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SERPENTINES AS THE INDICATORS OF GEODYNAMIC CONDITIONS OF MESOZOIC PERIDOTITES METAMORPHIC TRANSFORMATIONS IN THE MARMAROSH ROCKY ZONE (INNER UKRAINIAN CARPATHIANS)

Purpose. We investigated secondary serpentines in order to reconstruct the geodynamic conditions of the formation and transformations of the peridotites (Uholskyi complex), which are localized in the Marmarosh rocky zone in the Inner Eastern Ukrainian Carpathians and are most widely spread in the interfluve of Velyka and Mala Uholka-rivers. **Methods.** The work is based on the results of geological observations of the Uholskyi complex rocks in natural outcrops, as well as petrographic, mineralogical (including X-ray diffraction, thermal and microprobe analysis), and geochemical studies. For comparison, literary data on peridotites of the Ukrainian Carpathians and some studied in detail orogenic peridotite complexes have been used. **Results.** Peridotites form olistoliths in the Soimulska olistostrome-conglomerate strata (K_1) of the Marmarosh rocky zone (Vezhanskyi nappe) of the Inner Ukrainian Carpathians. The age of olistoliths of the Uholskyi complex peridotites of the Soimulska suite is T_2–K_1 (?). The rocks of the Uholskyi complex are represented by serpentinous peridotites and serpentinites. The metamorphic transformations of peridotites are revealed in the significant distribution of α- and β-lizardite and antigorite. Two groups have been identified among the studied serpentines. Serpentines of the first group have a lenticular-looped texture and are mainly represented by α-lizardite and bastite, which have high chromium content and contain large non-altered grains of chrome-spinellids. Serpentines of the second group have a striped-shale texture; they are represented mainly by β-lizardite and antigorite, which have high iron content and contain powdered particles of magnetite. Serpentines of the first group were formed under the conditions of regressive metamorphism of the greenschist facies upper part, which occurred under the geodynamic conditions of the spreading zone during raising and cooling of peridotites. Serpentines of the second group have the characteristics (albeit local) of progressive metamorphism of the lower greenschist–upper epidote-amphibolite facies. They were formed under the supersubduction conditions and confined to fragments of paleozones of shear-plastic deformations. This was accompanied by subduction-collision events between the terrains of Dacia and Tisza in the Jurassic–Early Cretaceous, which led to the closure of the Transylvanian-Mureş paleocean. Selected groups of serpentines, which differ in mineral, chemical composition and structural and texture peculiarities, belong also to various geodynamic and genetic groups: the first tend to primary mantle protoliths of the ultrabasic composition, and the second – to lithospheric protoliths of the basic composition. **Scientific novelty.** The research of serpentines, which developed on the peridotites of the Uholskyi complex, made it possible to divide them into two groups whose representatives have different thermodynamic and geodynamic history. It is determined that structural, textural, mineral, and other features of serpentines are the indicators of geodynamic conditions for the transformation of peridotites of the Marmarosh rocky zone as well as other regions. A model of the phased transformation of the Uholskyi complex peridotites has been proposed. **Practical value.** The study of serpentinites developed on peridotites of the Uholskyi complex is important for the determination of the types of metamorphism in primitive mantle protoliths and the stage of formation of fold-covering structures lithosphere (on the example of the Ukrainian Carpathians). The obtained results can be used for prediction of serpentinite mineralization, since lizardite rocks (group 1) contain elements of the platinum group, and antigorite rocks (group 2) – magnetite.

Key words: peridotite; serpentinite; serpentine; α- and β-lizardite, antigorite; Inner zone of the Eastern Ukrainian Carpathians.

Introduction

Formulation of the problem. Peridotites of ophiolite complexes are fragments of the oceanic upper mantle that have undergone several stages of partial melting and were brought to the surface due to tectonic movements. The composition of the restite peridotites is determined by the initial composition of the oceanic upper mantle, the degree of its melting, and processes of the interaction of the melt (or fluids) with the surrounding mantle rocks in the process of transportation from the field of generation to the upper crustal horizons. The dynamic stresses experienced by peridotites have affected their structure and texture, the change in the composition of rock forming, accessory, and secondary minerals. The role of these changes in the formation of the final mineral composition of apoperidotites is extremely important for petrologic constructions and geodynamic reconstructions.

Peridotites of ophiolite complexes have undergone metamorphic transformations almost immediately after its formation. Thanks to serpentinization, the mineral composition of the rocks became more complicated [Brianchaninova, 2004]. Mineralogical, petrographic and geochemical studies of serpentine peridotites and serpentinites indicate that both regressive and progressive (contact) metamorphism took place [Brianchaninova & Makeev, 1995; Brianchaninova, 2004; Saveliev, et al., 2009]. Regression stage is associated with peridotite solidification and elevation to higher levels of the lithosphere in the area of riftogenesis. The progressive stage was manifested in the case of warming the "cold" masses of rocks during a regional dynamic-thermal (and contact) metamorphism under subduction conditions. At this stage, there were not only tectonic dislocations, but also local warming during the intrusion of younger bodies (and granitization).

According to experimental data [Varlakov, 1986], regressive metamorphism occurred at the highest rate with the formation of α-lizaridite (90–450 °C), sporadically β-lizardite (on gabbro rocks) and chrysotile. By *PT*-conditions [Varlakov, 1986; Saveliev et al., 2009] the regressive stage is comparable to the zeolite facies and the lower part of greenschist facies of regional metamorphism. At this stage, the medium and high-temperature associations of serpentines, primarily β-lizardite and antigorite, at temperatures of 200–500 °C, developed most intensively. In the event of an increase in temperature to the level of the epidote-amphibolite facies, talc-antigorite and talc-olivine rocks were formed [Varlakov, 1986; Saveliev et al., 2009].

