

## Inner structure and kinematics of the Sushchany-Perga fault zone of the Ukrainian Shield according to the tectonophysical study

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The field tectonophysical works were carried out in the upper reaches of the Ubort River basin along the Zolnia-Maidan-Kopischany fault. The research aim was determination of the inner structure and kinematics of the Sushchany-Perga fault zone of the western part of the Ukrainian Shield. For investigation of fracturing and structural-textural elements of rocks the structural-paragenetic method of tectonophysics was used. It was determined that formation of the Sushchany-Perga fault zone continued during at least five phases of deformation. They were accompanied by the formation of differently oriented shear zones: Khmelivka, Sushchany, Perga, Rudnia-Khochin, Lopatychi. The Khmelivka and Sushchany shear zones are similar to striking of the Nemyriv and Khmelnik fault zones of the Ukrainian shield, which belong to the Nemyriv stage of faulting (~1.99 Ga). The Rudnia-Khochin and Perga phases are related to the fact that the Sushchany-Perga fault zone was quite active during the junction of the Fennoscandia and Sarmatia microplates. We have established that the development of thrust fault and normal down throw fault type shears, which took place in an area of compression and extension, respectively, is associated with the formation period of the Perga granitoids complex (1.80—1.70 Ga). This alternation of the compression and extension conditions has led to formation of the ore occurrences and deposits within the Perga tectonic joint. This investigation found that the Sushchany-Perga fault zone arose in the Late Paleoproterozoic at the Nemirov stage of fracture formation, simultaneously with Goryn, Lutsk, Teteriv and Nemyriv fault zones as a result of the junction of two ancient microplates — Fennoscandia and Sarmatia.

**Key words:** Ukrainian Shield, Sushchany-Perga fault zone, Perga tectonic joint, structural- and-textural elements, deformations, stress fields.

**Introduction.** The main results of tectonophysical studies of the Sushchany-Perga fault zone (SP) are presented in this article. It is situated on the northwestern part of the Ukrainian Shield (US) and separate Volyn Domain (VD) from Osnytsk-Mikashevichi igneous belt (OMIB).

The SP fault zone separates granitoids of the Zhytomyr (2.06—2.08 Ga) and Osnytsk (1.99 Ga) complexes deforming them as a sinistral strike — slip fault and uplifting the Tamoshgorod dyke (1.79 Ga) as a dextral strike — slip fault type [Gintov, 2014]. On the modern stage of investigations, SP fault zone is considered as one of the fault zones that

was formed at the Nemyriv stage of faulting in the Late Paleoproterozoic, simultaneously with Goryn, Lutsk, Teteriv and Nemyriv fault zones, due to the junction of two ancient microcontinents — Fennoscandia and Sarmatia [Bogdanova et al., 1996, 2013; Gintov, Pashkevich, 2010; Mychak, 2016; Gintov et al., 2018] (Fig. 1).

SP fault zone has been known since the beginning of the last century due to the presence of a unique rare metal mineralization. Since the 1920s, it was studied by M.I. Bezborodko, V.I. Luchitsky and L.G. Tkachuk. In the 1940—90s, I.I. Gurvich, N.A. Bezpalko, L.S. Galetsky, L.B. Zubkov, S.V. Metallidi, S.V. Nechaev,

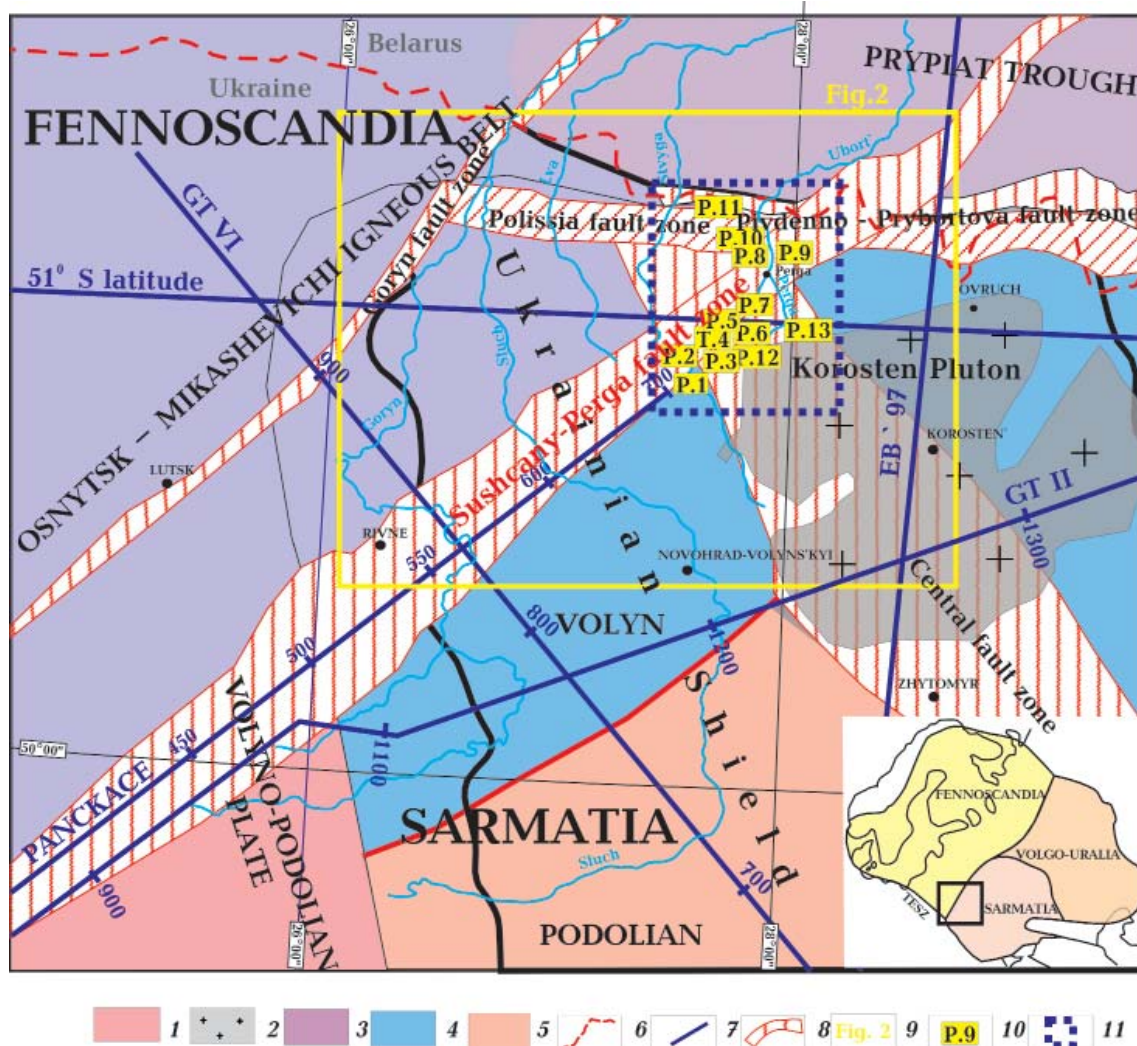


Fig. 1. Tectonic sketch of the main tectonic units of the Fennoscandia and Sarmatia crystalline basement [modified after Krylov, 1988, Starostenko et al., 2018]. The inset map to the right down shows the subdivision of the East European Craton into the three segments: Fennoscandia, Sarmatia and Volgo-Uralia [Bogdanova, 1993]. *Paleoproterozoic crust*: 1 — East European craton (Ukrainian Shield, KP — Korosten pluton), Volyno-Podolian plate, Prypiat Trough; 2 — 1.80—1.75 Ga Korosten pluton (KP), anorthosite—mangerite—charnockite—granite plutons; 3 — 2.0—1.95 Ga Osnytsk-Mikashevichi Igneous belt; 4 — 2.2—2.1 Ga Volyn and Ros domains. *Archean crust*: 5 — 3.7—3.8 Ga Podolian domain. *Others*: 6 — Ukrainian border, 7 — Seismic profiles: EUROBRIDGE'97 (EB'97), PANCAKE, VI and II geotransverses (GT VI and GT II); seismotomographic crosssection along 51°00' southern latitude; 8 — fault zones; 9 — position of the Fig. 2 — geological scheme of the crystalline basement of the western part of the Ukrainian Shield; 10 — the points of the field work in the Perga tectonic joint; 11 — research area.

