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Andriy NAZAREVYCH[1a], Lesya NAZAREVYCH[2], Galyna BAYRAK[3], Natalia PYRIZHOK[1b]

[1] Carpathian Branch of S. I. Subbotin name Institute of Geophysics of NAS of Ukraine, 3-B, Naukova str., Lviv, 79060, Ukraine, tel. +38(032)2648563, e-mai: nazarevych-a@gmail.com, [1a]https://orcid.org/0000-0002-1989-0790, [1b]https://orcid.org/0000-0002-3976-234X
[2] S. I. Subbotin name Institute of Geophysics of NAS of Ukraine, Department of seismicity of the Carpathian region, 27, Yaroslavenko str., Lviv, 79011, Ukraine, tel. +38(032)2706100, e-mail: nazarevych-l@gmail.com, https://orcid.org/0000-0001-8038-9535
[3] Ivan Franko National University of Lviv, Faculty of Geography, Department of Geomorphology and Paleogeography, 41, Doroshenko str., Lviv, 79000, Ukraine, tel. +038(032)2394598, e-mail: g_bajrak@ukr.net, https://orcid.org/0000-0002-4802-2706

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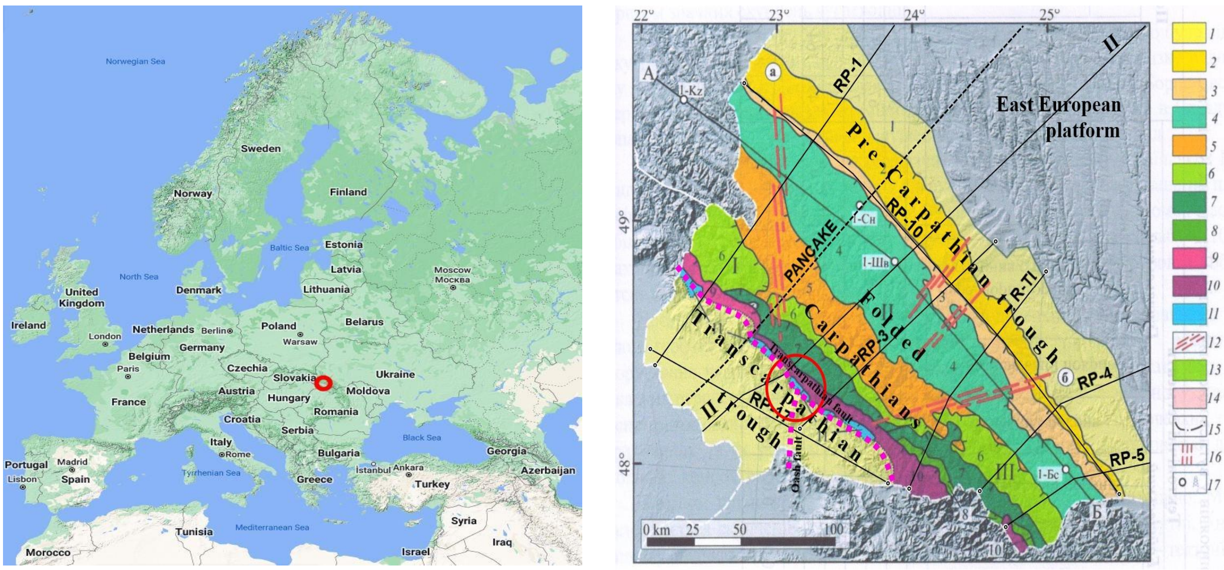
SEISMOTECTONICS OF THE OASH AND TRANSCARPATHIAN DEEP FAULTS JUNCTION ZONE (UKRAINIAN TRANSCARPATHIANS)

The purpose of the work is to study the features of seismotectonics of the junction zone of the Oash and Transcarpathian faults in the Ukrainian Transcarpathians. The research methodology combines a complex analysis of geological-tectonic, seismological, geomorphological and geodetic data on the studied area. For the clarification of coordinates and depths of local earthquake foci we applied methods of their hypocenters specification, using a calculated seismological hodograph and kinematic corrections. Geological and geophysical data, in particular on regional profiles, were used to link seismic events to specific geological structures. It was established that a number of seismic events were recorded at depths of 40–52 km in the studied zone, in its northeastern part. They occurred simultaneously with traditional deep localization of seismic sources in the crust of the Transcarpathian depression (0–27 km deep), including at the depths of the sole of thrust sedimentary strata/roof of the pre-Neogene basement of the Transcarpathian depression (2–3 km deep) in the southwestern part of the studied area. Since these earthquakes are spatially localized to the northeast of the zone where the Transcarpathian deep fault is traced by geological and geomorphological data on the surface, they indicate the subduction of the crustal structures of the Transcarpathian trough in this direction under the thrusts of the Folded Carpathians. This is also evidenced by the corresponding slope of the seismofocal zone at the intersection of the Transcarpathian Deep Fault at greater (15–30 km) depths. These and other features of local seismotectonics reflect the so-called “crocodile” tectonics in the Ukrainian Carpathians. The features encompass the reverse, south-west slope of the seismofocal zone at shallower (0–12 km) depths, as well as the features of the relief of the Carpathians in the studied seismogenic zone. They fully correspond to the characteristics of the “alpine” and “terrain” geodynamics of the region, i. e. compression and displacement in the northeastern and eastern directions, respectively. For the first time, the research established the presence of relatively deeper (30–55 km) seismic activity in the earth’s crust of the Ukrainian Transcarpathians – in the zone of subduction of the Moho border under the Carpathians in the area of junction of the Transcarpathian and Oash deep faults. Additionally, the geodynamic and tectonophysical justification for its presence was given in terms of combination of “alpine”, terrane and asthenolitic geodynamics of the region. Taking into account the features of seismotectonics of the Oash and Transcarpathian faults junction zone will contribute to clarifying the assessment of the characteristics and peculiarities of the spatial distribution of natural geoecological, in particular, seismotectonic risks and hazards in the central part of the Ukrainian Transcarpathians.

Key words: geodynamics; seismotectonics; the Ukrainian Transcarpathians; specified hypocenters of earthquakes; deep fault; seismofocal zone; “crocodile” tectonics.

