shear deformation in the Carpathians is uneven and characterized by a wide range of values ranging from 0.00010 to 0.0051 micro-strain / year [Savchyn & Bilashuk, 2023]. It should be noted that the accuracy of determining the total displacement is 5−17 %. The lowest values are recorded in the Serbian Carpathians, while the highest values are observed in the Outer Eastern Carpathians.

The distribution of deformation area values in the Carpathians, as shown in Fig. 8, is heterogeneous, which indicates a complex geodynamic situation in this region. The deformation area values in different parts of the Carpathians range from –0.0079 to 0.0052 micro-strain / year [Savchyn & Bilashuk, 2023], which indicates different types of geological processes occurring in these places. The accuracy of determining deformation area values is 7−16 %. Zones with the largest positive deformation values are observed in the Western Romanian Mountains, which may indicate the predominance of crustal stretching processes in this region. On the other hand, in the northern part of the Outer Eastern Carpathians, zones with the largest negative deformation values were found, which indicates the predominance of crustal compression processes.

Fig. 9 shows a distribution of rotation velocities.

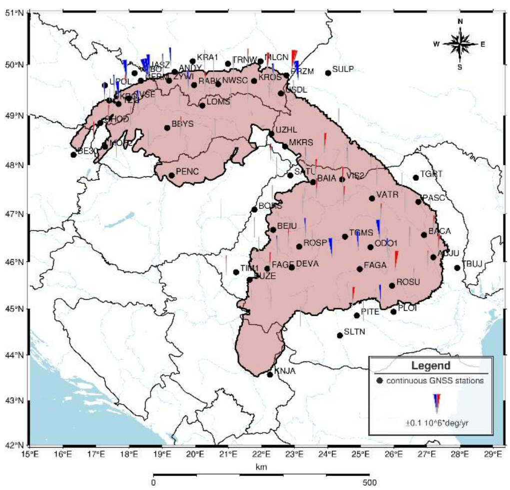

Fig. 9. Distribution of rotation rates velocities.

The range of values varies from −0.0040 to 0.0029 rad. The accuracy of determining rotation velocities is 4−18 %. It should be noted that rotational motion is observed in the northwest and southeast of the Carpathian Mountains, while parallel shear prevails in the central part, where values of rotational velocities are often close to zero.

Conclusions and Discussion

For the most part, the Carpathians were previously studied in separate parts [Roštínský et al., 2020; Doskich, 2021; Porkoláb et al., 2023], in our study we propose a universal algorithm for a comprehensive study of the Carpathian Mountain system. In order for the results of our study to be reproducible, the data of time solutions of permanent GNSS stations were taken from the site of the Nevada Geodetic Laboratory [Blewitt et al., 2018]. The determined velocities and directions of horizontal movements are well correlated with previous studies by other scientists [Staniszewska et al., 2023]. The results of our research show that the movement of the mountain system is heterogeneous and multidirectional, which causes various deformation processses. This is important for monitoring tectonic movements and predicting possible earthquakes. In particular, thanks to the received information about the compression and tension of the earth's surface, it is possible to determine potential seismic zones. However, the heterogeneous network of selected GNSS stations caused by the insufficient number of stations (which meet the requirements of Altamimi et al. (2017)) in free access became a major drawback in determining the velocities of horizontal movements. The consequence of this problem was a significant decrease in the accuracy of calculations of deformation parameters in individual sections. In order to fill this gap in future studies, it is advisable to use data from local GNSS networks.

Prospects for conducting research in this direction are:

- *Installation of new stations.* Installation and maintenance of new GNSS stations aims to thicken the networks of already installed stations and achieve maximum uniformity in the location of continuous GNSS points.
- *Densification of the investigated network due to the use of local networks.* This will make it possible to form a network as homogeneous as possible and achieve more accurate results.
- *The study of individual short periods.*
- *Combination of various research methods (seismic, hydrological, etc.).* Conducting research using different methods allows us to look at the in-depth cause-and-effect relationship of individual geodynamic processes, which in turn provides a deeper analysis of possible deformations of this region.

In our study, an algorithm for determining deformation parameters based on GNSS measurements is proposed. One of the main advantages of this algorithm is its versatility and the possibility of application in any research based on GNSS measurements. A GNSS network consisting of 50 stations was created. Values and directions of horizontal velocities were calculated. The results were consistent with previous studies. An analysis of the deformation processes of the Carpathian Mountain system was carried out. The obtained results confirm the presence of recent geodynamic processes and seismically active zones

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СУЧАСНІ РУХИ ЗЕМНОЇ ПОВЕРХНІ КАРПАТСЬКОЇ ГІРСЬКОЇ СИСТЕМИ ЗА ДАНИМИ ГНСС

Мета дослідження – диференціація сучасних геодинамічних процесів у межах Карпатських гір на основі вільнодоступних ГНСС-даних. Методика. Методика передбачала збирання, оброблення та аналіз ГНСС-даних. Запропоновано алгоритм оброблення, який складався із п'яти основних етапів: перетворення даних у внутрішній формат, перевірка часових рядів на відповідність вимогам, визначення горизонтальних швидкостей, розподіл мережі ГНСС на трикутники, визначення параметрів деформацій. Результати. У цьому дослідженні здійснено комплексний аналіз сучасних геодинамічних процесів, виконаний на основі ГНСС-даних, що надаються у вільному доступі в Невадській геодезичній лабораторії. Враховуючи вимоги до часових рядів, було відібрано та опрацьовано дані 50 ГНСС-станцій. Загалом отримано та проаналізовано абсолютні та регіональні швидкості протягом 2000–2023 рр. Регіональні швидкості горизонтальних рухів використано для розрахунку тензора деформацій та деформаційних параметрів. Результати дослідження, які узгоджуються і добре корелюють із результатами інших вчених, підтверджують наявність активних геодинамічних процесів у межах Карпат. Наукова новизна. Запропонований підхід дав змогу оцінити основні деформаційні параметри (величину і напрямок осей деформацій, загальний зсув і дилатацію) у межах Карпат. Це дає можливість аналізувати та прогнозувати сучасні геодинамічні процеси в регіоні. Практична цінність. На основі розрахованих значень побудовано карти розподілу векторів абсолютних і регіональних горизонтальних швидкостей, загальних швидкостей зсуву, дилатації та швидкостей обертання.

Ключові слова: Карпати, ГНСС-станції, горизонтальні швидкості, тензор деформацій, деформаційні процеси.

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