A.G. Marchenko and others studied metallogeny and mapped this zone. In this period SP fault zone was studied by gravimetric (scale is 1:200 000—1:50 000) and aero-, land magnetic (scale is 1:50 000—1:10 000) methods (O.L. Polivanchuk, V.M. Egorov, O.V. Teslenko, V.I. Starostenko, M.P. Koryak etc.).

Due to geophysical data SP fault zone has been traced to the south-west and north-east along its all length by almost 300 km. Detailed

geological studies were concentrated mainly in the Perga tectonic joint (PTJ) (Fig. 2). It is associated with the main metallogenic prospects of the region and formed as a result of intense tectonic activation, magmatism and metasomatic rocks substitution [Ponomarenko et al., 2017].

**Geological and geophysical setting.** The SP fault zone is up to 3 km of width on the flanks and up to 8—10 km of width in the mid-

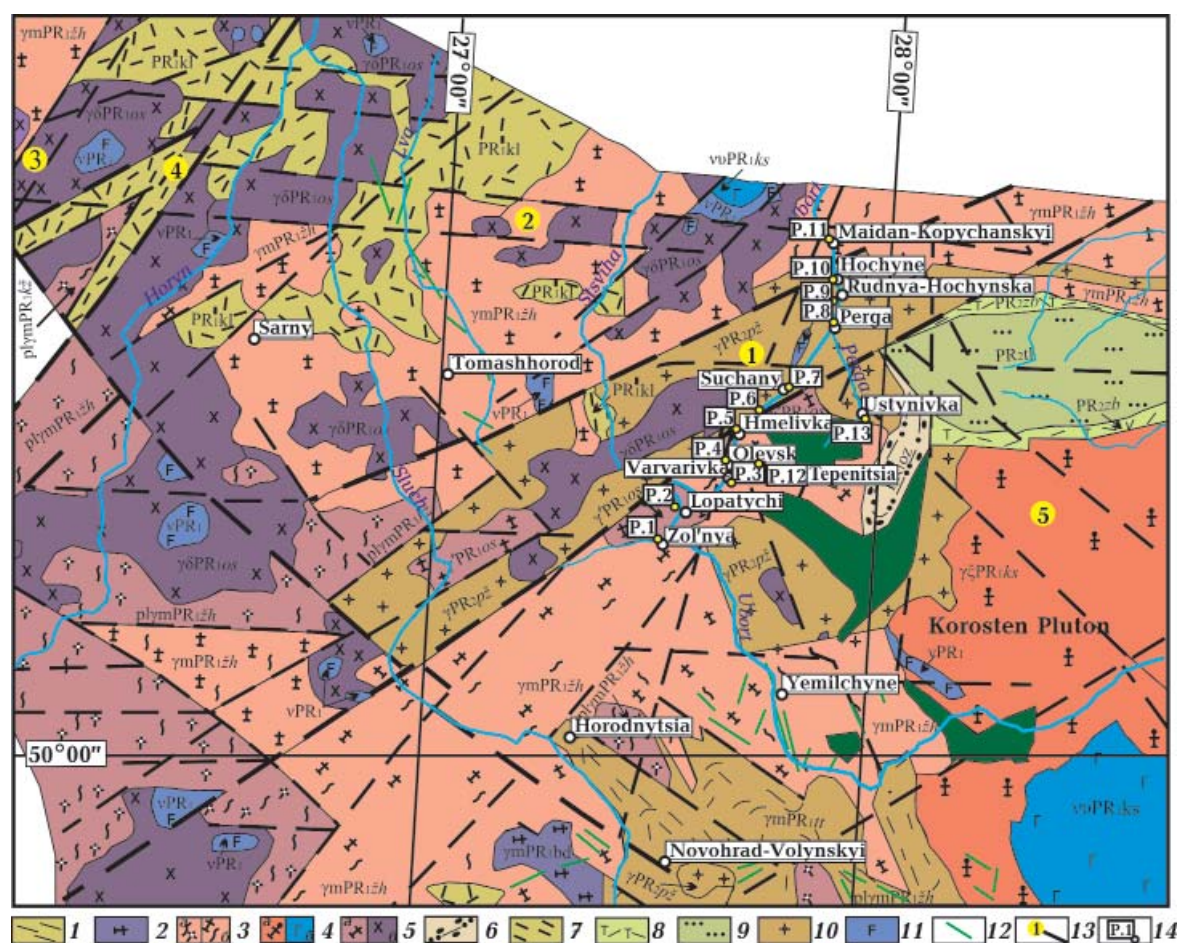


Fig. 2. Geological scheme of the crystalline basement of the NW part of the Ukrainian Shield scale is 1:1 000 000 (modified from [Scherbak, Volodin, 1984]): 1 — gneisses of the Teteriv series; 2 — granitoids of the Berdychiv complex; 3 — Zhytomyr complex (a — plagiogranites; b — migmatites); 4 — Korosten complex (a — gabbro anorthosites; b — rapakivi granites); 5 — Osnytsk complex (a — plagiogranites; b — migmatites); 6 — sedimentary rocks of the Ozeriany suite of the Pugachivka series; 7 — volcanic rocks of the Klesiv series; 8 — rhyolites of the Zbrankiv suite of the Ovruch series; 9 — quartzites of the Tovkachiv suite of the Ovruch series; 10 — granites of the Perga complex; 11 — gabbroids; 12 — dyke complex; 13 — fault zones (numbers in circles): 1 — Sushchany-Perga, 2 — Polissia, 3 — Horyn, 4 — Lutsk, 5 — Central; 14 — places of the field tectonophysical works carried out within the Perga tectonic joint.

dle part and trends in 50°NE direction within the US at a distance of ~150 km. Within the open part of the Ukrainian Shield, geologists have identified several differently oriented elementary faults (in tectonophysical terminology — shear zones) — Khochyn, Yastrubets, Golovny, Southern, Sushchany, Ustynivka, Yurivka, Ubort, Perga, Plotnytsk [Romanyuk, 2013; Ponomarenko et al., 2017]. The shear zones of various orientations are considered to be originated during long time in the different tectonic stress fields [Gintov et al., 2017].

The SP fault zone intersects the Polissya and Central fault zones of the NW ori-

entation (see Fig. 1, 2), fragments of which are traced in the SE direction through the Korosten pluton to the Kocheriv fault zone agree with [Metalidi, Nechaev, 1983], and further to the SE through Rosyn Domain, connecting with the Lelekiv fault zone of the Ingul Domain [Mychak, 2015].

The OMIB belongs to the Fennoscandian segment of the East European Craton, and the other tectonic units are included in the Sarmatian segment (see Fig. 1) [Bogdanova, 1993; Bogdanova et al., 2008]. The NE orientated OMIB is located in the northern part of the study region, where metamorphosed