Introduction

One of the actual problems of analyzing the deep structure and geodynamics of the Ukrainian Carpathians is the problem of studying the features of the structure, geodynamics and seismotectonics of the Transcarpathian deep fault zone. This fault is a structure that separates two large tectonic units – the Transcarpathian depression (trough) and the Folded Carpathians (Figs. 1, 2). The data of many geological and geophysical studies indicate that the fault zone is a complex tectonic structure ([Chekunov et al., 1969; Khomenko, 1978; Structure…, 1978; Melnychuk, 1982; Geodynamics, 1985; Lithosphere…, 1987–1993; Somov, 1990; Krupskyy, 2001, 2020; Boyko et al., 2003; Pavlyuk, Medvedev, 2004; Lyashkevich, Yatsozhinsky, 2005; Study…, 2005; Lozynyak, Misyura, 2010; Hnylko, 2011, 2012; Pavlyuk et al., 2013; Khomyak, Khomyak, 2013; Zayats, 2013; Shlapinskyy, 2015; Andrusov, 1974; Sandulescu, 1988; Csontos, Vörös, 2004; Bezak et al., 2004; Oszczypko et al., 2005; Grad et al., 2006; The Carpathian-Pannonian…, 2006; Kiss, Kovacs, 2011; Plasienka, 2012; Starostenko et al., 2013; Kiss, 2014, 2017; Kiss et al., 2018; Majcin et al., 2018] and others), including ours [Nazarevych A., Nazarevych L., 2002, 2003, 2004, 2006, 2007, 2016, 2019; Nazarevych L., 2006; Nazarevych L., Starodub, 2010; Lozynyak et al., 2011; Kováčiková et al., 2016; Nazarevych A. et al., 2002a, 2002b, 2016, 2021, 2022; Shlapinskyy et al., 2017; Nazarevych L., Nazarevych A., 2012, 2021]. It was formed mainly at the stage of pre-Alpine and Alpine tectonics as a result of a specific interaction of global (plate-tectonic) and regional (asthenolitic and terrain) geodynamic processes. And the tectonic structures present in the region (terrains and microplates, folded belts) actively participated in this. The data of our studies [Nazarevych A., Nazarevych L., 2007, 2016, 2019; Nazarevych L., Nazarevych A., 2012, 2021; Nazarevych A. et al., 2016] also indicate both the features and some peculiarities of the structure, geodynamics, and seismotectonics of the fault zone along its stretching. Within the study of such features we paid attention to the central segment of the fault zone, where our previous research [Nazarevych L., Starodub, 2010; Nazarevych A. et al., 2016] found foci of earthquakes of a relatively great depth (as for the Carpathian region of Ukraine, 40–55 km). Obviously, here the general seismotectonics of the Transcarpathian fault zone is superimposed by the features of the structure and geodynamics of the zone of Neogene Transcarpathian volcanism associated with it and the Vygorlat-Guta volcanic mountain range formed by it [Lyashkevich, Yatsozhinsky, 2005]. In particular, there is probable manifestation of specific influence of the meridional Oash fault zone structures, with which the central meridional segment of this mountain range is connected [Kováčiková et al., 2016]. All these prompted the authors to conduct more detailed and comprehensive study of the seismotectonics peculiarities of the specified zone. Since the studied area lies in the center of the Transcarpathian seismogenic zone of the Ukrainian Transcarpathians, it is geodynamically connected with the neighboring areas. In a certain way it reflects the general features of the geodynamics and seismotectonics of the region. The main results of these studies are presented below.



a b

Fig. 1. Studied area (marked by a red circle) on the map of Europe (Google maps) (a) and on the tectonic map of the Ukrainian Carpathians (b) (tectonics – see [Krupskyy, 2020], regional profiles – according to [Chekunov et al., 1969; Structure…, 1978; Krupskyy, 2001; Zayats, 2013], pink dashed lines are the main deep faults in the studied area)

Purpose

The purpose of the work is to study the features of seismotectonics of the junction zone of the Oash and Transcarpathian faults in the Ukrainian Transcarpathians.

Methods and data

The research methodology combines a complex analysis of geological-tectonic, seismological, geomorphological and geodetic data on the studied area. For the clarification of coordinates and depths of local earthquake foci we applied the methods of their hypocenters specification, using a calculated seismological hodograph and kinematic corrections. Geological and geophysical data, in particular on regional profiles, were used to link seismic events to specific geological structures.

Tectonics of studied area

The deep structure of the lithosphere of the Carpathian region of Ukraine has been studied for many decades, primarily with the help of deep seismic soundings along regional profiles (Fig. 1, b) ([Chekunov et al., 1969; Structure…, 1978; Lithosphere…, 1987–1993; Studies…, 2005; Starostenko, 2013; Zayats, 2013] and others). As for the studied area, the II geotraverse [Structure…, 1978] runs along its western edge, and the RP-17 regional profile [Chekunov et al., 1969] runs along its southern edge (Fig. 1, b).

The structure of the Transcarpathian deep fault zone is clearly reflected in the section along the II geotraverse [Structure…, 1978; Lithosphere…, 1987–1993], which crosses the fault transversely to its extension. In the near-surface horizons (up to 10–12 km), the structures of the southwestern vergence are traced here (nappes and folds of the Carpathian thrusts). In deeper horizons (from 15–18 km), the structures of the opposite, namely north-eastern vergence, can be traced. They correspond to the deep horizons of the Earth's crust, which in the process of tectonic evolution of the Transcarpathian lithosphere were submerged under the Carpathian thrusts. This structure of the fault zone gave academician A. V. Chekunov the reason to call the process of its formation "crocodile" tectonics.

The structure of the Oash Meridional Fault zone and its seismotectonics is clearly reflected in the section along the RP-17 profile [Chekunov et al., 1969, Nazarevych A., Nazarevych L., 2007; Nazarevych L., Nazarevych A., 2012; Kovachikova et al., 2016] (see further, Fig. 4, a). We can see that this fault also has a complex deep structure. However, it is significantly different from the Transcarpathian fault. It consists of vertical and slanted subfaults. The volcanites of the Vygorlat-Guta volcanic ridge were poured out on the vertical subfault in the Neogene (about 7 million years ago) [Lyashkevich, Yatsozhinsky, 2005]. Movements (thrusts/underthrusts), associated with the "terrain" component of the local geodynamic process, take place along the slanted subfault [Nazarevych L., Nazarevych A., 2012; Nazarevych A., Nazarevych L., 2019; Kovachikova et al., 2016].

Geology of studied area

The studied area is located in the southwestern part of the Carpathian region of Ukraine (see Fig. 2). It has a complex geological structure that has been studied by geologists for almost 3 centuries ([Chekunov et al., 1969; Khomenko, 1978; Structure…, 1978; Melnychuk, 1982; Lithosphere…, 1987–1993; Somov, 1990; Krupskyy, 2001, 2020; Boyko et al., 2003; Pavlyuk, Medvedev, 2004; Lyashkevich, Yatsozhinsky, 2005; Studies…, 2005; Lozynyak, Misyura, 2010; Hnylko, 2011, 2012; Pavlyuk et al., 2013; Khomyak, Khomyak, 2013; Zayats, 2013; Shlapinskyy, 2015] and others).

In the 21st century, new detailed geological survey work was conducted in the Ukrainian Carpathians. It included reinterpretation of previously obtained geological data, and construction of new geological maps [The Carpathian-Pannonian..., 2006; Hnylko, 2011, 2012; Shlapinsky et al., 2017]. This made it possible to clarify a number of debatable issues of the geology of the region.

According to the data of all studies, the geological structure of the upper horizons of the Ukrainian Carpathian crust consists of two rock complexes of different ages: the Outer (Flysch) Carpathians (formed during the period of late Alpine folding (28–22 million years ago and partly later)) and the Inner Carpathians (formed during the pre-Alpine and Early Alpine folding [Medvedev, Varichev, 2000]), which are demarcated by the Transcarpathian deep fault (see Fig. 1, b). The Inner Carpathians in the Carpathian region of Ukraine mainly lie in the pre-Neogene basement of the Transcarpathian trough and are buried under the Neogene strata of its sedimentary cover [Petrashkevich, Lozynyak, 1988; Medvedev, Varichev, 2000; Lozynyak et al., 2011].

The Outer (Flysch) Carpathians form a nappe-fold structure without a base composed of Cretaceous-Miocene turbidites and partly Neogene molasses, which was formed and pushed onto the southwestern edge of the East European platform in late Alpine time (Miocene). According to the classical approach of geological-structural analysis, a number of nappes that form the inner, central and outer zones of the Carpathian mountain structure have been identified in the Outer (Folded) Carpathians. The Inner zone includes the Rakhiv, Magura, Porkulets, Dukla, and Chornohora nappes; the Krosno nappe forms the central, and the Skyba nappe – the outer zone of the Folded Carpathians. The geological structure of the nappes is represented by sedimentary flysch strata of the Cretaceous and Paleogene ages, clay shales, marls, and sandstones. In section, these nappes have the appearance of multi-tiered thrusts and folds of sedimentary strata of northeastern vergence thrust onto the pre-alpine basement of the Carpathians (see below).

