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Recent Crustal Deformation and Geodynamic Processes in the Lviv Region Derived from GNSS Observations

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SUMMARY

This study investigates recent geodynamic processes and crustal deformation in the Lviv region of Ukraine, adjacent to the Carpathians, using high-precision Global Navigation Satellite System (GNSS) observations. Horizontal velocities derived from stations of the GeoTerrace network and selected Polish GNSS stations are estimated using double-difference processing in the Bernese GNSS Software. The resulting GNSS velocity field is integrated with geological cross-sections and regional tectonic maps to identify spatial deformation patterns, assess potential fault activity, and examine their relationship with the deep geological structure of the region. Despite limitations associated with the spatial density and regional coverage of the GNSS network, the obtained velocity estimates provide valuable information on the contemporary tectonic regime and crustal dynamics. The results contribute to an improved understanding of regional geodynamics and provide a basis for further geodynamic modelling and seismic hazard assessment. Future research should focus on extending the spatial and temporal coverage of GNSS observations and investigating correlations between contemporary crustal movements and geological structures along well-constrained cross-sections and major fault zones.

Keywords: Recent geodynamics; Horizontal velocities of GNSS stations; GeoTerrace GNSS CORS network; Geological profiles.

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Introduction

Understanding recent geodynamics and the deep structure of the lithosphere requires the integration of geological, geophysical and geodetic observations. Among modern geodetic techniques, Global Navigation Satellite Systems (GNSS) provide high-precision quantitative estimates of present-day crustal movements and allow deformation patterns to be monitored over time. The integration of GNSS observations with seismic, and geological data therefore provides an important basis for interpreting regional geodynamic processes. In Ukraine, however, GNSS observations may be affected by the conditions associated with current war situation, which can influence data continuity and quality (Brusak et al., 2024).

Such integrated investigations are particularly important for the Ukrainian Carpathians or adjusted territories, which are characterised by a complex tectonic structure and a heterogeneous geodynamic regime. Previous geological and geophysical studies have provided extensive information on the deep structure, fault systems and tectonic evolution of the region (Tretyak, Maksymchuk, & Kutas; 2015; Gintov et al., 2018; Murovska, 2019). Deep seismic and geophysical investigations performed within international projects, including DOBRE and PANCAKE, have contributed to refining models of the crust and upper mantle and reconstructing the tectonic evolution of the Carpathian region. Geological cross-sections have additionally provided important constraints on the regional tectonic style, including folding and thrusting processes within the sedimentary cover of the Ukrainian Carpathians.

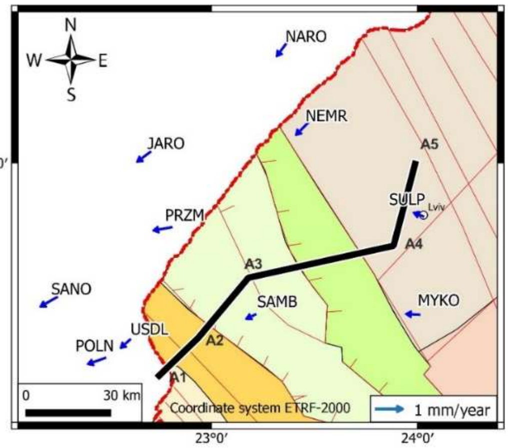
Geodetic investigations complement these geological and geophysical studies by providing direct measurements of recent crustal movements. Long-term observations within the Carpathian geodynamic polygon demonstrated the effectiveness of geodetic methods for detecting horizontal displacements, deformation rates and their spatial heterogeneity. More recently, GNSS-based studies have contributed to understanding present-day crustal movements in the Ukrainian Carpathians and adjusted territories (Doskich, 2021; Savchyn and Bilashuk, 2024). Nevertheless, existing studies remain constrained by the density and spatial distribution of GNSS stations, their geographical focus, and the limited integration of GNSS-derived velocity fields with detailed geological structures.

Therefore, this study focuses specifically on the Lviv region near the Ukrainian Carpathians and combines GNSS-derived horizontal velocities with regional tectonic information and selected geological cross-section A1-A5 (State Geological Map of Ukraine, 2005; Murovska, 2019; Lozynskyi, et al., 2020) that have not previously been considered in GNSS-based geodynamic analyses. The comparison of surface movements with geological and tectonic structures provides an opportunity to identify spatial relationships between observed crustal deformation, major structural zones and faults. This integrated approach is intended to improve the interpretation of the present-day geodynamic regime of the region and provide a basis for further geodynamic modelling and assessment of tectonically active zones.

Data and Method

Networks of continuously operating GNSS reference stations (CORS) represent a key data source for geodynamic monitoring, providing long-term coordinate time series required to quantify crustal movements. Coordinate time series exceeding approximately 2.5 years are generally considered sufficient for reliable assessment of present-day geodynamic trends (Wang, 2022).

In this study, observations from 10 GNSS stations belonging to ukrainian GeoTerrace (Tretyak, K., Navodych, & Tretyak, R., 2026) and polish networks across the Carpathian region were analysed. Most of these stations operated continuously between 2019 and 2025, providing a consistent dataset for estimating regional crustal motions. The spatial distribution of the GNSS stations used in the analysis is presented in Fig. 1.