During serpentinization, olivine and orthopyroxene are easily altered, and clinopyroxene remains fresh. Orthopyroxene (enstatite) is replaced by bastite. At low temperatures, loopy α-lizardite without magnetite separation develops on olivine; β-lizardite and antigorite develop on olivine in mid- and high-temperature conditions in the areas of shear-plastic deformations, and this process is accompanied by crystallization of a significant amount of dust-like magnetite [Dobrosotsky, 2013].

Analysis of recent publications. Among the geological problems concerning the Ukrainian Carpathians, the issues of magmatism, as well as the reconstruction of the geodynamic environment with which it is connected, have a prominent place. Mesozoic igneous rocks are represented by the basic complexes of T_2–K_1. These rocks have "mixed" petrochemical parameters, by which one can distinguish among them spreading, subduction, and platform varieties [Gnilko & Generalova, 2013]. The Uholskyi complex contains ultramafites (peridotites) and belongs to the ophiolite complex [Liashkevich et al., 1995; Stupka, 2013]. In the writings of recent decades, it is noted that the most common secondary mineral in the peridotites of the Uholskyi complex is serpentine, the content of which is 50–80 % of the rock [Liashkevich et al., 1995]. It is represented by antigorite, chrysotile, bastite, and other varieties. In the work of O. O. Stupka, paragenesis of antigorite with ferritic nickel has been noted, which, according to the author, is possible only under reducing conditions and the presence of reducing gases [Stupka, 2013]. In view of this, it is assumed that serpentinization of peridotites is a deep process that occurs at T = 450–600 °C, P = 13–16 kbar typically at a depth of 40–50 km (up to 100 km).

Geological position of peridotites of the Uholskyi complex. Serpentinous peridotites are widely represented in the basin of the Tereblya-river – in the interfluve of Velyka and Mala Uholka (Fig. 1). They comprise olistoliths in the Lower Cretaceous olistostrome and olistostrome-conglomerate strata, which belongs to the Soimulska suite. This suite begins a stratigraphic section (Palaeogene–Cretaceous) of the Marmarosh rocky zone (known as the Vezhanskyi nappe) of the Inner Eastern Carpathians [Tretiak et al., 2015].

The olistostrome stratum of the Soimulska suite contains large olistoliths of two rock groups. The first group includes fragments of Uholskyi complex rocks of the Mesozoic (T_2–K_1 [Liashkevich et al., 1995] ophiolite association (serpentinous peridotites, metabasalts, red jaspers, limestones). The second group of olistoliths is composed of rocks that are similar to the rocks of the Marmarosh massif (crystalline schists, gneisses, granitoids, quartz conglomerates of *P*–*T*, limestones and dolomites of *T*–*J*). The matrix of the olistostrome is represented by chaotic formations of debris-flows [Gnilko et al., 2015].

The Marmarosh rocky zone and the Marmarosh massif are the north-western end of the composite microcontinental terrane Tisza–Dacia. The rocks of the Soimulska suite were formed on the south-western slopes of the now immersed section of the Marmarosh massif (Marmarosh "Cordillera"); this corresponded to the geodynamic conditions of the Late Cretaceous–Palaeogene passive margin of the continental slope of the Tisza–Dacia continent [Gnilko & et al., 2015]. Such conditions arose after the formation of early Alpine Early Cretaceous Transylvanian and Marmarosh nappes. Transylvanian ophiolite nappes are likely to be denudated in the territory of Ukraine (Fig. 1).