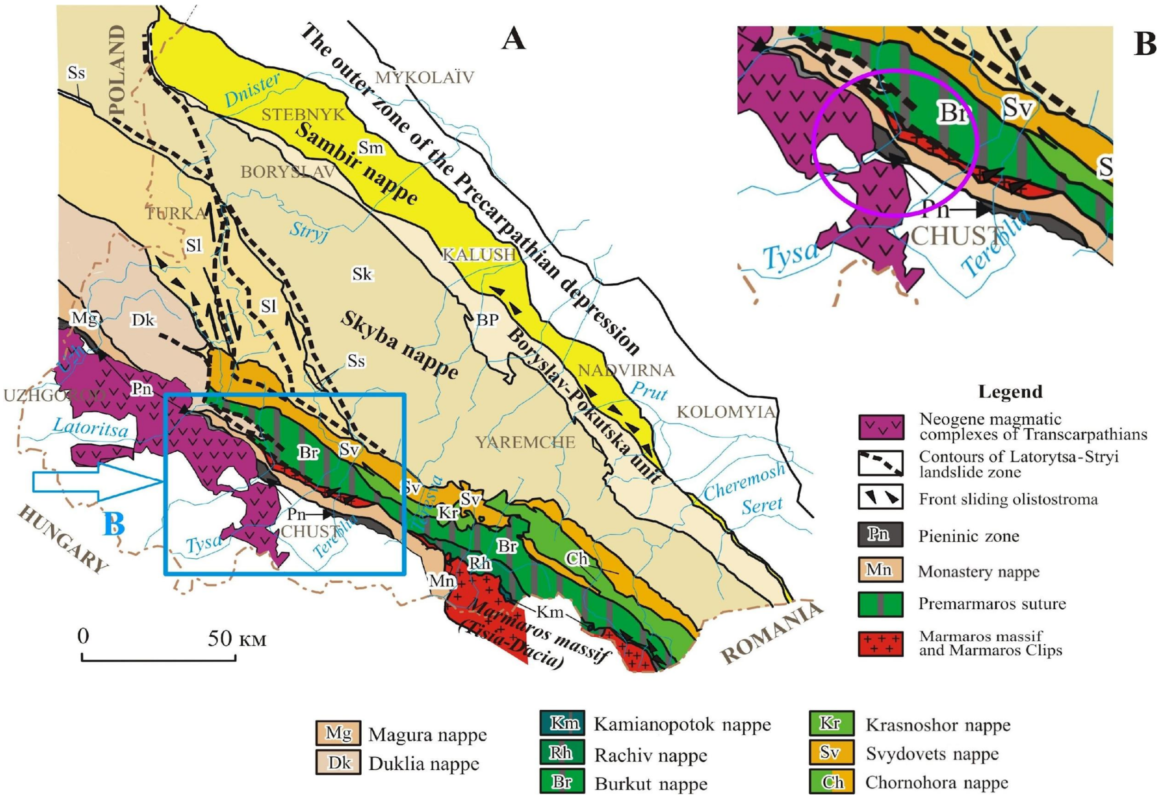
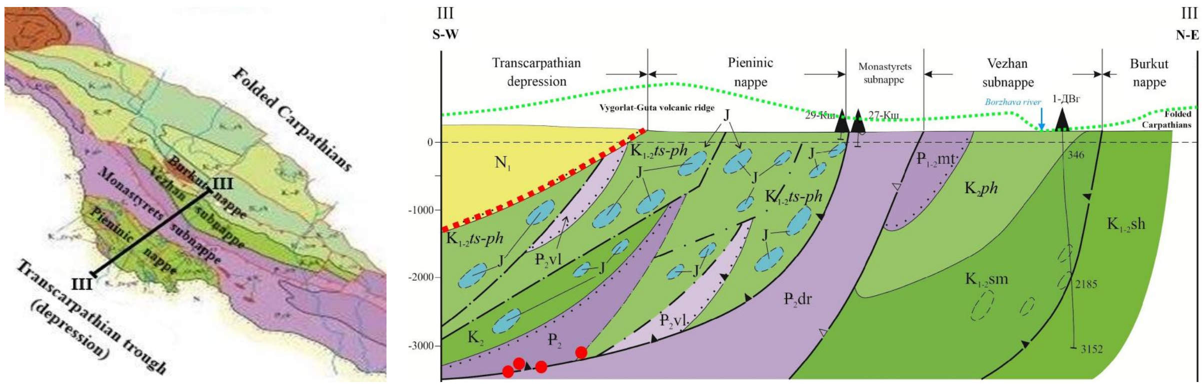


Fig. 2. General schemes of tectonic zoning of the Ukrainian Carpathians (A) and the studied area (B) [Hnylko, 2011]

In tectonic sense, the Transcarpathian depression is an imposed Neogene depression laid on the heterogeneous basement of the Inner Carpathians ([Khomenko, 1978; Petrashkevich, Lozynyak, 1988; Lozynyak, Misyura, 2010; Lozynyak et al., 2011] and others). Its formation was accompanied by magmatic activity [Lyashkevich, Yatsozhinsky, 2005] and the accumulation of molasse sediments during the Miocene-Holocene age [Petrashkevich, Lozynyak, 1988; Lozynyak, Misyura, 2010; Lozynyak et al., 2011]. Sediments are represented by sandy-clay and saline Neogene rocks [Khomenko, 1979; Bokun, 1981; Petrashkevich, Lozynyak, 1988; Lozynyak, Misyura, 2010; Lozynyak et al., 2011]. Volcanic formations are composed of andesites, andesite-basalts, trachytes, tuffs of Miocene age [Maleev, 1964; Merlich, Spitkovskaya, 1974; Lyashkevich, Yatsozhinsky, 2005; Pavlyuk et al., 2013].

The data of various researchers (e.g., [Petrashkevich, Lozynyak, 1988; Lozynyak et al., 2011; Hnylko, 2011, 2012; Shlapinskyi et al., 2017] and others) present the detailed geological and tectonic structure of the studied area (limited by the pink circle in Fig. 2, *b*). Geologically, the zone of the Transcarpathian deep fault in the near-surface (up to 3 km) horizons of the crust is the contact zone of the southeastern edge of the Pieninic nappe of the Ukrainian Carpathians with the Neogene molasses of the Transcarpathian trough of different ages (Fig. 3). Below (at depths of 3–5–7 km), there is a zone of tectonic contact of the same nappe with the pre-Neogene basement of the trough. This zone is characterized by isolated rootless depths of limestones of tens to hundreds of meters of Jurassic and Neocomian age, which are located in a matrix of marls and clays of Upper Cretaceous age. On the side of the Transcarpathian trough (depression), the fault zone is overlain by the volcanic stratum of the Vygorlat-Guta ridge in significant areas (Fig. 3, *b*).



a b

Fig. 3. Geological map of the nappes of the Ukrainian Carpathians (a) in the strip adjacent from the northwest to the structures of the Transcarpathian deep fault (fragment) in the studied area (see Fig. 2, b) [Shlapinskyy et al., 2017]; geological structure and seismicity (b) of the upper (0–3 km) horizons of the earth's crust along the III–III profile (geology – according to [Shlapinskyy et al., 2017], the red dashed line is the near-surface contact zone (nominal plane) of the Transcarpathian fault, red circles – foci of earthquakes, green dashed line – profile of mountain ridges – Vygorlat-Guta volcanics and Folded Carpathians mountain massifs 5 km west of the geological profile line)

The rock massifs of the Burkut nappe and the Monastery and Vezhan subnappe (Figs. 3, a and 3, b) lie in the structure of the Folded Carpathians in the studied area to the north of the zone of the Transcarpathian fault and the Pieninic nappe. Their deep structure was studied in detail by V. Shlapinskyy and his colleagues [Shlapinskyy et al., 2017]. It should be noted that the structure of these nappes on the III–III profile (Fig. 3, b) clearly shows the general Carpathian direction of thrusting these sedimentary strata from the southwest to the northeast. A similar pattern can be traced in all areas of the Folded Carpathians, including adjacent to the Transcarpathian deep fault zone (e.g., [Nazarevych et al., 2016]).