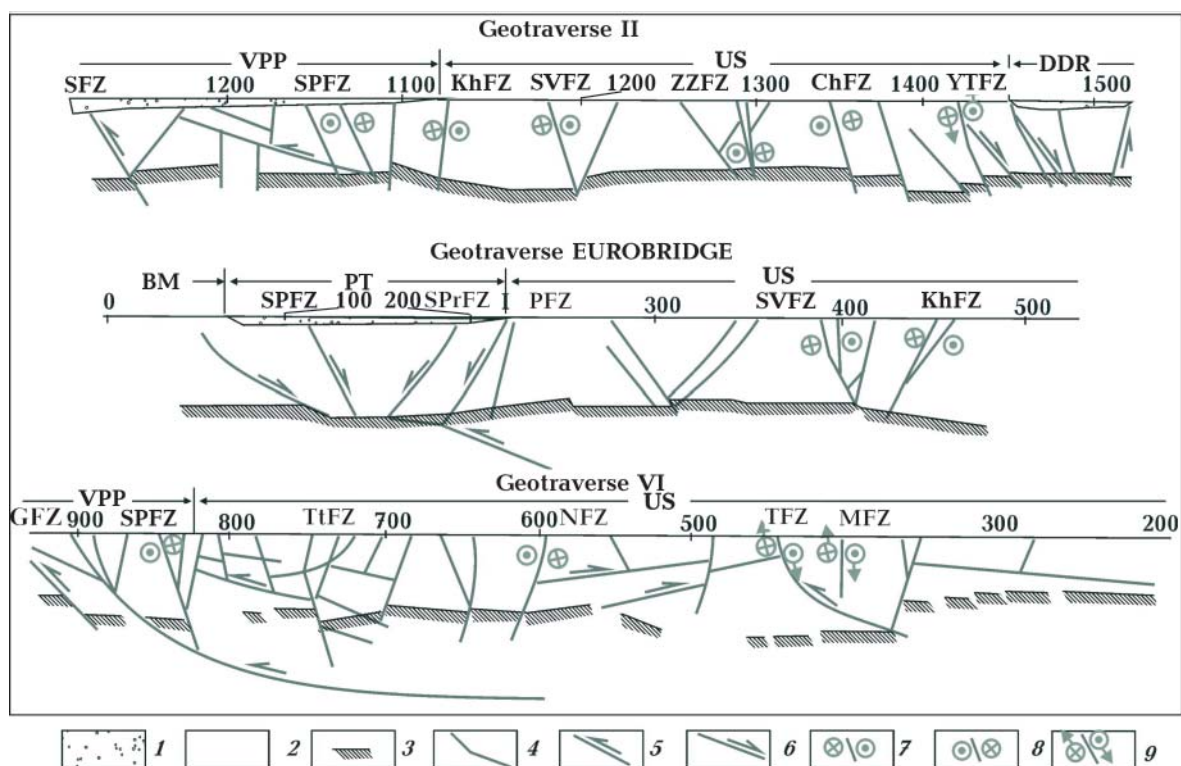


Fig. 3. Kinematic characteristics of the main fault zones along the seismic profiles: II and VI DSS geotraverses and WARR EB`97 profile [Gintov, 2019]: 1 — sedimentary cover, 2 — crystalline rocks of the earth crust, 3 — Moho surface, 4 — fault zones, 5–9 — kinematic signs (5 — thrust fault, normal fault, underthrust fault, 6 — reverse fault, 7 — dextral strike — slip fault, 8 — sinistral strike — slip fault, 9 — reverse or normal strike — slip fault (depending on the slope of the zone). Regions: VPP — Volyno-Podolian plate, US — Ukrainian shield, DDR — Dnieper-Donetsk Rift, BM — Belarusian massif, PT — Pripjat trough. Fault zones: SFZ — Stokhodsk, SPfZ — Sushchany-Perga, KhfZ — Khmelnyk, SVfZ — Sarny-Varvarivka, ZZfZ — Zvizdal-Zaliska, ChfZ — Chernobyl, YfZ — Yadliv-Traktemyriv, SPfZ — South Pripjat, PFZ — Polissia, GFZ — Goryn, TtFZ — Teteriv, NFZ — Nemyriv, TFZ — Talnivka, MFZ — Moldovka.

sedimentary and volcanic Palaeoproterozoic rocks were intruded by many bodies of granodiorites—diorites in the period 2.0—1.95 Ga.

The other three domains: Volyn, Podolian and Ros are related to the Ukrainian Shield. The Podolian domain (PD) is the oldest block in the region where rocks of granulitic metamorphic grade mafic granulites and pyroxene-bearing gneisses of the Archean age (3.4—2.6 Ga) are exposed among Palaeoproterozoic granitoids of different composition. This domain represents the oldest stage of evolution of the continental crust with formation of the Archean granulitic cores [Chekunov, 1989]. The Volyn domain (VD), located between the PD and the OMIB includes mostly gneiss formations of the Teteriv complex of amphibolitic metamorphic grade with gra-

nitic intrusions of the Zhytomyr complex with an age of 2.06 Ga [Shcherbak et al., 1998]. Subsequent fault activation, accompanied by anorogenic magmatic activity, represented by intrusions of various compositions, from peridotites to granodiorites, is caused by tectonic events occurring within the limits of the OMIB. As a result of a successive stage of tectonic stabilization of the craton, terminated by a second episode of anorogenic magmatism (1.8—1.73 Ga), the large, complex Korosten Pluton (KP), composed of rapakivi granites and anorthosites, was formed. At the platform stage, the domain was covered by sedimentary and volcanic rocks. The Ros domain, located in the southeastern part of the region, is made of sedimentary and volcanic rocks subjected to amphibolites grade of meta-

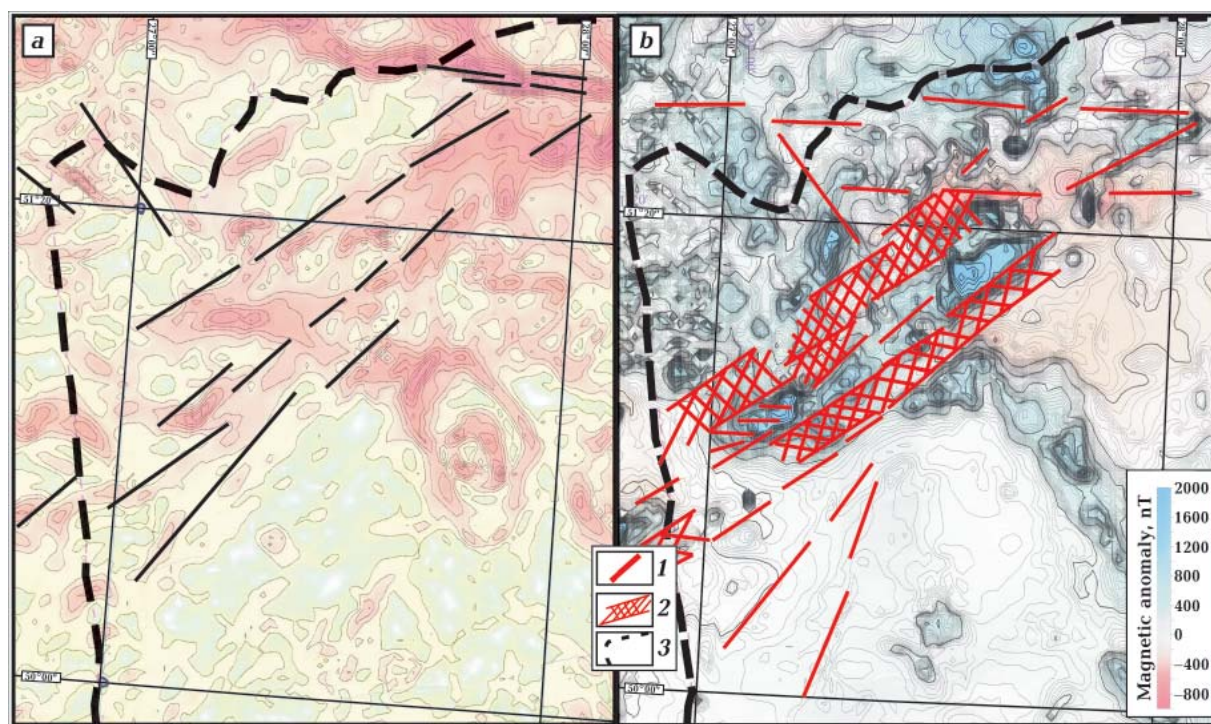


Fig. 4. Geophysical fields of the Sushchany-Perga fault zone [Yentín et al., 2002]. Scale is 1:500 000: *a* — residual gravity anomalies  $\delta g$  (Suxova—Nigard formula,  $R=8$  km,  $r=1$  km); *b* — anomalous magnetic field (isodines  $Z_a$  and  $\Delta T_a$ ); 1 — echeloned shears; 2 — shear zones; 3 — contour of US.

morphism (amphibole-bearing and biotite gneisses, plagiogneisses and amphibolites).

The SP fault zone is bounded by granitoids of the Osnytsk complex with bodies of sub-silicic rocks and persilicic volcanic outliers of the Klesiv series on the NW. Granitoids of the Zhytomyr complex and gneisses of the Teteriv series, as well as (on the north) quartzite-sandstones of the Ovruch series are developed from the SE (see Fig. 2).