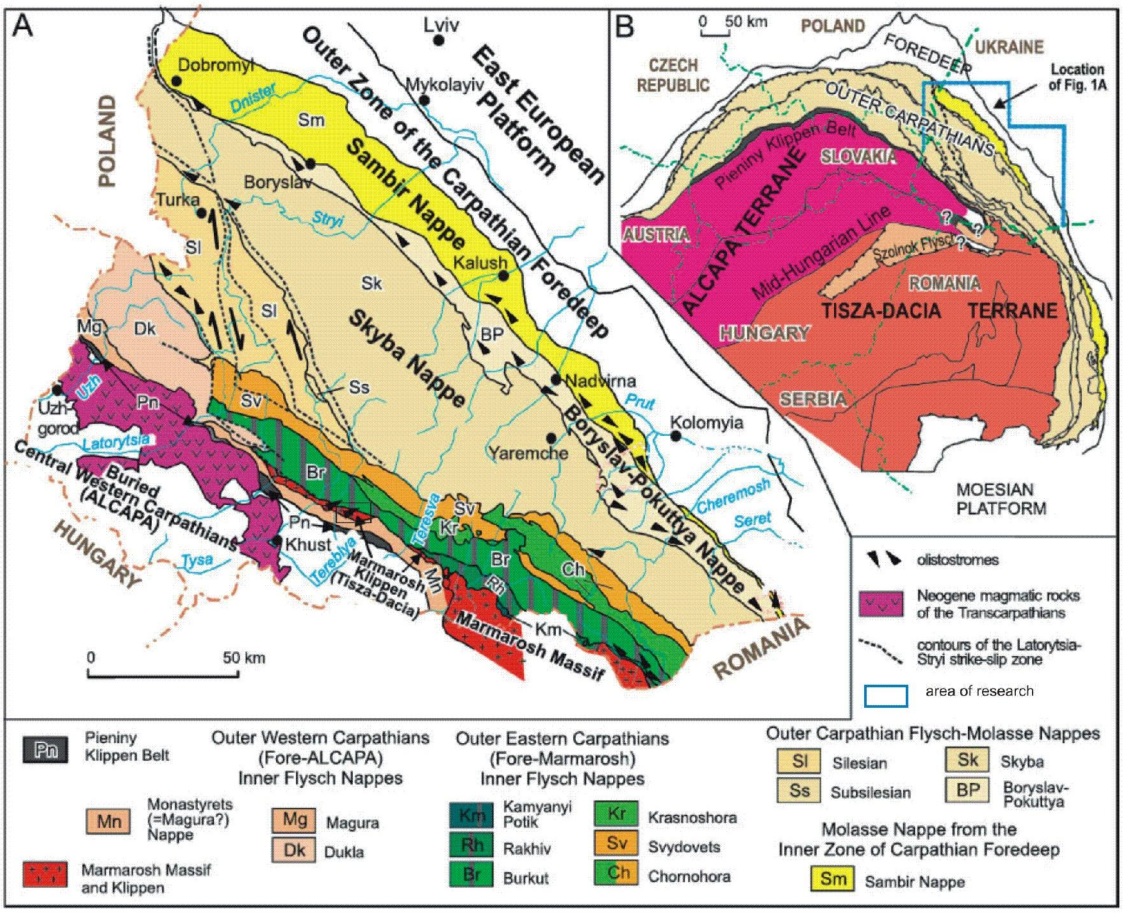


Fig. 1. A – The main tectonic units of the Ukrainian Carpathians (Hnylko, 2012).
B – Tectonic setting of the Ukrainian Carpathians, position of the terranes and main geological boundaries
(Kovač et al., 1998; Csontos & Vörös, 2004; Schmid et al., 2008); simplified, partly modified (Hnylko, 2014)

In the territory of Romania they were preserved in the form of tectonic outliers of the Transylvanian Early Cretaceous nappes, which were thrust over the crystalline massif of the Central Eastern Carpathians (in Ukraine the massif called Marmarosh is part of the Dacia terrane). The roots of Transylvanian nappes are located between the microcontinental terranes of Tisza and Dacia in the Mureş zone [Csontos & Vörös, 2004]. This zone belongs to the Transylvanian-Mureş (Vardar-Mureş) suture zone, which was formed as a result of the collision between the two mentioned terranes. This collision has led to the formation of a composite terrane Tisza–Dacia [Hnylko, 2012; Gnilko & et al., 2015; Tretiak et al., 2015]. The Transylvanian-Mureş sutura, as well as the olistoliths of the Transylvanian nappes in the Soimulska suite, "contains information" on the geodynamic processes occurring in the ocean basin, which divided the micro-continental terranes of Tisza and Dacia. Given the modern theoretical concepts, we believe that the thermodynamic parameters of the formation and metamorphic changes of peridotites from the ophiolites of the Uholskyi complex (which are fragments of the Transylvanian Early Cretaceous nappes of the Ukrainian Carpathians) are currently not sufficiently analyzed.

Purpose

The purpose of the study is to investigate and characterize secondary serpentines for the reconstruction of the geodynamic conditions of the formation and transformation of peridotites of the Uholskyi complex.

Research methods

Complex research has been conducted covering field observations of rocks in natural outcrops and laboratory petrographic, mineralogical and petrogheochemical studies of apoperodotytic serpentinites.

Serpentinites and serpentinous peridotites in natural outcrops were studied during geologic mapping and thematic works.

Samples of serpentinites, which differ in mineral composition and structural and texture features, were sampled for laboratory studies. They were studied in thin sections under the microscope of the firm "OLYMPUS". The polished sections of serpentinous peridotites were investigated in the laboratory of the Faculty of Physics (Ivan Franko National University of Lviv) with a raster (scanning) electron microscope REMMA-102-02 (Sumy, Ukraine) equipped with an energy-dispersive analyzer "EDAR". The parameters of the analysis are as follows: accelerating voltage – 20 kV, current of the probe – 1 nA, diameter of the probe – 0.1 microns. The standard mark used to calibrate the instrument is NERMA. GEO1.25.10.74 GT (the manufacturer – "Geotechnology", Ukraine). The following standards are used to calibrate individual elements: Na – albite; Mg – periclase; Al, Si, Ca – anorthite; P – fluorapatite; S – pyrite; K – microcline; Ti – macedonite; Cr – escolaite; Mn – manganite; Fe – hematite; As – GaAs (synthetic); Ba – barite; Sc, Co, Ni, Cu, Zr, Ag, Au are pure elements. "Magallanes 3.2" Software was used to process the obtained data.

Complex thermal analysis (thermogravimetric TG, differential thermogravimetric DTG and differential thermal DTA) was performed on a derivative digitizer Q-1500D of the "Paulik-Paulik-Erdey" system connected to a personal computer (laboratory of the Chemical Faculty of Lviv Polytechnic National University) in temperature range of 20–1000 °C with free access of air to the furnace. The heating rate is 10 °C/min. The weight of the samples was on average 10 mg. The standard substance used was aluminium-oxide. The results of the analysis are presented in the form of thermograms. The interpretation of the serpentinous rocks composition was carried out using catalogues of standard thermograms of serpentine varieties (lizardite, chrysotile, antigorite), and other minerals of peridotites [Ivanova et al., 1974; Shteinberg & Chashchukhin, 1977; Varlakov, 1986; Brianchaninova & Makeev, 1995; Brianchaninova, 2004].

X-ray structural analysis has been performed in the X-ray laboratory of the Geological Faculty (Ivan Franko National University of Lviv) on the diffractometer DRON-3 (analyst A. Dvorianskyi). Parameters of analysis: CuK_{α}-radiation, voltage – 40 kV, current strength – 25 mA, speed of rotation – 1 deg/min. Identification of minerals is done using MINCRYST Internet resources, Mindat, and using Match (version 9).

Research results

The investigated rocks are serpentinites and/or serpentinous peridotites, in which the content of secondary minerals, mainly serpentine, is 80–100 %. The peridotites consist of olivine, rhombic, and monoclinic pyroxenes, spinellids [Liashkevich et al., 1995; Stupka, 2013; Bilyk, et al., 2016; Stepanov, et al, 2016], which makes it possible to assume their mainly mantle primary paragenesis of the restite type. According to the results of our research, metamorphic transformations of peridotites from olistoliths of the Soimulska suite are found in the widest distribution of α- and β-lizardite and antigorite.