In general modern studies ([Pavlyuk, Medvedev, 2004; Lozynyak et al., 2011] and others) established that the Transcarpathian deep fault zone is a suture (deep suture zone) of a complex structure between the structures of Pannonia (the Transcarpathian depression is the northeastern edge of the northern end Alkapa terrain) and the structures of the Ukrainian Carpathians. The Oash fault is considered by geologists as the boundary between the Chop-Mukachevo and Solotvyno troughs (depression) of the Transcarpathian depression (units with their own peculiarities of the structure and Neogene geodynamics of the earth's crust) and as a vertical channel for the flow of volcanic material to the meridional segment of the Vygorlat-Guta ridge ([Khomenko, 1978; Lyashkevich, Yatsozhinsky, 2005; Pavlyuk et al., 2013] and others).

Features of relief of studied area

In relief, zone of extension of the Transcarpathian deep fault (its near-surface structures) is marked by a chain of valleys of the Carpathian direction (northwest – southeast) between the northeastern slopes of the Vygorlat-Guta volcanic range and the southwestern slopes of the Folded Carpathians, a narrow strip of Marmarosh and Pieninic rocks (Fig. 2). According to the definitions of geomorphologists, the fault zone corresponds in relief to the Berezne-Lipcha (Turya) intermountain valley, the occurrence of which is associated with the stage of Neogene volcanic activity. The morphology of the valley, in particular, a wide bottom with steep slopes, indicates the tectonic nature of the foundation of this structural unit [Kravchuk, 2008, 2021; Kravchuk, Khomyn, 2011] (see Fig. 5). The Oash meridional Fault in the studied area is marked in the terrain by the volcanic ridge Velykyy Sholles of the north direction, which, due to the special structure and geodynamics of this fault (for details, see below, in particular, Fig. 4, *a*), has lower absolute heights than other volcanic formations of the Vygorlat-Guta range. The massif was formed due to the activity of an ancient polygenic stratovolcano [Kravchuk, 2021].

It should be noted that the relief of the Transcarpathian fault zone undergoes noticeable changes in the studied area [Bayrak, 2006] (Fig. 5). In the north-western part of the area, the fault zone is represented by a rather wide valley of the Borzhava River with a north-northwest direction (azimuth 330–335º) between the villages Kushnytsya – Bron'ka –

Dovge (absolute heights less than 200 m). From the southwest, this valley is bounded by the northeastern spurs of the Buzhora mountain massif of the Vygorlat-Guta volcanic ridge, from the northeast it is bounded by the southwestern slopes of the Kuku mountain massif, part of the large Borzhava mountain massif. Further south from the village Dovge, the valley of the Borzhava River abruptly changes its direction to the southwest (azimuth 230–235º), crossing the zone of the Vygorlat-Guta volcanic ridge in a direction, orthogonal to the general extension of the Carpathian ridges.

In the southeastern part of the studied area, the relief of the Transcarpathian fault zone is low-mountainous (Fig. 5). Between the villages Dovhe and Lypetska Polyana, there is a very narrow (up to 100–200 m wide) mountain valley (absolute height up to 280–300 m) of the Dovhyy brook (its south-western side is the northeastern spurs of the Velykyy Sholles volcanic ridge, northeastern side is the southwestern spurs of the Palenyy Grun` mountain massif). And then the fault zone is traced to southeast through a number of obliquely secant small mountain ridges (heights up to 350–400 m) and valleys (south direction, azimuth 170–190º) towards the villages Kraynye, Monastyrets and Horinchovo. The latter one is already located in the valley of the Rika River, which runs orthogonally to the Carpathians. The active nature of the fault zone is indicated by the structure of the valley and the distinct dynamics of the Tysa River when it crosses the Velykyy Sholles and Oash mountain ranges [Bayrak, 2011].

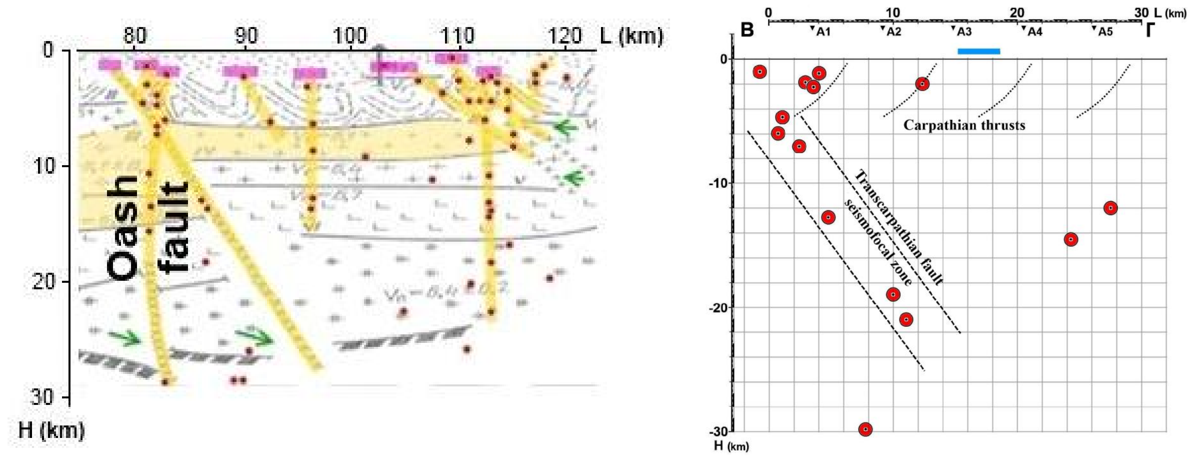
The change in the relief of the Transcarpathian fault zone, as well as the dynamics of rivers, in our opinion, is directly related to a change in the geodynamic regime of the earth's crust in this area, which will be discussed in more detail below. Such a regime change is traced here according to geological and geodetic data [Somov, 1990; Nazarevych A., Nazarevych L., 2004, 2007; Lozynyak et al., 2011] from the Upper Miocene (Sarmatian (Tortonian)) to the present.

Seismological data

We use specially developed methods for determining the hypocenters of local earthquakes [Nazarevych A., Nazarevych L., 2002, 2003; Nazarevych L., Nazarevych A., 2004a, 2004b; Nazarevych L., 2006; Kováčiková et al., 2016] and others) to study the features of local seismotectonics of Oash and Transcarpathian faults junction zone. These methods are based on the use of calculated seismological hodographs. These hodographs were built on the basis of averaged velocity models of the lithosphere of the region according to the data of studies using the DSZ-RWCM methods on regional profiles. We also developed and applied additional methods for specifying the hypocenter of local earthquakes. There we used averaged residuals of seismic wave and kinematic corrections out of the velocity structure deviations of the earth’s crust in specific zones from the averaged velocity model of the region’s lithosphere. Application of all named methods helped to achieve the accuracy of determining the coordinates and depths of local earthquake foci (the resulting residuals did not exceed 0.7–1.2 km on average). This made it possible to reliably link registered local earthquakes to fault tectonic structures known from geological and geophysical data. We were also able to compare their mechanisms with the geomechanics of the corresponding structures (traced from these data) and to draw reasonable conclusions about the peculiarities of their seismotectonics [Nazarevych A., Nazarevych L., 2002, 2003; Nazarevych L., Nazarevych A., 2004a, 2004b; Nazarevych L., 2006; Kováčiková et al., 2016].