Granitoids of the Zhytomyr and Osnytsk complexes deformed to mylonites and blastomylonites are also developed in the zone itself. In the northeastern part, at the intersection with the WE Trending Polissia fault zone, within the Perga tectonic joint, metasomatically and dynamometamorphically altered granites of the Perga complex. Structural and textural features of these granites are developed, among which the following varieties are distinguished: Khochyn, Ustyniv, Perga, Lviv, Yastrub, as well as aplites, vein granites and metasomatites [Metallides, Nechaev, 1983; Gintov, 2005; Kostenko, 2010], which

differ mainly in grain size and variations of textural features.

In the study region, SP fault zone was studied by Soviet deep seismic sounding (DSS) and modern wide-angle reflection/refraction (WARR) methods. Here, field researches are carried out at different times. The deep structure of this region is defined by II and VI DSS profiles [Ilchenko, 1985; Sollogub, 1986, 1988; Sollogub et al., 1988], modern WARR deep seismic researches PANCKAKE [Staroctenko et al., 2013], EUROBRIDGE 97 profiles [Thybo et al., 2003] and seismotomographic cross-section along  $51^{\circ}00'$  southern latitude [The creation ..., 2006].

We are mainly interested in the reflectors isolated on the P and S waves, according to which it is possible to trace the depth of the SP fault zone and the earth crust structure.

The SP fault zone crosses the Moho surface on the all three profiles (Fig. 3). On the EUROBRIDGE profile, the SP fault zone reaches the surface of the crystalline basement under the Prypiat Trough, crossing the Moho surface

and dipping in the mantle. On the geotraverse VI, SP fault zone crosses Moho, connecting with the surface of Fennoscandia and Sarmatia subduction zone and goes to a 100 km depth, and according to seismotomography its depth reaches 300—400 km [Gintov, 2019].

From NW to SE VI geotraverse crosses OMIB, VD, PD and the SP fault zone (see Fig. 1). SP and Horyn fault zones dipping to the SE and can be traced to the Moho surface at a depth of 55 km in the obtained section [Ilchenko, 1985; Sollogub, 1986, 1988]. It was reinterpreted the seismic materials and constructed a seismic tomographic model along the VI line of geotraverse that made it possible to clarify the earth crust structure in the vicinity of SP fault zone [Lysynchuk et al., 2019, 2020]. At the profile distances between the PC 900—840 in terms of the velocity structure (within the velocity values of 5.0 to 6.0 km/s) we can observe a trough down to the depth of 15 km which corresponds to the trough of the OMIB with the Paleoproterozoic crust. The OMIB is separated from the structure of the US by the Goryn and Sushchany-Perga fault zones. Further to the southeast, along the section line, we can observe velocity uplifts in the Earth's crust within the Ukrainian Shield, corresponding to the main tectonic domains. E.g. between PC 840—750, at the depth of 30 km and below, from the 7.0 km/s isoline of the lower crust top, there is a rise up to the surface with the speed of 5.0 km/s corresponding to the Volyn Domain. The Moho is located here at the depth of 45 km. In the Podolian Domain between 750—620 pickets, velocity uplift is marked at the depth of 25 km from the velocity isoline of 7.0 km/s in lower crust up to the surface at PC 650 with a velocity of 5.25 km/s. The upper crust of the Volyn block lies at depths of 7—21 km, the middle crust — at depths of 20—35 km, and the surface of Moho lies at a depth of 45—50 km [Lysynchuk et al., 2020].

Geotraverse II [Sollogub et al., 1988] is sub-parallel and close to the PANCAKE profile (see Fig. 1) [Starostenko et al., 2013]. It allows us to consider the structure of the SP fault zone along its central part and across the main domains of the study area: Volyno-Po-

dolian plate and Volyn Domain of the western slope of the US. According to the PANCAKE section data, a thick layer of the upper crust lies at a depth of 25 km. It includes low velocity lenses (with  $V_p \sim 6.1$  km/s) at depths of 12—18 km and 15—18 km respectively, which traced to the Carpathians and marks at depths of 12—18 km within the VD and PD on the EB'97too. The middle crust has a thickness of ~9 km in depth ranges from 20—25 km to 27—33 km. The lower crustal layer (down to Moho at 44—48 km depth) has a high velocity with  $V_p = 7.2 \div 7.4$  km/s.

The EB'97 profile crosses SP fault zone in the crossing point of the Pivdenno-Prybortova, Polissia fault zones on the northern slope of the Ukrainian Shield between Korosten pluton and Prypiat trough (see Fig. 1). EB'97 gives a clear seismic reflection of subduction markers of structures and traced under Moho. This is recognized in [Ilchenko, 2002; Thybo et al., 2003], where a two-dimensional inversion of the travel time of seismic waves was performed. In [Bogdanova et al., 2006] these data are supplemented by density modeling using the dependences of density on the velocities of *P*- and *S*-waves, as well as data from petrology and other geological data.

The seismotomographic cross-section along 51°00' S latitude also confirms the existence of the dipping of Fennoscandia under Sarmatia, which is traced to the upper mantle [Gintov, 2019] and the formation of a boundary between the ancient microplates by Gorin and Sushchany-Perga fault zones in the earth's crust. Section along 51°00' S latitude compiled by I.K. Pashkevich et al. [The creation..., 2006] intersects OMIB, Volyn Domain and Korosten Pluton. It crosses of the SP fault zone in the area of its intersection with the Central fault zone of the Ukrainian Shield (see Fig. 1). The Central fault zone was traced to a surface of the 50 km depth and dipping to the SE. Seismotomography data indicate a sloping depression of the relatively high-velocity lithosphere of the SW edge of the East European Craton under the relatively low-velocity lithosphere of adjacent plates [Gintov, Pashkevich, 2010].

Thus, according to the seismic data giv-

en above, the SP fault zone was formed as a result of the activation of the joint zone of Fennoscandia and Sarmatia. The SP and Horyn faults zone separate OMIB from the US structure. Moho depths below the OMIB increase to 50 km and more, whereas the average depths beneath the PD and VD are about 45 km. The PT and KP are outlined by a Moho uplift to a depth of 35–37 km.

According to geophysical data [Gintov, 2005], the SP fault zone is traced to NE to the Prypiat trough, and SW in the Volyno-Podolian plate basement and continues as the Kremenets fault zone. The zone is quite well manifested in gravity and magnetic fields. It is most clearly fixed by the large gravity step of the NE orientation (Fig. 4, *a*). It limits the most intense Rokytnia gravity maximum in the SE that is located outside the study area.

Gravity step associated with SP fault zone. It has a width of up to 8 km, amplitude of up to 10–18 mGal and extends from the N boundary of the US (near the Perga town to the Ostrog town) and further SW toward the Precarpathian trough. Several (2–3) localized linear anomalies are clearly traced on the residual gravity anomaly map  $\delta g$ , which correspond to some shear zones of SP fault zone.

In the magnetic field, the SP fault zone is characterized by the alternation of linear positive and negative anomalies in Fig. 4, *b*. Positive anomalies can be traced over the rocks of the Osnytsia complex with striped volcanic bodies and intrusions of the subsilicic rocks. Negative anomalies correspond to bands of tectonites and granitoids of the Zhytomyr complex. The nature of the increased gradients of the magnetic field indicates a dip of the SP fault zone in the NW direction in the average 50° to 80° angle at the SE edges of the positive anomaly.

**Methods.** Tectonophysical studies of the SP fault zone were started in 1985 by O.B. Gintov, V.M. Isai, V.B. Kobylansky, P.V. Bilychenko. The works were performed by the Gzovsky-Stoyanov structural-paragenetic method. Plastic (brittle-ductile) deformations of rocks were studied by measuring dynamometamorphic striation. The main results of these studies are in [Gintov, 2005].

The studying of the tectonites and secondary structural textural elements (STE) (striation (migmatite, granitogenesis), schistosity (crystalline and shale), cleavage) (classification agree [Shevchuk et al., 2002, 2013; Shevchuk, Pavlov, 2003]) (Fig. 5 *f–c*) were performed by the authors of this article. STE term we used in our article but it named *fabric* divided on the *foliation* and *lineation* in the English literature classification [Fossen, 2010].

Previously in the tectonophysical study of SP fault zone, not enough attention was paid to the rock fracturing of the crystalline basement. We determined that the brittle fracturing forms clear structural paragenesis. It allows us to determine the kinematics and stress-strain state of SP fault zone at late stages of tectogenesis when the rocks already were exhumated to the surface.