Macroscopically serpentinous rocks are represented by two varieties that differ in structure and texture. The rocks of the first group have lens-loop texture, and the second one – striped-shale.

Under a polarization microscope it was discovered that in the rocks of the first group, serpentine is represented by band-shaped and loop-shaped aggregates up to 1.0–1.5 mm in size. They are usually colourless, have a negative elongation, straight extinction, n_g = 1.546. There are also table-shaped crystals of sliced serpentine with an eminent cleavage – a bastite. The mineral is developed as pseudomorphosis on rhombic pyroxenes (Fig. 2A).

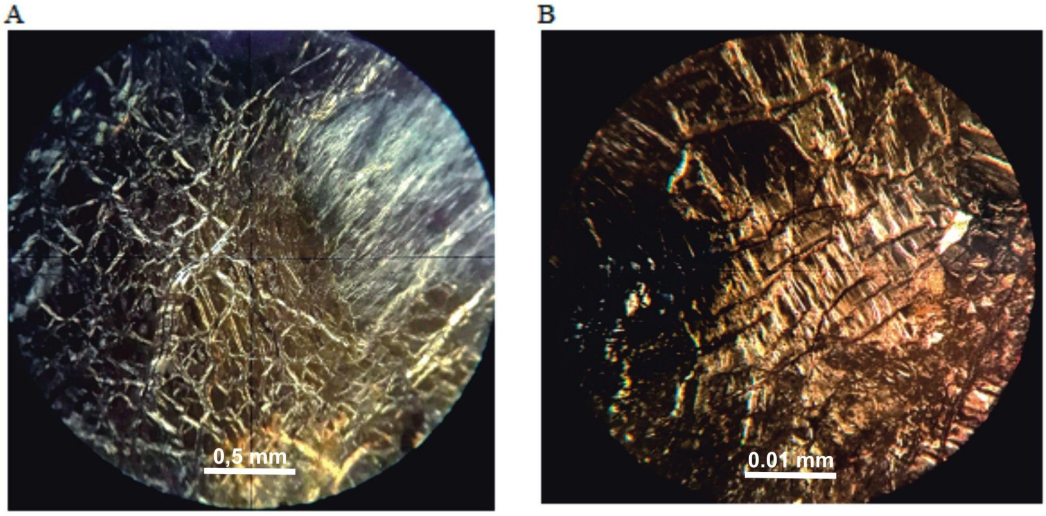


Fig. 2. Apoperidotite serpentinites of the Uholskyi complex in thin sections:
A – looped and tabular lizardite and bastite: (left – looped α-lizardite, right – sliced bastite); B – elongated-tabular to the needle-like antigorite (white). The basin of Mala Uholka, right side of the Hrebinskyi-stream, 250 m upstream from the mouth of the stream Poharskyi Runkul, at the outskirts of the village Mala Uholka

The crystalloptical characteristics of both varieties are identical and correspond to α-lizardite, which is confirmed by thermal analysis: the DTA-curves show a clear endoeffect at T = 630 °C, which corresponds to α-lizardite (Fig. 3B) [Saveliev, et al., 2009; Dobrosotsky, 2013].

In thin sections of the second group rocks, serpentine is also represented by ribbon and loop aggregates, but they are full of point-like and dust-like inclusions of magnetite. According to [Briancha-ninova, 2004; Saveliev et al., 2009; Dobrosotsky, 2013], the magnetite allocation is characteristic of β-lizardite. There are also a few (< 5 %) needle-like (up to 0.01 mm in length) and latticed individuals of serpentine, whose refractive index n_g = 1.565 corresponds to antigorite (see Fig. 2B).

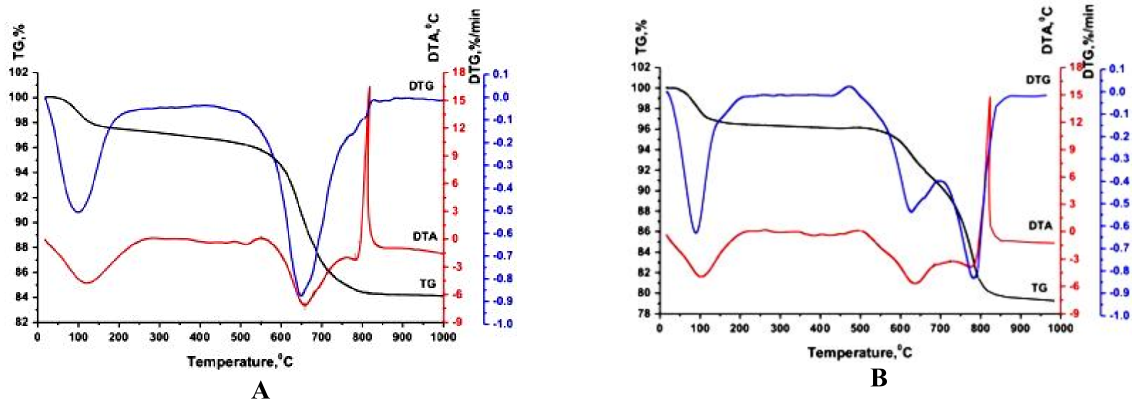


Fig. 3. Termograms of serpentines from apoperidotites of the Uholskyi complex:
DTG – differential-thermogravimetric curve; DTA – differential heating curve; TG – mass loss curve.
Apoperidotites with: A – β- lizardite and antigorite; B – α-lizardite

The relationship between antigorite and β-lizardite is complex, possibly these minerals are syngenetic. On the DTA-curves (see Fig. 3A) there are two distinct endoeffects at 670 and 780 °C, which confirm the presence of β-lizardite and antigorite, respectively. According to the area of the indicated effects, it is determined that the ratio of β-lizardite and antigorite is 1:2.