Data from printed and electronic annual seismological bulletins for the period of instrumental observations of the Carpathian Seismological Network of Ukraine (since 1955) were used as primary instrumental data on seismicity [Catalog..., 1958–1975; Seismological..., 1980–1988; Seismological..., 1989–1992; Seismological..., 1995–2004; Carpathian..., 2022]. In addition, literary data on historical and modern seismicity of the region were taken into account ([Evseev, 1961; Pronyshyn, Pustovitenko, 1982; Kostyuk et al., 1997] and others).

According to seismological data, both the Transcarpathian and Oash deep faults are seismotectonically active. In particular, both sub-faults of the Oash Meridional Fault show such activity. The foci of instrumentally registered local earthquakes in the last decades are confined to them [Nazarevych A., Nazarevych L., 2003; Nazarevych L., Starodub, 2010; Kováčiková et al., 2016] (Fig. 4, b). The Transcarpathian deep fault is also seismotectonically active, both the foci of perceptible, including historical, and weak instrumental earthquakes are confined to them [Evseev, 1961; Kostyuk et al., 1997; Nazarevych A., Nazarevych L., 2007]. They include the foci of the strongest known local earthquake, the 1908 Svalyava earthquake with a magnitude $M = 4.7$ and 7.5 points shaking in the epicenter. According to the results of our previous works [Nazarevych A. et al., 2002, 2016; Nazarevych L., 2006; Nazarevych L., Starodub, 2010; Nazarevych A., Nazarevych L., 2019], the features of the “crocodile” tectonics are characteristic to the fault (thrust of the upper rock horizons to the northeast on the edge of the structures of the East European platform and subduction in the same direction of the lower horizons of the crust). They are clearly visible on the nominal cross-fault profile east of the research area [Nazarevych A. et al., 2016] (Fig. 4, *b*) and associated with the "alpine" component of the local geodynamics and seismotectonic process [Nazarevych A., Nazarevych L., 2002, 2006, 2019].



a b

Fig. 4. Seismotectonics of the Oash Meridional Fault zone (see Fig. 2) on the RP-17 profile (fragment) [Nazarevych A. Nazarevych L., 2003; Kováčiková et al., 2016] (a); seismotectonics of the Transcarpathian deep fault zone (see Fig. 2) [Nazarevych et al., 2016] in the area of the Tereblya-Rika HPS (to the east of the area of our research) (b) (red dots mark foci of earthquakes)

Geodetic data

As mentioned earlier, the modern geodynamic regime of the Earth's crust in the Carpathian region of Ukraine has been studied in sufficient detail by geodetic methods, including modern methods of space geodesy ([Somov, 1990; Demediuk et al., 1998; Smirnova, 2002; Modern…, 2015] and others). According to these and our extenzometric data [Nazarevych A. Nazarevych L., 2004, 2007; Studies…, 2005; Nazarevych et al., 2019], a change of the geodynamic regime of the earth's crust is observed in the studied area of junction of the Transcarpathian and Oash deep faults, namely from stretching and subsidence in the southwest, west, and northwest to compression and uplift in the north, northeast, and east [Nazarevych A. Nazarevych L., 2004, 2007]. These data are fully consistent with geological data [Lozynyak, Misyura, 2010; Lozynyak et al., 2011] about the spatial changes of geodynamic regime of the Earth's crust of Transcarpathian trough (depression) in post-Pannonian (post Tortonian) times (7.5–6 million years ago) after the processes of activation of Transcarpathian Neogene volcanism and the formation of the central segment of the Vygorlat-Guta volcanic ridge.

Results

The results of our studies of the seismotectonics of the zone of junction of the Oash and Transcarpathian faults in Ukrainian Transcarpathians using the specified methods and approaches are shown in Figs. 5 and 6. We established that the zone of intersection of these faults is characterized by specific seismotectonics. As mentioned before, we could observe this during our study of the Transcarpathian trough seismotectonics features [Nazarevych A. Nazarevych L., 2002, 2004, 2007] and the Folded Carpathians [Nazarevych L., 2006; Nazarevych L., Starodub, 2010; Nazarevych L. Nazarevych A., 2012] (see Figs. 4), in particular, of the Tereblya-Rika HPS area in the Ukrainian Transcarpathians [Nazarevych et al., 2016].

Let us consider the obtained research results in more detail (see also [Nazarevych A. et al., 2022]). Seismicity in the southwestern segment of the studied zone (see Figs. 5 and 6), south of the Transcarpathian Fault, within the crust of the Chop-Mukachevo depression of the Transcarpathian Trough, is shallow. The foci of earthquakes lie mainly within the main here seismogenic layer, i. e., at depths of 3–10 km, at the top and thickness of the basement and "granites"' layers [Nazarevych A., Nazarevych L., 2002, 2004, 2007; Nazarevych L. Nazarevych A., 2012; Kováčiková et al., 2016].