Processing and interpretation of field measurements of the STE of the rock fracturing were performed by structural-paragenetic method of tectonophysics for III-IV levels of depth [Stoyanov, 1977; Gintov, 2005] using the Stereonet program [Allmendinger et al., 2012; Cardozo, Allmendinger, 2013]. The planes of the STE are showed on stereograms by planes and poles on the upper hemisphere (Fig. 5). Cracks are showed on stereograms by poles, which are the intersection points of the normal to the plane of the crack and the upper hemisphere (Fig. 6).

**Tectonophysical studies of the Sushchany-Perga fault zone.** Tectonophysical studies were carried out on the outcrops of the river Ubort near villages: Zolnia (P. 1), Lopatichi (P. 2), Varvarivka (P. 3), Olevsk, (P. 4) Khmelivka (P. 5 and P. 6), Sushchany (P. 7), Rudnia-Khochynsk (P. 9), Khochyne (P. 10), Maidan-Kopyshchanskyj (P. 11), Tepenytsia (P. 12), and along the Perga River at the settlements of Perga (P. 8), Ustynivka (P.13) (see Fig. 1, 2 and Table 1). As mentioned above, the focus of the SP fault zone study was on the measurement of STE. Totally, the 113 measurements of striation, schistosity and cleavage were performed. It was possible only in 97 cases to establish azimuths and angles of their dips due to weathering of rocks. This study

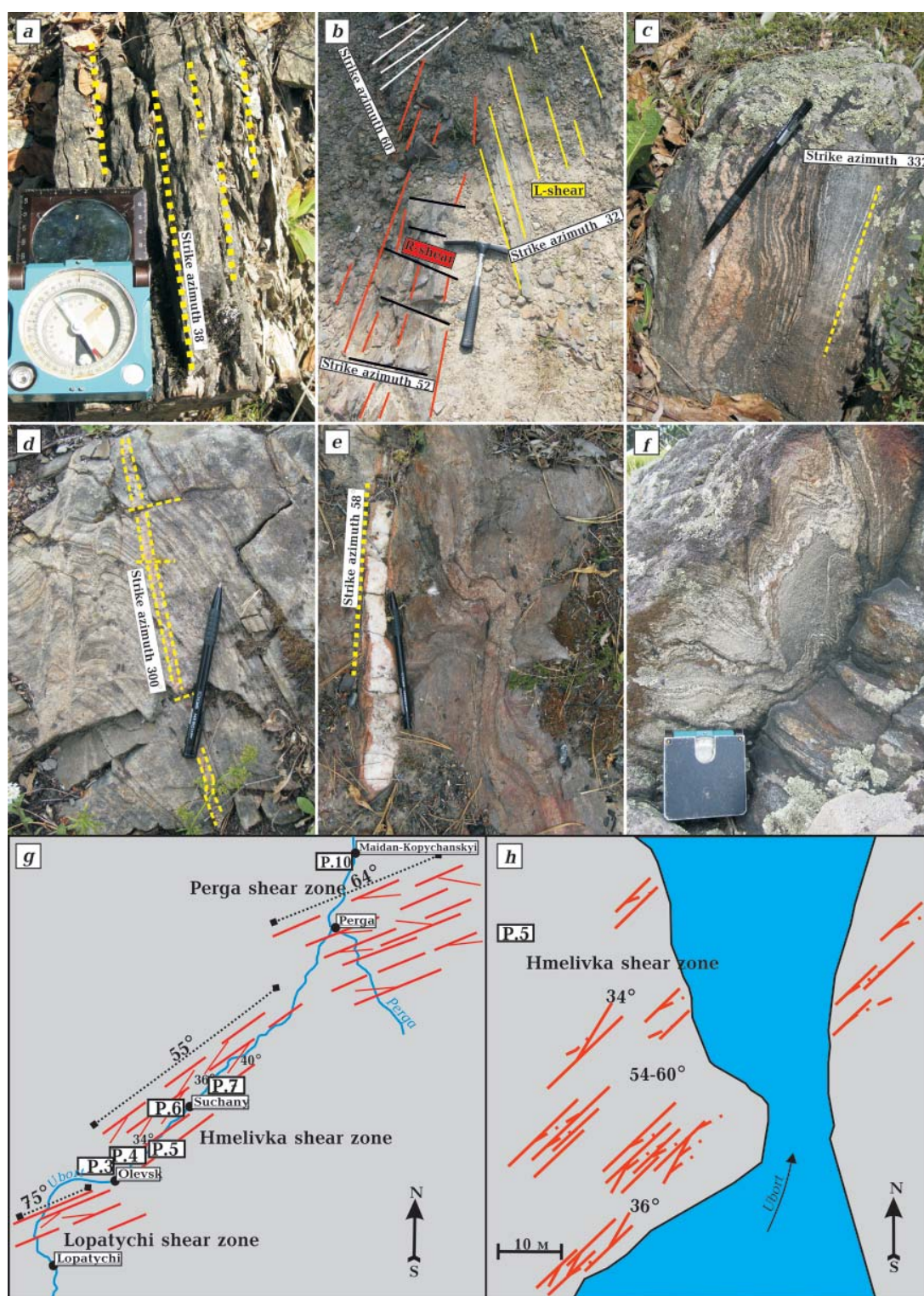


Fig. 5. Deformation structures in the rocks of the Sushchany-Perga fault zone [Mychak, Farfuliak, 2019]: *a* — tectonic stratification of Osnytsk complex granitoids. The left side of the Ubort River near Sushchany (P.7); *b* — fracturing of the Zhytomyr complex. The left side of the Ubort River near Khmelivka (P. 5); *c* — migmatite zoning in the Zhytomyr complex granitoids between Khochyne (P. 10) and Maidan-Kopyshchanskyj (P. 11); *d* — The gneiss fold is broken by granite vein in the horizontal area. The left side of the Ubort River near the Varvarivka (P. 3); *e* — The quartz vein lies along the fold of the gneiss. The left side of the Ubort River near Khmelivka (P. 5); *f* — Microfolding is situated in the vertical wall of the gneiss outlet. The left side of the Ubort River near Olevsk (P. 4); *g*, *h* — tectonophysical scheme of orientation of the structural and textural elements within the Perga tectonic joint.