Spreads with interplanar spacings of 0.73, 0.454, 0.363, 0.253, 0.249, 0.245 nm, which correspond to lizardite and antigorite were found on the diffractograms of serpentine (Fig. 4). Characteristically, in the case of the predominance of α-lizardite rocks, the intensity of the peak of 0.363 nm is much lower than in the rocks with antigorite dominance.

The results of the microprobe analysis are plotted on the triangular diagram $Al^{\#}$–$Fe^{\#}$–$Cr^{\#}$ (Fig. 5), from which it is evident that the figurative points of the investigated minerals are grouped in two directions.

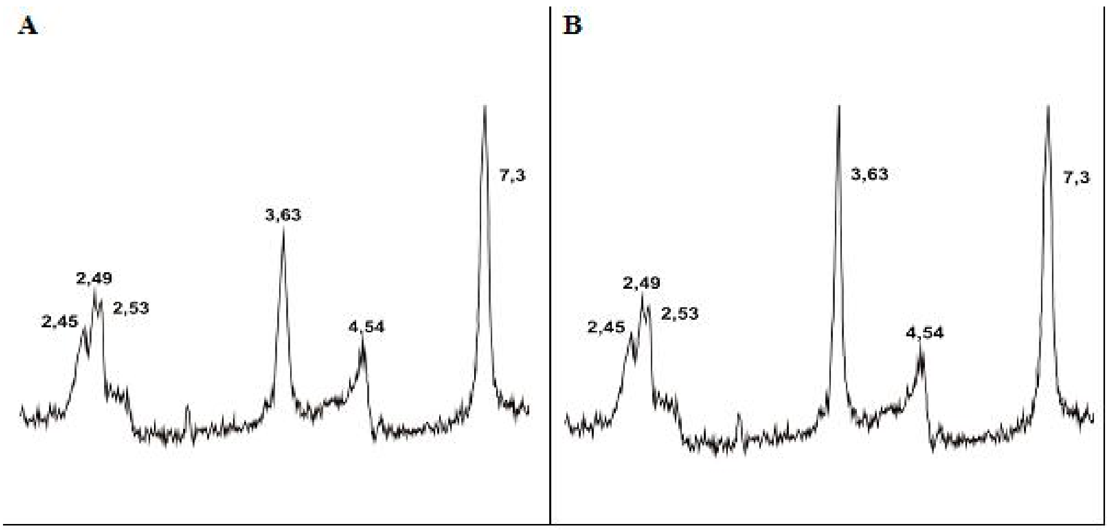


Fig. 4. Diffractograms of serpentines from apoperidotites of the Uholskyi complex:
A – with α-lizardite; B – with β- lizardite and antigorite

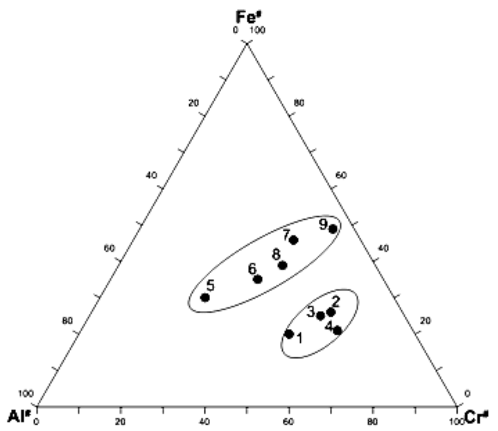


Fig. 5. Distribution of figurative points of serpentines on the triangular diagram $Al^{\#}$–$Fe^{\#}$–$Cr^{\#}$:
analyzes 1–4 – field of lizardite; 5–9 – field of antigorite; $Fe^{\#} = Fe/(Fe+Mg) \cdot 100$ %; $Al^{\#} = Al/(Al+Si) \cdot 100$ %; $Cr^{\#} = Cr/(Cr+Al) \cdot 100$ %

Group I (analyzes 1–4) is represented by α-lizardite, group II (analyzes 5–9) – by antigorite. In the grains of group I, is the higher content of Cr and less Fe content, whereas in the grains of group II the opposite is true.

The chemical composition of serpentines [Bilyk & et al., 2016] has been investigated using the technique given in the papers (Schwartz et al., 2012; Lafay et al., 2013; Wu et al., 2018). It is determined that the studied serpentines are represented by two groups. In the binary diagram of SiO_2–Al_2O_3, analyzes 1–4 are in the field of lizardite, and 5–9 – in the field of antigorite (Fig. 6). That is, in the transition from lizardite to antigorite, the serpentine is enriched with silica, which correlates with its depletion of alumina (Table 1).

Table 1

Content of SiO_2 and Al_2O_3 in serpentine according to chemical analysis, wt. %

Oxides	Content, wt. %								
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
SiO_2	43.08	42.11	42.02	41.09	44.12	43.92	43.90	42.96	44.10
Al_2O_3	0.61	1.99	1.59	1.95	0.21	0.99	0.55	1.86	0.87

In α-lizardite grains, relatively large (up to 0.3 mm) virtually unaltered grains of chrome-spinellids were found (Fig. 7A). In β-lizardite and antigorite spinel is found in the form of point-like relics, and most often it is practically completely altered into magnetite. Visually, the content of dust-like magnetite (see Fig. 7B) in serpentine grains does not exceed 5–10 %. According to the study of metamorphic transformations in peridotites of different regions of the World, in particular the Urals [Saveliev & et al., 2009; Dobrosotsky, 2013, etc.], the separation of dust-like magnetite in serpentines suggests that the geodynamic situation has changed.