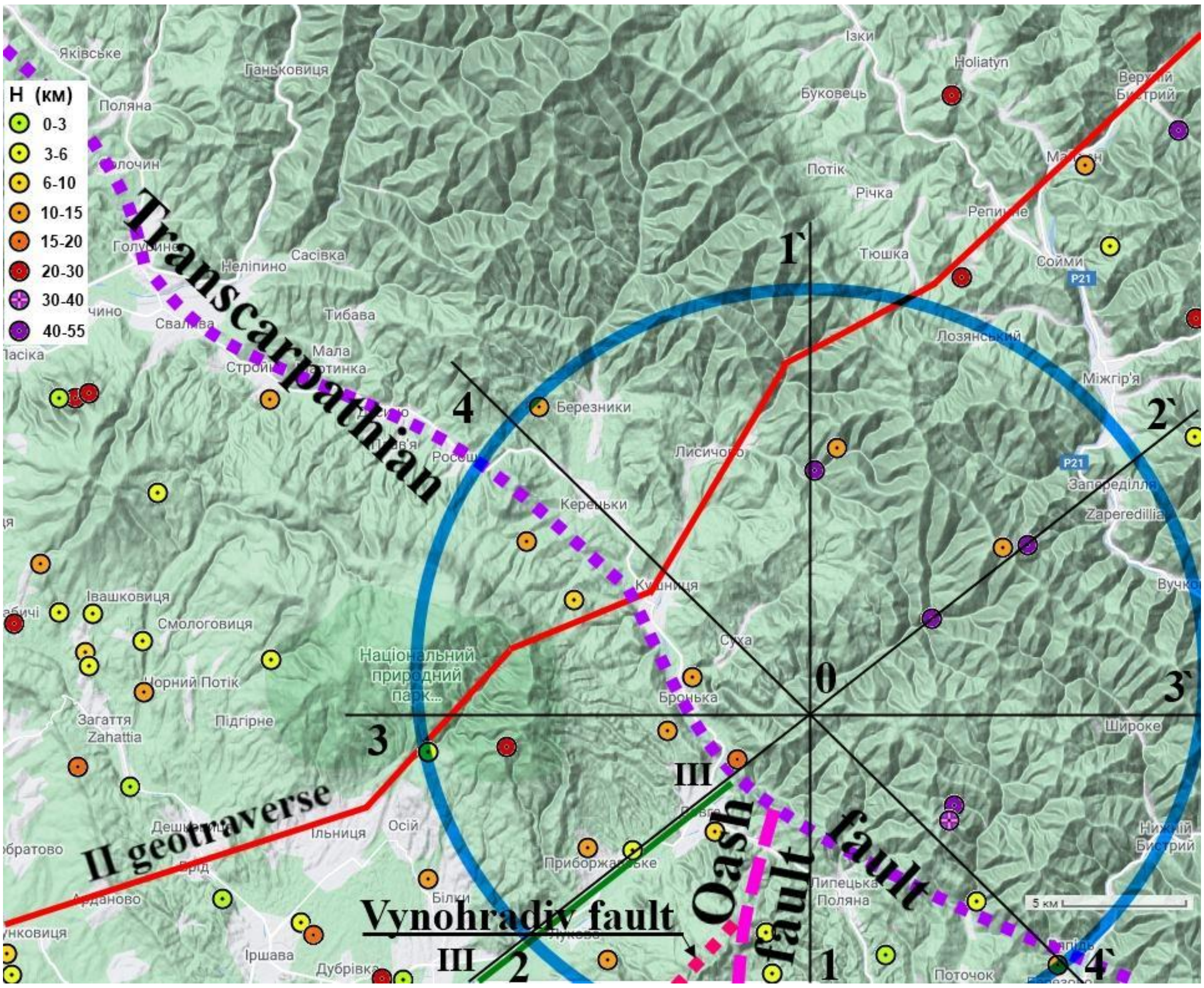


Fig. 5. Seismicity of the studied area (outlined by a blue circle) – zone of intersection of the Oash and Transcarpathian faults (indicated by pink and purple dashed lines, respectively) on the Google Maps (small circles are epicenters of earthquakes of various depths (depths of foci are marked by color)); black lines are nominal profiles for depth-spatial analysis of seismicity and seismotectonics (see Fig. 6), III–III is a fragment of nominal profile, detailed shown in Fig. 3)

A similar depth distribution of seismicity is also observed in the tectonic structures of the Transcarpathian depression located to the southwest and west of the studied area. Several fairly deep (at depths of 20–27 km, in the "basalt" layer, above the Moho border) earthquake foci are localized on subvertical faults of the Carpathian direction. Effusives of the Vygorlat-Guta volcanic ridge in particular, of the Borliiv Dil mountain massif, poured out on them in the Neogene [Lyashkevich, Yatsozhinsky, 2005]. They indicate the modern seismotectonic activity of these faults and adjacent blocks of the earth's crust. One of these foci is located within the studied area, specifically under the peak of Mount Buzhora (see Fig. 5), the other 2 are located further north-west, under the massif of Mount Dehmaniv.

The depth distribution of seismicity in the northeastern segment of the studied area (in the structures of the Folded Carpathians) is significantly different [Nazarevych L. Nazarevych A., 2012]. Here we can see several earthquakes at depths of 10–15 km, that is, within the sole of the lower layer of thrusts and folds (the top of tectonic basement of the Carpathian thrusts). The upper layer of thrusts and folds (see Figs. 5 and 6) does not demonstrate seismotectonic activity here.

But the most remarkable here is the presence of a number of fairly deep (40–52 km deep) earthquakes to the north, northeast, and east of the junction of the Transcarpathian and Oash faults at near-surface depths. According to our conclusions, these earthquakes correspond to the dipping of the seismofocal zone of the Transcarpathian and Oash faults to the northeast and east, respectively (see Fig. 6). This conclusion corresponds to the appropriate dipping of these faults and seismofocal structures traced by us [Nazarevych et al., 2016; Kováčiková et al., 2016] in the areas adjacent to the studied area (see Fig. 4). In the structure of the Carpathian massifs, this is the zone of morphostructures of the Vodytsya-Yastremble and Kuk – Palenyy Grun` mountain ridges, while the near-surface zone of the Transcarpathian Fault corresponds in relief to the Berezne-Lypcha (Turya) intermountain valley [Kravchuk, Khomyn, 2011; Kravchuk, 2021] (see Fig. 5). This dipping of the seismofocal zone of the Transcarpathian fault under the Carpathians is fully consistent with the deep structure of the crust in this area according to geotraverse 2 research data (see Fig. 5) [Structure…, 1978; Lithosphere…, 1987–1993], it traces the dipping of the Moho surface under the Carpathians at these depths (40–52 km).