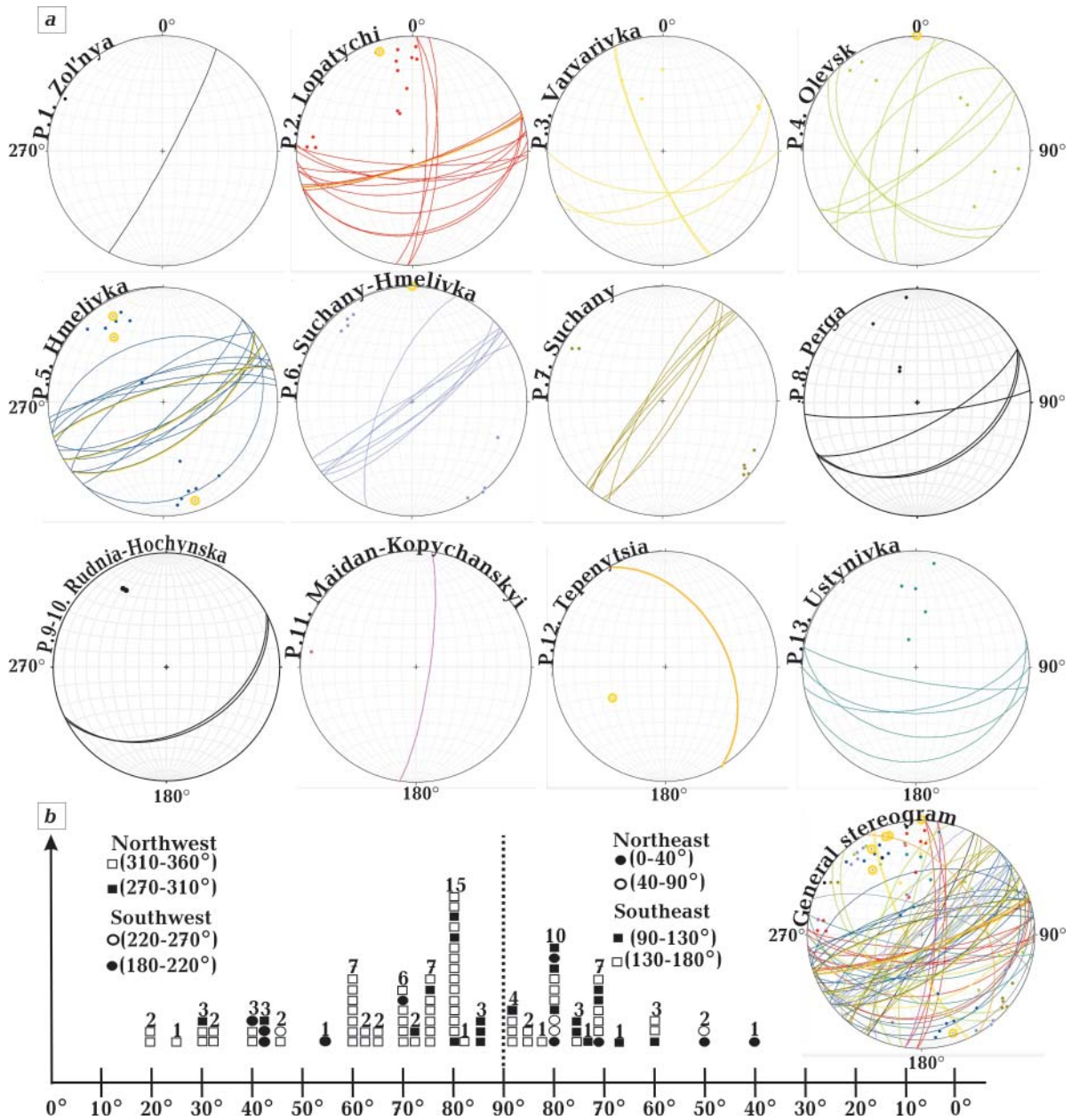


Fig. 6. Elements of planes (a) and histogram of azimuths and dip angles (b) of structural and textural elements of rocks within the studied area of the Sushchany-Perga fault zone. The numbers of points correspond to the areas in Figs. 1, 2, 5.

allowed to distinguish shear zones and their sequence and to reconstruct the stress-strain state of rocks. In the same area we carried out 462 measurements of brittle cracks strike and dipping.

It makes possible to determine kinematics and the stress-strain state of the SP fault zone for the later stages of tectogenesis. In addition to our own data we used previous field tectonophysical data of O.B. Gintov`

for generalization in the context of our task.

**Structura-and-textural elements of the Sushchany-Perga fault zone.** The SP fault zone has clear structural and textural anisotropy due to our field tectonophysical study (Fig. 6). Stratification and mylonitization sometimes reach high intensity (Sushchany village, Fig. 6, a), that was consider to be sedimentary bedding (the so-called «perga suite» [Gintov, 2005]).

The dipping trend and angles of shale, migamite and granite-gneiss striation are shown in Fig. 6, *a, b* that in table 1. The majority of them (62 planes) is steeply dipping with angles 70—90° and 34 planes dipping to the NW. The incline dipping (20—60°) is in 34 % (35 measurements) cases and in 80 % (28 measurements) cases of that dipping to the NW.

The multiphase development of SP fault zone was accompanied by the formation of differently oriented shear zones (see Fig. 7 and Table 2), which relative age was determined by the nature tucks in of the L and R-shear fractures.

The shear zones and deformation phases were identified in the order of decreasing age: Khmelivka — 140/88 (strike azimuth 50°), Sushchanska — 130/88 (strike azimuth 40°), Perga — 334/50 (strike azimuth 64°), Rudnia-Khochynsk — 345/42 (strike azimuth 64°),

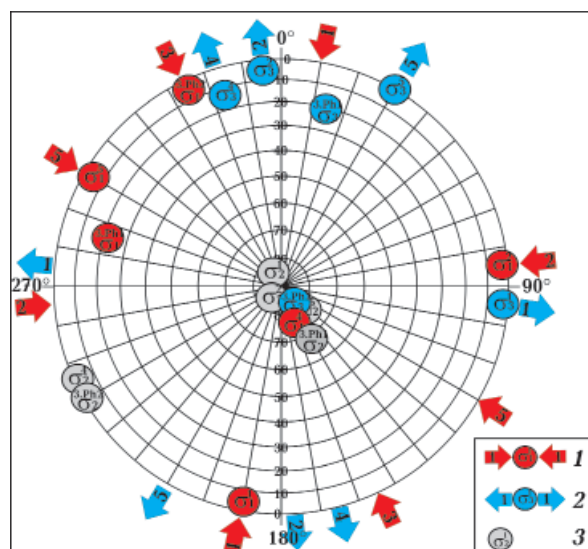


Fig. 7. The results of the inverse kinematic task for the Sushchany-Perga fault zone: 1 — Compression ( $\sigma_1$ ); 2 — extension ( $\sigma_3$ ); 3 — intermediate principal stress ( $\sigma_2$ ) and their superscript is stress strain deformation phases (Table 2).

**Table 1. Coordinates of the STE bedding in the Sushchany-Perga fault zone**

Points Fig. 1, 2	Coordinates		Locality	Strike azimuth STE (average value)	Dip azimuth STE	Rocks
	Latitude	Longitude				
P. 1	51°05'02,5"	27°31'0,3"	Zolnya	20°	NW	Osnytsk granites
P. 2	51°09'47,5"	27°32'41,4"	Lopatychi	70—80° (75°)	NW	Osnytsk granites
P. 3	51°12'55,9"	27°35'17,6"	Varvarivka	60°	NW	Granitoids of the Zhytomyr complex
				300°	NE	
P. 4	51°14'11,3"	27°40'1,28"	Olevsk	50—60° (65°)	NW NE	Osnytsk granites
P. 5	51°14'54,8"	27°40'59,9"	Hmelivka	50—60° (55°)	NW NE	Osnytsk granites
P. 6	51°16'49,3"	27°43'57,7"	area Suchany- Hmelivka	65°	NW	Osnytsk granites; Granitoids of the Zhytomyr complex
					NE	
P. 7	51°18'21,2"	27°45'48,6"	Suchany	30—55°	NE	Lvivkivsk granites
					NW	
P. 8	51°23'46,0"	27°53'28,6"	Perga	64°; 84°	NW	Perga granites
P. 9	51°26'14,4"	27°53'54,1"	Rudnya-Ho- chynska	62—70° (64°)	NW	Perga granites
P. 10	51°27'59,2"	27°52'51,6"	Hochyne	—	—	Perga granites
P. 11	51°30'57,8"	27°52'33,1"	Maidan- Kopychans-kyi	12°	W	Granitoids of the Zhy- tomyr complex
P. 12	51°13'33,5»	27°41'44,6»	Tepenytcia	315°	NW	Pink-gray granite
P. 13	51°20'14,8»	27°56'1,7»	Ustynivka	75—80°	NNW	Ustynivka granites

Lopatychska — 345/83 (strike azimuth 75°) [Gintov, 2005].

1. *Khmelivka shear zone* (P. 4—P. 7, see Fig. 4, 5, d). This zone trends to the (54—60°) NE (see Fig. 5, d) with dip angle a 70 to 88° NW (see Fig. 6 and Table 1). Such shears are found in the outcrops along the Ubort River on the Olevsk` NW outskirts, as well as on the Khmelivka and Sushchany villages SW and N outskirts. Elementary shears are represented by mylonites and blastomylonites. Brittle displacements along the shears are not observed. There are left and right S-Z tucks under the shears. Elementary shears are combined into echeloned fault zone (see Fig. 5, e).

2. *Sushchany shear zone* (P. 1, P. 4—7, see Figs. 2, 5, d). This zone strikes in a NE direction at an angle of 40° with a dip to the SE at an angle of 80—85°. The L-shears of this zone have the same elements as the axial plane. R-shears strike with 34° in a NE direction, dip-

ping to a NW angle of 82°. It is established that along the shearing zone in the process of its formation there were left-slip — strike-slip movements.