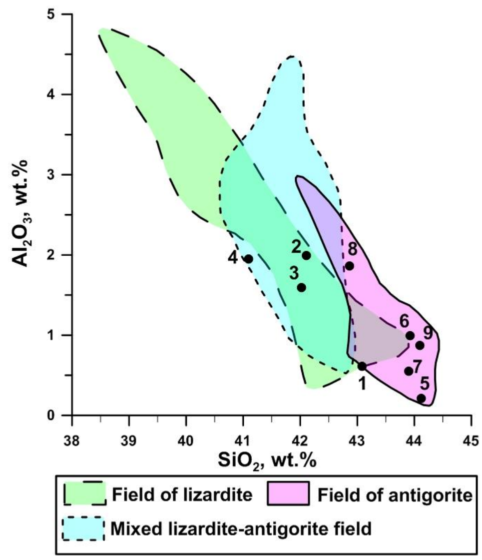
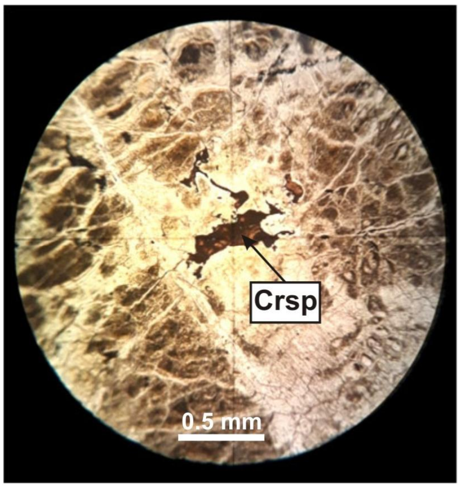


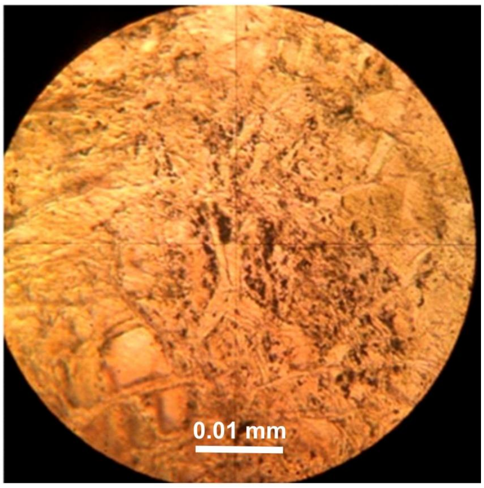
Fig. 6. Distribution of figurative points of serpentines according to the data of microprobe analysis on the SiO_2–Al_2O_3- diagram
(Schwartz et al., 2012; Lafay et al., 2013)

We assume that the presence of magnetite in serpentine is an indicator of the onset of progressive metamorphism. It took place in the Jurassic–Early Cretaceous during the process of subduction of the oceanic crust of the Transylvanian-Mureş paleobasin [Gnilko & et al., 2015] under the encymatic arc, which was located west of the microcontinental terrane of Dacia.

According to Yu. M. Raznitsyn and others, low- and high-temperature serpentinization are distinguished according to thermometric and dynamic parameters. Due to high-temperature serpentinization, antigorite-containing rocks are formed, which develop on peridotites. Most researchers are of the opinion that this is happening over subduction zones. Numerous manifestations of antigorite serpentinites in deep-water troughs are found among modern oceanic structures, while they are absent in the mid-ocean ridges [Raznitsyn et al., 2018]. Low-temperature serpentinization results in the formation of lizardite (partly chrysotile) rocks. The process is inherent in the spreading zones and develops at low and moderate pressure at a depth of 3.5–4.5 km. It is noted that in this case the chrome-spinellids remain unaltered (magnetite does not replace them).

The studied serpentines of apoperidotite serpentinites differ in mineralogical-geochemical characteristics which makes it possible to distinguish two groups between them. They were formed in different geodynamic conditions and have different genesis. In the complex of signs the serpentines of the first group gravitate to the primary mantle protoliths of the ultrabasic composition, and the second – to the lithospheric protoliths of the basic composition.





A B

Fig. 7. Accessory minerals in serpentinites of the Uholskyi complex apoperidotites:
A – chrome-spinellid (Crsp) in loopy α-lizardite;
B – dusty magnetite (black dots) in the striped-slaty serpentine (β-lizardite, antigorite). The upper part of the basin of the Mala Uholka-river, interfluve of east Hrebinskyi and Poharskyi Runkul streams

Practical value

The study of serpentinites developed on the peridotites of the Uholskyi complex is important for the determination of the types of metamorphism experienced by the primary-mantle protoliths and the stages of formation of the fold-napping structures lithosphere (on the example of the Ukrainian Carpathians). The obtained results can be used for prediction of mineralization in serpentinites, because the elements of the platinum group are associated with lizardite rocks, and magnetite with antigorite ones.

Scientific novelty

The results of the complete set of field and laboratory studies of serpentinites formed on peridotites of the Uholskyi complex, made it possible to distinguish between them two groups that have different thermodynamic and geodynamic history. It is determined that structural and texture features of rocks, and their mineralogical and geochemical peculiarities are indicators of geodynamic conditions of the transformation of peridotites from ophiolites of the Marmarosh rocky zone and other regions. The model of the phased transformation of peridotites of the Uholskyi complex in the Inner zone of the Eastern Ukrainian Carpathians has been proposed.

Conclusions

The complex investigations of serpentines from the apoperidotites of the Uholskyi complex have made it possible to specify the model of their transformation in the structure of the Transylvanian-Mureş paleocean and their subsequent penetration into the Marmarosh rocky zone.

The use of well-known techniques for the study of serpentinites and serpentinous apoperidotites clearly demonstrates the possibility of periodization of the processes of primary rocks transformations under different geodynamic conditions. Comparing our results with known data for other regions makes it possible to distinguish groups of rocks that have been altered at least twice.

Serpentines with lenticular-looped textures are indicators of geodynamic conditions for peridotites alteration at the first, earlier stage. There are, above all, α-lizardite and bastite, which have high content of Cr and contain large unaltered grains of chrome-spinellids. This stage corresponds to the regressive metamorphism of the top of the greenschist facies. It occurred under the geodynamic conditions of spreading during the rise and cooling of peridotites.