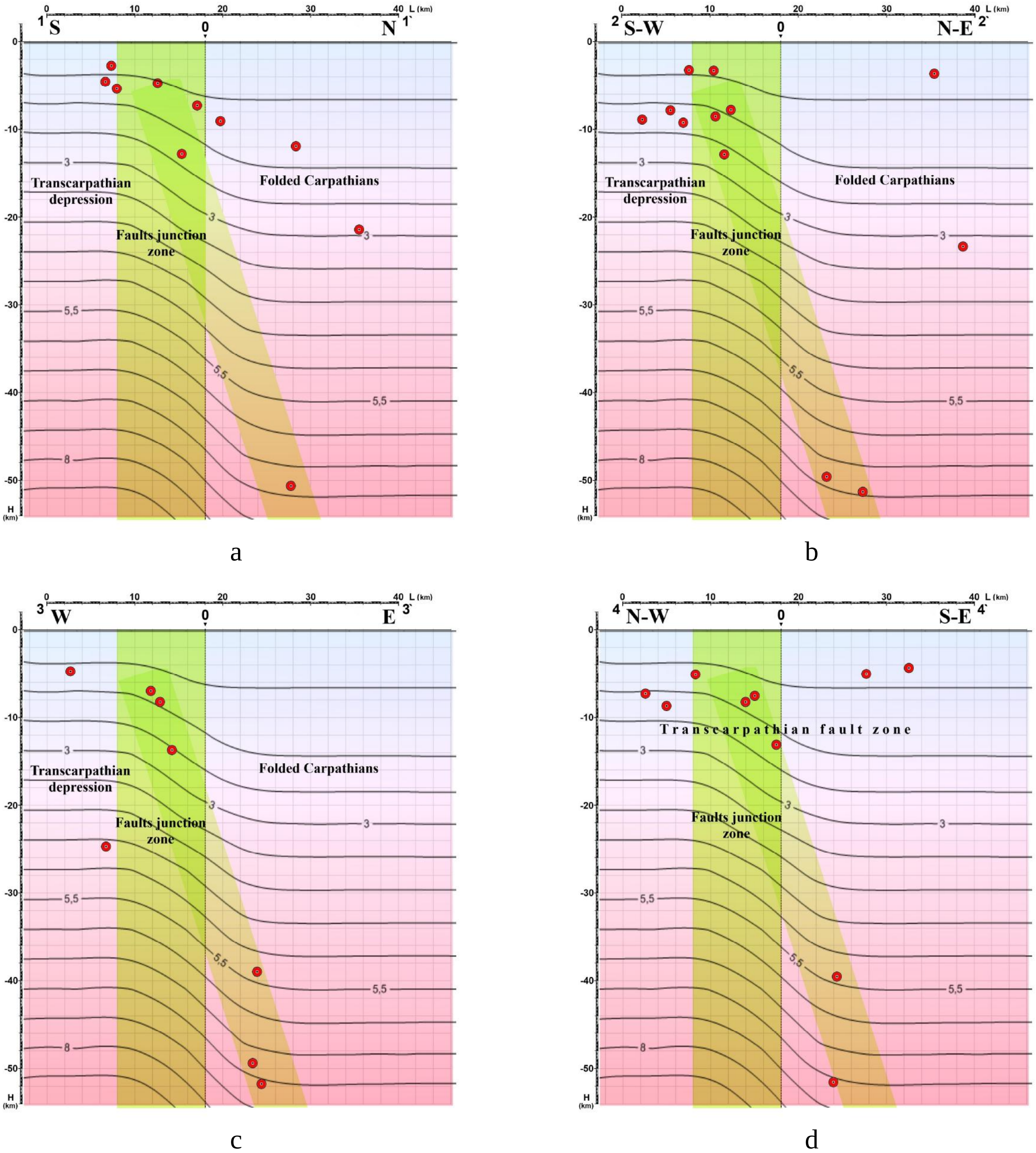


Fig. 6. Depth-spatial localization of earthquake foci on the nominal profiles (see Fig. 5) 1–1` (a), 2–2` (b), 3–3` (c), 4–4` (d) in the studied area (zones of gradients of deep temperature and geomechanical characteristics of the geological environment are schematically shown)

Discussion

The peculiarities of the deep-spatial distribution of seismic activity in the earth's crust of the studied area (zones of junction of the Transcarpathian and Oash deep faults) established by us are genetically related to the peculiarities of the structure, geodynamics, and rheology of this crust.

This especially applies to the area of deep seismic activity identified here (see Figs. 5 and 6). We detected a change in the geodynamic regime of the earth's crust based on geological [Lozynyak et al., 2011], geodetic [Somov, 1990] and geomorphological (see above) data – from the stretching and lowering of the earth's surface in its southwestern and western parts to compression and uplift in the northeastern and eastern parts [Nazarevych A., Nazarevych L., 2002a, 2002b, 2004, 2007]. This change was inherited from the upper Miocene (Sarmatian (Tortonian)) [Lozynyak et al., 2011]. Previously, we connected such a change with the influence of asthenolitic processes on this territory [Nazarevych A., Nazarevych L., 2002a, 2002b, 2004]. And now we relate it to the influence of both asthenolitic (relaxation subsidence of the earth's crust of the Chop-Mukachevo depression (the western part of the Transcarpathian trough) over the fading northern jet of the convective asthenolitic flow) and terrain processes (shifting of the Alkapa terrain with its crustal structures of the Transcarpathian depression to the east).

Concerning the "dipping" of the seismofocal zone from the junction of the Transcarpathian and Oash faults in the eastern direction, it should be noted that, in our opinion, this is the result, first of all, of influence of the terrain component of the regional geodynamic process (the movement of the lithosphere of the Alkapa terrain and its northeastern segment – lithosphere of the Transcarpathian trough – in the eastern direction), though the influence of the asthenolitic component of this process is also present (see below). A reflection of all this is the presence and seismic activity of an inclined (at an angle of about 60º) fault with thrust-subduction kinematics (in the northwest-southeast direction, respectively) a little further south, in the area of the regional profile RP-17 (see Fig. 4, a).

Concerning the geomechanical causes for the presence and seismotectonic activity of eastward-inclined faults in this area, it is possible to point to the obvious reaction of resistance of the large ancient Marmarosh crystalline massif (located 70 km southeast) with sufficiently deep, cold and "hard" (relative to the asthenosphere under Pannonia) "roots" in the mantle (judging by the much smaller heat flow here, compared to that in the area of the Chop-Mukachevo depression) [Lithosphere…, 1987–1993; Studies…, 2005; Modern…, 2015; Kováčiková et al., 2016]. This reaction of the resistance of this massif causes the existence of a regime of expressed horizontal latitudinal compression of the crust located east of the Oash fault of the Solotvyno depression. This appears in the presence of a number of inclined faults here – and the already mentioned inclined Oash subfault and more sloping Tyachiv thrust-subduction fault (inclination angle of about 45º) located 30 km to the east, and others, and in their high seismic activity. This compression also appears in the uplift of the earth's surface in the east of the studied area and further east in the Solotvyno depression and the adjacent Carpathian mountain massifs at a rate of 1–2 mm/year [Somov, 1990].

We also note that the similar tectonic structure (with the presence of fault zones inclined to the east) has the joint zone of the Alkapa and Tisza-Dacia terranes in the territory of Hungary [Kiss et al., 2018] (see Figs. 4, a and 6, c, d).

To what has been said, let us add that the features of the structure and geodynamics (including the Neogene) of the Oash fault zone (intersection in the near-surface area of vertical and inclined faults and the mode of latitudinal compression caused by the eastward terranes displacement of the deep horizons of the crust) are, in our opinion, the reason for the above-mentioned relatively low (compared to Buzhora and Dekhmaniv mountain range) relief of the Velykyy Sholles mountain range. After all, such a structure and geodynamics of the fault zone made it difficult for volcanites to erupt here, and as a result, both the total volume of this volcanic ridge (this is clearly visible in Fig. 2) and its height (see Fig. 5) are comparatively significantly smaller.

The following can be concluded regarding the influence of the asthenolitic component of the regional geodynamic process on the seismotectonics of the studied area. Such an influence is undoubted, since the Neogene volcanism of Transcarpathians is genetically related to the asthenolitic activation of the northeastern and eastern edges of the Chop-Mukachevo depression [Lyashkevich, Yatsozhinsky, 2005]. It is also connected with the formation processes of the western (along the Transcarpathian deep fault) and central (along the Oash meridional fault) segments of the Vygorlat-Guta volcanic ridge. This is also confirmed by the features of changes in the geodynamic regime and processes of sedimentation in the entire Transcarpathian Trough in the Neogene [Lozynyak et al., 2011], as well as the features of its modern geodynamics [Nazarevych A. Nazarevych L., 2005, 2007, 2019]. A more detailed analysis of the features of such influence requires special consideration involving a significant amount of relevant geological and geophysical data.

Here we will only add that at the same time that local earthquakes are tied to tectonic discontinuities of various levels and depths, these earthquakes are also tied to zones of changes in the temperature regime and geomechanical characteristics of the geological medium in the direction from the Chop-Mukachevo depression of the Transcarpathian trough to the Solotvyn depression and the Folded Carpathians (see Fig. 6). Such zones are zones of thermorheological gradients, on one side of them (in relatively hotter and rheologically weakened areas of the lithosphere) tectonic movements occur in the form of plastic deformations, and on the other (in colder and geomechanically solid areas) tectonic movements occur in the form of brittle fracturing. Namely, in the gradient zones, the most intensive accumulation and discharge of tectonic stresses by relatively weak earthquakes occurs, since these stresses here can no longer be completely discharged due to plastic deformations (the rheological viscosity of rocks increases with a decrease of temperature). They, however, cannot accumulate to significant values, because the mechanical hardness of these rocks is not yet high enough. The subduction of such gradient zones under the Folded Carpathians (Fig. 6) is also caused by the fact that the changes of the operating pressure also affect the changes of the geomechanical and rheological characteristics of rocks, along with influence of temperature changes ([Korchyn et al., 2013] and others). In our opinion, everything described can be briefly called the thermorheological influence of the Pannonian asthenolite. A number of aspects of this influence were analyzed by researchers earlier (see, for example, [Chekunov, 1988; Lithosphere…, 1987–1993; Kiss, 2017] and others).