3. *Perga shear zone*. This zone is represented by Perga (see P. 8, Fig. 4), Osnytsk (P. 6), Ustyniv (P. 13) granites. Perga granites are considered intrusive rocks and are genetically related to Korosten pluton [Sheremet, 2013]. The obtained dates for cirtolite (1760±5 Ga [Shcherbak et al., 2008]) confirm the affinity with this complex [Dubina, Kryvdik, 2014].

Two phases of the strains are defined in Perga shear zone. The first phase has strike from 58 to 64° (see Fig. 5, 6, g) with a NW dip at an angle of 72° and is L-shear. Their strike coincides with the strike of the axes of magnetic anomalies (see Fig. 4, b) in the area of distribution of these shears. Shears are composed mainly of mylonites. There are right tucks in of the NE 84° strike, at the 82° angle

**Table 2. Deformation phases of the Sushchany-Perga fault zones according to the structural-textural elements**

№	Phases	Axes of stress			Kinematics	
		$\sigma_1$ (compression)	$\sigma_3$ (extension)	$\sigma_2$ (intermediate principal stress)		
1	Hmelivka	185/02°	95/02°	330/88°	Left-lateral strike-slip	
2	Suchany	85/05°	355/05°	220/85°	Right-lateral strike-slip	
3	Perga	Phase 1	286/20°	12/20°	150/70°	Right-lateral strike-slip
		Phase 2	335/05°	140/85°	240/02°	Thrust fault
4	Rudnia-Hochynsk	150/78°	342/12°	246/02°	Normal Downthrow fault	
5	Lopatychi	300/07°	30/02°	135/83°	Right-lateral strike-slip	

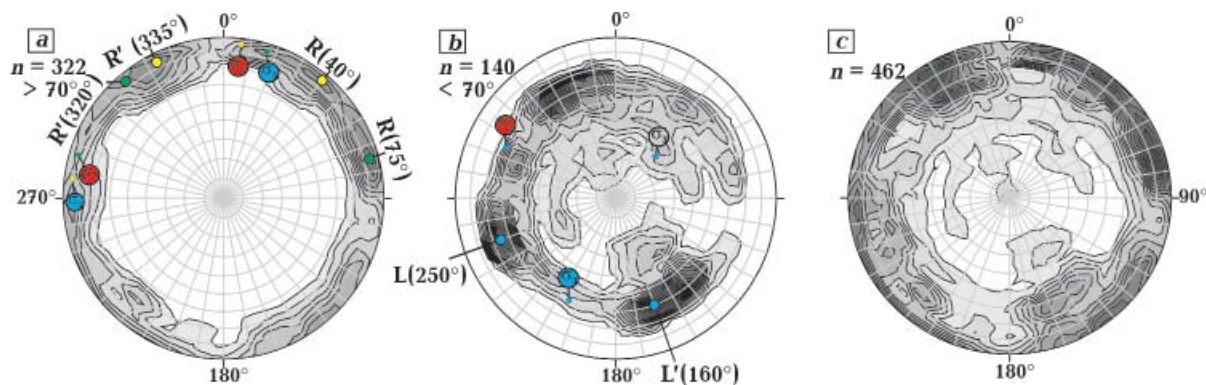


Fig. 8. Stereograms of elements of occurrence (dip azimuths) of rock cracks within the Sushchany-Perga fault zone: a — subvertical dippig of the shears (70—90°); b — inclined cracks (40—70°); c — common stereogram of the dip cracks.

of the dipping in the NW rhumbs under the shears. They were identified as R-shear, which corresponds to the right-lateral shear.

4. *Rudnia-Khochynsk shear zone* (P. 9, 10, see Fig. 2) morphologically is a downthrow with a gentle NW dipping at an angle of 40—42° and has a strike of 64°. The area is represented by Perga granites, thin schistose, mylonites and cataclasites.

5. *The Lopatychi shear zone* (P. 2, see Fig. 2) is represented by the Osnytsk complex of granites and strikes in the NW rhumbs at an angle of 75° with a dipping to the NW of 60—70° (see Fig. 4, d). There are left and right S-Z tucks in at an angle of 37 and 21° with a NW dipping at an angle of 45° with a left type of displacement, under the shears.

After analysis of the inverse kinematic task (see Fig. 7 and Table 2), we can conclude that the Khmelivka and Sushchany phases of SP fault zone of strains are similar to the phases of formation of the Nemyriv and Khmilnyk fault zones. Therefore, these phases can be corresponding to the Nemyriv faulting stage. Similar [Gintov, 2005] Sushchany faulting phase is observed in both the Nemyriv and Khmilnyk fault zones. In the Khmelivka shear zone, Zhytomyr granites have been recycled into blastomylonites, mylonites and migmatites. In the Sushchany shear zone, Osnytsk granites are mylonitized.

The SP fault zone was quite active during the time of the interaction between Fennoscandia and Sarmatia at the Rudnia-Khochynsk and Perga phases [Bogdanova et al., 1996, 2013]. Such interaction in the form of compression and tension, thrust and downthrow occurred during the Perga complex formation (1.80—1.70 Ga) with increased fracturing, stratification or schistosity and propagation of STE.

**The nature and conditions of the Sushchany-Perga fault zone fracturing.** The crack systems of the shearing and rupturing (represented by granite and quartz reefs, pegmatites) are characteristic structural elements of the study area. In one case, they have the same elements of occurrence with STE and in another case they cross the rocks of the crystalline basement, including STE shear zones.

The kinematics of SP fault zone by fracturing is shown in Fig. 8. Cracks are often subvertical (70 %), although sometimes there are systems of inclined ruptures (30 %). The angles between the paragenetically linked cracks indicate the most frequent R-shear formation in the condition of the I-II levels depth. The study of the main systems of cracks of the SP fault zone allows us to assess the evolution of its stress-strain state in the context of the general history formation of the Volyn domain of the US in the Proterozoic stages.

According to the measurements of the subvertical cracks (Fig. 8, a) two stress fields are determined:

R (40/86°) — R' (335/86°),  $\sigma_1$  — 07/86,  $\sigma_3$  — 277/86,  $\sigma_2$  —  $\perp$ , right-lateral shear;

R (75/85°) — R' (320/85°),  $\sigma_1$  — 287/85,  $\sigma_3$  — 17/86,  $\sigma_2$  —  $\perp$ , left-lateral shear.

In accordance with measurements of the inclined cracks (Fig. 8, b), the stress field (L (250/65°) — L'(160/60°),  $\Sigma_1$  — 295/25,  $\sigma_3$  — 207/30,  $\sigma_2$  — 45/60) is close to the fifth deformation phase (Lopatychi). Most likely, this field began to form immediately after the last phase of STE.

Turning to the question of Ore-bearing Sushchany-Perga fault zone it should be noted [Nechaev et al., 2019] that the most number of deposits and ore occurrences of US minerals are associated with fault zones. Faults serve as channels for the entry into the upper layers of the platform covered of hydrogen-gas fluids and the exhalation of chemical elements in the form of free atoms and ions. The structures of the extension (rupture cracks) the most penetrating for upward flows in the fault zone are, then in decreasing order: Riedel shears and next L-shears. However it is proved [Nikolaevsky, 1982; Gintov, Isai, 1984] that in the process of plastic deformation of rocks in the fault zone, even during compression, there is dilatancy — loosening of the rock, which reaches a degree of one to several percent. This is clearly seen by gravimetric data, which indicate to the decompression of the earth's crust in fault zones.

The process of deposit formation and the nature of mineral ore formation are multi-stage ones and stretched over time. It is first

of all related to the kinematic features of the Precambrian plate tectonic process, which is primarily due to the orientation of the fault zones during their initiation, as well as their stress-strain state during activations. The distribution area of metasomatites of great importance for the localization of ore fields and around the general mineral deposits as well as for localization in the hard blocks of the ancient basement.

As mentioned above, the SP fault zone was influenced by several phases of activation (like lateral shear and downthrow — upthrow), especially in connection with the subduction-collision processes that occurred during the joining of the Fennoscandia and Sarmatia microcontinents.