Serpentines, which have a striped-shale texture, are represented mainly by β-lizardite and antigorite, which are characterized by increased Fe deficiency and the presence of dusty magnetite grains. The corresponding rocks were formed at the second, later stage, which parameters (although, perhaps, somewhat local) correspond to the progressive metamorphism of the lower greenschist–upper epidote-amphibolite facies. Serpentines at this stage were formed under supersubduction conditions and confined to fragments of paleozones of shear-plastic deformations. In the Jurassic–Early Cretaceous times, these deformations were accompanied by subduction-collision events between the terrane Dacia, the encymatic island arch of the Tethys-ocean and/or Tisza-terrane. The collision of the terranes Dacia and Tisza led to the closure of the Transylvanian-Mureş ocean (part of the main branch of the Tethys-ocean) and the formation of large early Alpine nappes [Csontos & Vörös, 2004; Gnilko & et al., 2015], including Transylvanian ophiolites. Just before the front of the ophiolite plates there was an olistostromic basin (in particular, the Marmarosh), in which the olistoliths from these plates shifted [Gnilko & et al., 2015].

Distinguished varieties of serpentine, which differ in mineral, geochemical and structural-texture peculiarities, belong to different genetic groups. Serpentines of the first group tend to the primary mantle protoliths of the ultrabasic (restitious) composition, and the minerals of the second group – to the lithospheric protoliths of the basic composition. The studied serpentines, developed on the peridotites of the Uholskyi complex, were, apparently, confined to the Mesozoic suture zone between the terranes of Dacia and Tizsa.

References

Bilyk, N. T., Heneralova, L. V., Yatsenko, I. H., Stepanov, V. B. (2016). Mineralogical and geodynamical conditions of transformation of peridotites from ophiolites in the Marmarosh zone roc. (Ukrainian Carpathians). *Geodynamics, 2*(21), 71–83 (in Ukrainian). https://doi.org/10.23939/jgd2016.02.071

Brianchaninova, N. S. (2004). Serpentinites and serpentines of Polar Urals. *Abstract of the thesis for doctor's degree in geol.-mineral. sciences.* Syktyvkar, 44 (in Russian).

Brianchaninova, N. S., Makeev, A. B. (1995). Methods for the study of ultrabasite serpentinization. In *Mineral Individuals, Aggregates, Paragenesises*. *Proceedings of the Institute of Geology, Komi SC, UrB of RAS, 88*, 4–11 (in Russian).

Csontos, L., Vörös, A. (2004). Mesozoic plate tectonic reconstruction of the Carpathian region. *Palaeogeography, Palaeoclimatology, Palaeoecology, 210*, 1–56.

Dobrosotsky, S. V. (2013). Features of the material composition of ultrabasites of dunite-harzburgite association of the Niadokotinsky ore field (Olysia-Musiursky massif, Sub-Polar Urals). *Bulletin of Voronezh University, ser. Geology* (1), 64–74 (in Russian).

Gnilko, O. M., Generalova, L. V. (2013). Early Alpine evolution of Ukrainian Carpathians. In *Geological history, possible mechanisms and problems of formation of basins with oceanic/sub-oceanic crust in regions with continental crust* (pp. 48–53). GEOS, Moscow (in Russian).

Gnilko, O. M., Gnilko, S. R., Generalova, L. V. (2015). The formation of the structures of the cliff zones and the inter-cliff flysch of the Inner Ukrainian Carpathians – the result of convergence and collision of microcontinental terranes. *Bulletin of St. Petersburg University, ser. 7* (2), 4–24 (in Russian).

Hnylko, O. (2014). Olistostromes in the Miocene salt-bearing folded deposits at the front of the Ukrainian Carpathian orogen. *Geological Quarterly, 58* (3), 381–392. doi: 10.7306/gq.1132

Hnylko, O. M. (2012). Tectonic zoning of the Carpathians in terms of the terrane tectonics. Article 2. The Flysch Carpathian – ancient accretionary prism. *Geodynamics, 1* (12), 67–78 (in Ukrainian). https://doi.org/10.23939/jgd2012.01.067

Ivanova, V. P., Kasatov, B. K., Krasavina, T. N., & Rozinova, E. L. (1974). Thermal Analysis of Minerals and Rocks. Nedra, Leningrad, 399 (in Russian).

Kovač, M., Nagymarosy, A., Oszczypko, N., Ślączka, A., Csontos, L., ... & Márton, M. (1998). Palin-spastic reconstruction of the Varpathian-Pannonian region during the Miocene. In *Geodynamic development of the Western Carpathians* (pp. 189–217). Geological Survey of Slovak Republic, Bratislava.

Lafay, R., Deschamps, F., Schwartz, S., Guillot, S., Godard, M., Debret, B., Nicollet C. (2013). High-pressure serpentinites, a trap-and-release system controlled by metamorphic conditions: Example from the Piedmont zone of the western Alps Romain. *Chemical Geology, 343,* 38–54.

Liashkevich, Z. M., Medvedev, A. P., Krupsky, Yu. Z., Varichev, A. S., Timoshuk, V. R., & Stupka, O. O. (1995). Tectono-Magmatic Evolution of the Carpathians. Naukova Dumka, Kiev, 132 (in Russian).

Raznitsin, Yu. N., Savelieva, G. N., Fedonkin, M. A. (2018). The hydrocarbon potential of paleo- and modern suprasubduction zones: tectonic, geodynamic, mineralogical-geochemical, and biochemical aspects. Pacific geology, 37, 2. 3–16. (in Russian).

Saveliev, D. E., Bazhyn, Ye. A., Snachev, V. I., Chernikova, T. I. (2009). Serpentinization of ultrabasites of Kyshtym area. *Geological Collection of IG UrSC RAS, 8,* 129–137 (in Russian).

Schmid, S., Bernoulli, D., Fugenschuh, B., Matenco, L., Schefer, S., ... & Ustaszewski, K. (2008). The Alpine-Carpathian-Dinaric orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences, 101,* 139–183.