Another notable feature of the studied area is the absence of instrumentally recorded (since 1961) seismic activity in the area of the Polonyna Borzhava mountain massif (to the northwest of the considered zone of junction of the Transcarpathian and Oash faults). One of the possible explanations claim that this is a “lull zone” in the area of the mentioned strong 1908 Svalyava earthquake (taking into account the 125 years period of recurrence of such events here established by historical data [Evseev, 1961; Pronyshyn, Pustovitenko, 1982; Kostyuk et al., 1997]).

Another thing is that this massif is a three-dimensional geomechanically strong massif surrounded by softer sedimentary strata (like an iceberg in a sea of tailings). Significant geomechanical stresses are not accumulated in his body; they are accumulated and discharged by earthquakes on its periphery. The third possible option is a combination of the first two. But more reasonable conclusions can be made here after detailed comprehensive studies of modern seismotectonic activity in this zone and in the areas surrounding it from the north and west.

Originality

For the first time, the research managed to establish the presence of relatively deeper (30–55 km) seismic activity in the earth’s crust of Ukrainian Transcarpathians – in the zone of subduction of the Moho border under the Carpathians in the area of junction of the Transcarpathian and Oash deep faults. In addition, the geodynamic and tectonophysical justification of this was given in terms of the combination of “alpine”, terrane and asthenolitic geodynamics of the region.

Practical significance

The article presented the features of seismotectonics of the zone of junction of the Oash and Transcarpathian faults. Taking them into account will contribute to clarifying the assessment of the characteristics and peculiarities of the spatial distribution of natural geoecological, in particular, seismotectonic risks and hazards in the central part of Ukrainian Transcarpathians.

Conclusions

Based on the presented research results, the following conclusions can be drawn.

The research established that along with the deep localization of seismic sources in the crust of the Transcarpathian depression (0–27 km deep), which is traditional for Ukrainian Transcarpathians, a number of seismic events were recorded at depths of 40–52 km in the studied zone of junction of the Oash and Transcarpathian faults. These earthquakes, by their localization, indicate the subduction of crustal structures of the Transcarpathian depression in the northeast direction under the thrusts of the Folded Carpathians. They reflect, in particular, the so-called “crocodile” tectonics in the Ukrainian Carpathians and are fully consistent with the characteristic features of the “alpine” and “terrain” geodynamics of the region, namely compression and displacement in the northeast and east directions, respectively. The influence of asthenolite from late Pannonia also plays its role (namely, thermorheological)

In general, it can be concluded that the features of seismotectonics of the studied area are caused by the simultaneous influence of a complex of geodynamic and tectonophysical factors, each of which contributes to these features both independently and in combination with other factors.

Note that conducted by us in the Carpathian region of Ukraine monitoring seismoprognostic geophysical research is important in the study of the peculiarities of geodynamics of the region and its specific zones. The results of the selection and geomechanical and seismotectonic interpretation of geophysical anomalies – precursors of local earthquakes – give important information about the geomechanical regime of tectonic structures and zones of the crust and its time-spatial changes ([Nazarevych A., Nazarevych L., 2002, 2004; Nazarevych A. et al., 2002b, 2019; Studies..., 2005] and others).

The next step of our research will consist of a detailed comparative analysis of seismotectonics and geodynamics of this and neighboring segments of the Transcarpathian deep fault zone.

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Андрій НАЗАРЕВИЧ[1a], Леся НАЗАРЕВИЧ[2], Галина БАЙРАК[3], Наталія ПИРІЖОК[1б]

[1] Карпатське відділення Інституту геофізики ім. С. І. Субботіна НАН України, вул. Наукова, 3-б, Львів, 79060, Україна, тел. +38(032)2648563, ел. пошта: nazarevych.a@gmail.com, [1a] https://orcid.org/0000-0002-1989-0790, [1b] https://orcid.org/0000-0002-3976-234X

[2] Інституту геофізики ім. С. І. Субботіна НАН України, відділ сейсмічності Карпатського регіону, вул. Ярославенка, 27, Львів, 79060, Україна, тел. +38(032)2706100, ел. пошта: nazarevych.l@gmail.com, https://orcid.org/0000-0001-8038-9535

[3] Львівський національний університет імені Івана Франка, географічний факультет, кафедра геоморфології і палеогеографії, вул. Дорошенка, 41, Львів, 79011, Україна, тел.+038(032)2394598, ел. пошта: g_bajrak@ukr.net, https://orcid.org/0000-0002-4802-2706

СЕЙСМОТЕКТОНІКА ЗОНИ ПЕРЕТИНУ ОАШСЬКОГО І ЗАКАРПАТСЬКОГО ГЛИБИННИХ РОЗЛОМІВ (УКРАЇНСЬКЕ ЗАКАРПАТТЯ)

Мета роботи – дослідити особливості сейсмотектоніки зони зчленування Оашського і Закарпатського глибинних розломів в Українському Закарпатті. Методика досліджень об'єднує комплексний аналіз геолого-тектонічних, сейсмологічних та геодезичних даних щодо досліджуваного району. Для уточнення координат і глибин вогнищ місцевих землетрусів застосовано методики уточнення їх гіпоцентрій з використанням розрахункового сейсмологічного годографа та кінематичних поправок. Для прив’язки сейсмічних подій до конкретних геологічних структур використано геолого-геофізичні дані, зокрема, за регіональними профілями. Встановлено, що поряд з традиційною для Українського Закарпаття неглибокою локалізацією сейсмічних джерел у земній корі Закарпатського прогину (глибини 0–27 км), зокрема в районі підошви насувних осадових товщ/покрівлі донеогенового фундаменту Закарпатського прогину (глибини 2–3 км) у південно-західній частині досліджуваного району, в його північно-східній частині зафіксовано низку сейсмічних подій на глибинах 40–52 км. Оскільки ці землетруси просторово локалізовані північно-східніше від простеженої за геологічними та геоморфологічними даними зони Закарпатського глибинного розлому на поверхні, вони вказують на занурення структур кори Закарпатського прогину в цьому напрямку під насуви Складчастих Карпат. Про це ж свідчить і відповідний нахил сейсмофокальної зони в перетині Закарпатського глибинного розлому на більших (15–30 км) глибинах. Ці та інші особливості місцевої сейсмотектоніки (зокрема, зворотний, південно-західний нахил сейсмофокальної зони на менших (0–12 км) глибинах), а також особливості рельєфу Карпат у дослідженій сейсмогенній зоні, відображають, зокрема, так звану “крокодилову” тектоніку в Українських Карпатах і повністю узгоджуються із характерними рисами “альпійської” та “терейнової” геодинаміки регіону – стисканням і зміщенням у північно-східному та східному напрямках відповідно. Вперше встановлено наявність порівняно глибшої (30–55 км) сейсмічної активності в земній корі Українського Закарпаття – у зоні занурення границі Мохо під Карпати в районі зчленування Закарпатського та Оашського глибинних розломів і подано геодинамічне та тектонофізичне обґрунтування її наявності із позицій поєднання “альпійської”, “теренової” та астенолітної геодинаміки регіону. Врахування викладених у статті особливостей сейсмотектоніки зони зчленування Оашського і Закарпатського розломів сприятиме уточненню оцінок характеристик та особливостей просторового розподілу природних геоекологічних, зокрема, сейсмотектонічних ризиків і небезпек у центральній частині Українського Закарпаття.

Ключові слова: геодинаміка; сейсмотектоніка; Українське Закарпаття; уточнена гіпоцентрія землетрусів; глибинний розлом; сейсмофокальна зона; “крокодилова” тектоніка.

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