Legend:

ZOLH - GNSS station,
Lviv - settlements;
- tectonic faults

Sedimentary cover formed in Hercynian:
- Galicia–Volyn depression;

The depth of crystalline rocks:
- > 4000 m;

Boundary deflections and depressions:
- Pre-Carpathian depression. Outer zone;
- Pre-Carpathian depression. Internal zone;

Folded region of the Carpathians:
- Outer Anticlinal zone;
- Central Syncline zone;

Figure 1. *– Annual velocities of GNSS stations in ETRF-2000 from 2019 to 2025 and the locations of geological cross section A1-A2 in Lviv region (based on Glushko & Kruglov, 1986; State Geological Map of Ukraine 2005)*

The geological cross-section extends from the Carpathian folded region toward the Pre-Carpathian Depression and crosses several distinct tectonic zones. The A1–A5 cross-section represents a SW–NE transect across the principal tectonic units of the study area. The A1–A2 segment crosses the Outer Carpathians, A2–A3 extends through the Pre-Carpathian Depression, while A3–A4 marks the transition from the depression toward the adjacent platform domain. The A4–A5 segment is located within the platform area characterized by a sedimentary cover overlying the Hercynian basement.

Data

The Table 1 below presents the annual velocities of the GNSS stations in the ETRF2020 reference frame.

Table 1. *Annual velocities of GNSS stations in ETRF-2020 system*

Name	B	L	D	V-N-mm	V-E-mm
JARO	50.017	22.6678	1.4	-0.82	-1.1
MYKO	49.5238	23.9794	0.9	0.05	-0.88
NARO	50.3502	23.3378	3.8	-3.04	-2.27
NEMR	50.1031	23.4351	1.5	-1.08	-1.05
POLN	49.3742	22.4336	1.7	-0.59	-1.64
PRZM	49.792	22.7528	1.7	-0.31	-1.72
SAMB	49.5195	23.2007	0.4	-0.16	-0.33
SANO	49.5598	22.2008	1.8	-0.92	-1.6
SULP	49.8356	24.0145	0.4	0.15	-0.4
USDL	49.4329	22.5858	0.8	-0.56	-0.62

Table 1 presents the annual horizontal velocities of the GNSS stations in the ETRF2020 reference frame. The velocity magnitude (D) ranges from 0.4 mm/year at SAMB and SULP to 3.8 mm/year at NARO. Most stations show velocities below 2 mm/year, with predominantly negative eastward components indicating a general westward motion across the study area.

Result and Analysis

Figure 2 presents the A1–A5 geological profile superimposed with GNSS-derived horizontal velocities, illustrating the relationship between the geological structure and contemporary crustal movements (modified by State Geological Map of Ukraine, 2005; Murovska, 2019).

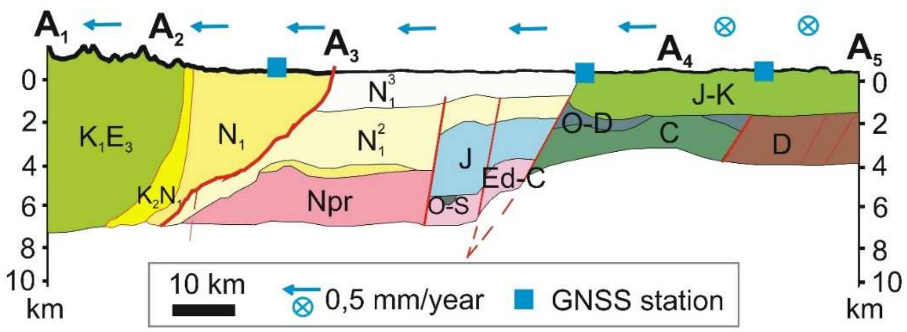


Figure 2. – Geological profile superimposed with GNSS-derived horizontal velocities (modified by State Geological Map of Ukraine, 2005; Murovska, 2019)

As can be seen from Figure 2 the A1–A5 geological profile illustrates the relationship between the geological structure, major tectonic faults, and recent crustal movements derived from GNSS observations. The profile extends across several tectonic domains characterised by contrasting lithological units and structural patterns. The red lines indicate major tectonic faults, while the blue arrows represent the horizontal GNSS velocity components and therefore reflect present-day crustal movements.

Within the A1–A2 segment, the geological structure is characterised by strongly deformed units and several closely spaced tectonic faults. The GNSS velocity vectors are predominantly directed to the left along the profile. A similar direction of recent horizontal motion is observed between A2 and A3, although the geological structure changes substantially across the major fault zone located near A3. This boundary separates the relatively thick sedimentary sequence on the A2–A3 segment from the structurally more complex units occurring farther along the profile.

The A3–A4 segment is characterised by pronounced structural complexity and several steep tectonic faults extending to considerable depths. The juxtaposition of Jurassic (J), Ordovician–Silurian (O–S), Ediacaran–Cambrian (Ed–C), and older units indicates significant fault-controlled segmentation of the crust. Despite these structural changes, the GNSS vectors remain generally directed to the left, suggesting that the contemporary horizontal movement maintains a broadly consistent orientation across this part of the profile.

An important change is observed toward the A4–A5 segment. While the geological structure becomes comparatively less disrupted near the surface, the GNSS observations indicate a change in the orientation of the horizontal velocity component. In contrast to the predominantly profile-parallel vectors observed from A1 to A4, the ⊗ symbols indicate motion directed away from the observer (into the plane of the profile). Thus, the GNSS data suggest a spatial change in the direction of recent crustal motion toward the A4–A5 part of the profile.

Conclusions and Discussion

The integration of GNSS observations with geological data reveals predominantly westward crustal movements and spatial variations in deformation across the heterogeneous tectonic structure of the Lviv near Carpathian region. Overall, the comparison indicates that present-day crustal movements are superimposed on a strongly heterogeneous geological and fault structure. The changes in GNSS velocity direction, particularly toward the A4–A5 segment, together with the concentration of major tectonic faults in the central part of the profile, may indicate spatial variations in the recent deformation regime. However, establishing a direct relationship between individual faults and GNSS-derived motions would require denser geodetic observations and further quantitative analysis.

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