Schwartz, S., Guillot, S., Reynard, B., Lafay, R., Debret, B., ... & Auzende, A.-L. (2012). Pressure–temperature estimates of the lizardite/ antigorite transition in high pressure serpentinites. *Lithos, 178,* 197–210.

Shteinberg, D. S., Chashchukhin, I. S. (1977). Serpentinization of Ultrabasites. Nauka, Moscow, 312 (in Russian).

Stepanov, V. B., Bilyk, N. T., Heneralova, L. V., Hnylko, O. M., Dykyi, V. V. (2016). Mineralogy and formation conditions of peridotites from ophiolites of Marmarosh rocky zone. In *Academician Yevhen Lazarenko Tenth Scientific Readings* (pp. 93–95). Ivan Franko National University of Lviv, Lviv (in Ukrainian).

Stupka, O. O. (2013). Ophiolites of the Ukrainian Carpathians. *Abstract of the thesis for candidate's degree in geol. sciences.* Lviv, 20 (in Ukrainian).

Tretiak, K. R., Maksymchuk, V. Yu., Kutas, R. I., Rokytnianskyi, I. I., Hnylko, O. M., ... & Tereshyn, A. V. (2015). Modern Geodynamics and Geophysical Fields of the Carparhians and Adjacent Territories. Publishing House of Lviv Polytechnic National University, Lviv, 420 (in Ukrainian).

Varlakov, A. S. (1986). Petrology of the Processes of Serpentinization of Ultrabasites in Folded Regions. Sverdlovsk, 224 (in Russian).

Wu, K., Ding, X., Ling, M., Sun, W., Zhang, L., Hu, Y., Huang, R. (2018). Origins of two types of serpentinites from the Qinling orogenic belt, central China and associated fluid/melt-rock interactions. *Lithos, 302–303,* 50–64. doi.org/10.1016/j.lithos. 2017.12.019

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СЕРПЕНТИНИ – ІНДИКАТОРИ ГЕОДИНАМІЧНИХ УМОВ МЕТАМОРФІЧНИХ ПЕРЕТВОРЕНЬ МЕЗОЗОЙСЬКИХ ПЕРИДОТИТІВ МАРМАРОСЬКОЇ ЗОНИ СКЕЛЬ (ВНУТРІШНІ УКРАЇНСЬКІ КАРПАТИ)

Мета. Виконано дослідження вторинних серпентинів для реконструкції умов становлення й перетворення перидотитів угольського комплексу, які локалізовані в Мармароській зоні скель внутрішніх Східних Українських Карпат і поширені в межиріччі Великої та Малої Угольок. **Методи.** Робота ґрунтується на результатах геологічних спостережень порід угольського комплексу в природних відслоненнях, а також петрографічних, мінералогічних (рентгеноструктурний, термоваговий і мікрозондовий аналізи) та геохімічних досліджень. Для порівняння використано літературні дані щодо перидотитів Українських Карпат і окремих детально вивчених перидотитових комплексів орогенів. **Результати.** Перидотити утворюють олістоліти в нижньокрейдовій соймульській олістостромово-конгломератовій товщі Мармароської зони скель (Вежанський покрив) внутрішніх Українських Карпат. Вік олістолітів (соймульська світа) перидотитів угольського комплексу – T_2–K_1 (?). Породи представлені серпентинізованими перидотитами й серпентинітами. Метаморфічні перетворення перидотитів олістолітів виявлено у значному поширенні α- і β-лізардиту й антигориту. Серед вивчених серпентинів виділено дві групи. Серпентин першої групи має лінзоподібно-петельчасту текстуру і представлений, головно, α-лізардитом і баститом; ці мінерали містять порівняно великі незмінені зерна хромшпінелідів і мають підвищену хромистість. Серпентин другої групи, представлений, зазвичай, β-лізардитом і антигоритом, смугасто-сланцюватої текстури, містить включення пилоподібного магнетиту й підвищену кількість заліза. Мінералам першої групи притаманні термодинамічні характеристики регресивного метаморфізму верхів зеленосланцевої фації, який міг бути реалізований за геодинамічних умов спредингу під час підняття й охолодження перидотитів. Серпентини другої групи мають параметри, хоча й локальні, прогресивного метаморфізму низів зеленосланцевої–верхівепідот-амфіболітової фації. Вони формувались за надсубдукційних умов і приурочені до фрагментів палеозон відколово-пластичних деформацій, які супроводжували в юрі–ранній крейді субдукційно-колізійні події між терейнами Дакія і Тисія, що привели до закриття Трансильвансько-Муреського палеоокеану. Виділені групи серпентинів мають різний генезис і формувались за різних геодинамічних умов: мінерали першої групи тяжіють до первинно-мантійних протолітів ультраосновного складу, а другої – до літосферних протолітів основного складу. **Наукова новизна.** Використання комплексу методів дослідження серпентинів дало змогу розділити їх на дві групи, які мають різну термодинамічну й геодинамічну історію. Структурно-текстурні, мінералогічні, геохімічні та інші особливості серпентинів є індикаторами геодинамічних умов перетворення перидотитів Мармароської зони скель та інших регіонів. Запропоновано модель поетапного перетворення перидотитів угольського комплексу. **Практичне значення.** Дослідження серпентинітів, розвинутих по перидотитах угольського комплексу, важливе для з'ясування типу метаморфізму вихідних первинно-мантійних протолітів і стадійності формування літосфери складчасто-покривних споруд (на прикладі Українських Карпат). Отримані результати можна використовувати для прогнозного оцінювання зруденіння серпентинітів, оскільки визначено, що з лізардитовими серпентинітами пов'язані елементи групи платини, а з антигоритовими асоціює магнетит.

Ключові слова: перидотит; серпентиніт; серпентин; α- і β-лізардит, антигорит; внутрішня зона Східних Українських Карпат.

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