In the area of intersection with the Central fault zone within the Perga joint, we have the Perga beryllium (genthelvin) deposit with gold ore, rare metal and sulphide mineralization, including Sn. The Yuriyivsky massif of titanium-bearing gabbroids, Yastrubets massif of syenites (comes from the Korosten pluton [Mitrokhin, 2011; Dubyna, Kryvdik, 2014]), Sushchany disthene deposit, as well as, placers and bed-rocks of the tin (cassiterite), tantalum-niobium ores are situated in the field of Perga granites. Scheelite skarns with superimposed sulfide and precious metal (Ag, Au) mineralization and other minerals are known in the area [Bogdanova et al., 2004; Kondratenko, Kostenko, 2015; Galetsky et al., 2016; Ponomarenko et al., 2017; Nechaev et al., 2019]. Molybdenum mineralization is located within the area of distribution of medium-coarse-grained leukogranites of the Ustynivka ore in the area of propagation [Kondratenko, Kostenko, 2016].

**Discussion.** The tectonic SP fault zone is a south-eastern boundary of the Osnytsk-Mikashевичi volcanic-plutonic belt and is one of the frontal parts of the strike-slip structure, which was formed in the compression geodynamic conditions due to relaxation tectonic movements on the later stages of the two microplates of the Eastern European craton collision: Fennoscandia and Sarmatia (see Fig. 1). Modern deep seismic sounding data show the process of paleosubduction by

Fennoscandia under Sarmatia [Bogdanova et al., 2006].

The author [Gintov, 2019] substantiates the assumption of the existence of two paleosubductions of Fennoscandia under Sarmatia according to seismic and tectonophysical data and that the Suzhany-Perga fault zone was formed as a result of the second paleosubduction.

The authorsin [Ponomarenko et al., 2017] proved that components of rocks such as fluorine and lanthanides participated in the crystallization of fluorite of the Sushchany-Perga fault zone of the VD of the US, which have a mantle origin. This is one of the evidences that SP fault zone has a mantle origin.

That is, on the EUROBRIDGE 97 profile a reflector was found at depths of 45—80 km, from the northern edge of the Prypiat trough to the middle of the Korosten pluton [Ilchenko, 2002; Thybo et al., 2003], which is the joint zone of Fennoscandia and Sarmatia plates.

Thus, along the PANCKAKE and EB`97 profile in the SP fault zone and adjacent areas the high velocities may represent modified lower crust, at least in part, by magmatic underplating or mafic intrusion, as interpreted in other locations worldwide [Yegorova et al., 2004; Bogdanova et al., 2004, 2006].

The results of interpretation presented in the work allowed to clarify that formation of the Sushchany-Perga fault zone continued during at least five phases of deformation. They were accompanied by the formation of differently oriented shear zones: Khmelivka, Sushchany, Perga, Rudnia-Khochin, Lopatycki, which belong to the Nemyriv stage of faulting (~ 1.99 Ga).

We have established that the development of thrust fault and normal down throwfault types hears, which took place in an environment of compression and extension, respectively, is associated with the formation period of the Perga granitoids complex (1.80—1.70 Ga). This alternation of the compression and extension condition sent ailed resulted in the ore occurrences and deposits formation.

**Conclusions.** The tectonophysical research of the SP fault zone of the Volyn Do-

main of the western part of the US allows us identifying changes in the stress-strain state in space and time.

The formation of the SP fault zone occurred during at least five stages (five phases) of deformation according to structural/textural elements and three stages — according to jointing. It was accompanied by the formation of differently oriented shear zones, whose age has been determined using their structured relationship and near fault folding. The following shear zones and deformation phases are identified in the order of decreasing age: Khmelivka — 140/88 (numerator — dip azimuth, denominator — dip angle), Sushchany — 130/88, Perga — 334/50, Rudnia-Khochyno — 345/42, Lopatychi — 345/83.

The Khmelivka and Sushchany phases are

similar to the phases of formation of the Nemyriv and Khmilnyk fault zones of the Nemyriv stage. These shear zones cut and deform both Osnytsa (~1.99 Ga) and Zhytomyr granites (2.06—2.08 Ga). Thus, their age, as well as the whole Nemirov stage, is not earlier than about ~1.99 Ga. The Rudnia-Khochyno and Perga phases are a result of the SP fault zone activation at the time of the interaction between Fennoscandia and Sarmatia microcontinents. We determined that compression and extension interaction took place during the formation of the Perga complex (1.80—1.70 Ga).

The next step should be a detailed geological and geophysical study of other parts of the Sushchany-Perga fault zone within the Ukrainian Shield and its slope.

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## Внутреннее строение и кинематика Суцано-Пержанской зоны разломов Украинского щита по результатам тектонофизических исследований

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С целью выяснения внутреннего строения и кинематики Суцано-Пержанской зоны разломов Волынского мегаблока Украинского щита проведены полевые тектонофизические измерения в бассейне верхнего течения р. Уборть по маршруту Зольня—Майдан—Копищенский. Проведено изучение трещиноватости и структурно-текстурных элементов горных пород структурно-парагенетическим методом тектонофизики с учетом глубины их формирования. По результатам интерпретации установлено, что формирование Суцано-Пержанской зоны разломов продолжалось в течение не менее пяти фаз и сопровождалось образованием соответствующих различно ориентированных зон скальвания: Хмелевской, Суцанской, Пержанской, Рудня-Хочинской, Лопатичской. Фазы формирования Хмелевской и Суцанской зон скальвания аналогичны по простиранию Немировской и Хмельникской зонам разломов Украинского щита, которые сформировались в немировский этап разломообразования (~1,9 млрд лет). Рудня-Хочинская и Пержанская фазы связаны с активизацией Суцано-Пержанской зоны разломов во время взаимодействия микроплит Фенноскандии и Сарматии. Установлено, что с периодом формирования комплекса пержанских гранитоидов (1,80—1,70 млрд лет) связано развитие разрывов надвигового и сбросового типов, которые происходили в обстановке сжатия и растяжения соответственно. Такое чередование обстановок сжатия и растяжения повлекло за собой образование рудопроявлений в пределах Пержанского тектонического узла. Данное исследование установило, что Суцано-Пержанская зона разлома возникла в позднем палеопротерозое на немировском этапе разломообразования одновременно

с другими разломными зонами Украинского щита (Горинской, Луцкой, Тетеревской и Немировской) в результате сочленения микроплит Фенноскандии и Сарматии.

**Ключовые слова:** Украинский щит, Суцано-Пержанская зона разломов, Пержанский тектонический узел, структурно-текстурные элементы, деформации, поля напряжений.

## Внутрішня будова і кінематика Суцано-Пержанської зони розломів Українського щита за результатами тектонофізичних досліджень

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З метою визначення внутрішньої будови і кінематики Суцано-Пержанської зони розломів Волинського мегаблока Українського щита виконано польові тектонофізичні дослідження в басейні верхньої течії р. Уборть за маршрутом Зольня—Майдан—Копищенський. Проведено вивчення тріщинуватості і структурно-текстурних елементів гірських порід структурно-парагенетичним методом тектонофізики з урахуванням глибини їх формування. За результатами інтерпретації встановлено, що формування Суцано-Пержанської зони розломів тривало протягом не менше п'яти фаз і супроводжувалося утворенням відповідних різноорієнтованих зон сколювання: Хмельівської, Суцанської, Пержанської, Рудня-Хочинської, Лопатичівської. Хмельівська та Суцанська зони сколювання аналогічні за простяганням Немирівській та Хмільницькій зонам розломів Українського щита, які сформувалися в немирівській етап розломоутворення (~1,9 млрд років). Рудня-Хочинська і Пержанська фази пов'язані з активізацією Суцано-Пержанської зони розломів під час взаємодії мікроплит Фенноскандії та Сарматії. Встановлено, що з періодом формування комплексу пержанських гранітоїдів (1,80—1,70 млрд років) пов'язаний розвиток розривів насупного і скидового типів, що відбувались в обстановці стиснення і розтягу відповідно. Таке чергування ситуацій стиснення і розтягу спричинило утворення рудопроявів в межах Пержанського тектонічного вузла. Встановлено, що Суцано-Пержанська зона розломів виникла в пізньому палеопротерозої на Немирівському етапі розломоутворення одночасно з іншими розломними зонами Українського щита (Горинською, Луцькою, Тетерівською і Немирівською) в результаті зчленування мікроплит Фенноскандії та Сарматії.

**Ключові слова:** Український щит, Суцано-Пержанська зона розломів, Пержанський тектонічний вузол, структурно-текстурні елементи, деформації, поля напруг.