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TECTONIC DEFORMATIONS AND PALEOSTRESS FIELDS IN THE ROCK COMPLEXES OF THE PIENINY KLIPPEN BELT IN THE CITY OF SZAWNYCTA (POLAND)

Purpose *of the paper is study of faults and folds and reconstruction of paleostress fields in rock complexes of the* Pieniny Klippen Belt *in Pieniny Mts. area (Southern Poland).*

Methods *of field geological and structural research were involved, including the kinematic method with subsequent reconstruction of paleostress fields using the program Win-Tensor.*

The results. *On the right bank of the Danube River in the south-western outskirts of the city of Szczawnytsia (Southern Poland), numerous fold and fault deformations, their kinematic types and structural patterns were studied in the large rootless block of the PKB. Paleostress fields of the thrust, normal and strike-slip kinematic types have been restored. In the inverse stress field, thrusts were formed on the border of competent and incompetent rocks. Drug-folds, mélange and broken formations zones were formed in the more ductile rocks of the lower block. In the normal-type stress field, the former thrusts were activated as normal faults and cuted by the ortogonal and oblique sinistral strike-slip faults. The kinematic sence of the thrusts changed to an oblique normal faults with a component of the sinistral strike-slip, in the bodering zones of the activated faults, drag folds ans s-type folds were formed. In the youngest stress field, the former thrust surfaces were activated as strike-slip ones. Shear deformations were also recorded along thrust-limiting orthogonal and oblique surfaces. Kinematic types of tectonic deformation and folded structures in the different parts of the studed rootless block vitnesses the rotation of the fault wings in the horizontal and vertical planes. The wavy shape of the surface of the movement of the rootless block may be the reason for the simultaneous existence of a field of compression and tension in its various segments.*

Scientific novelty. *As a result of the research, the kinematic types of fault, their relationships and features of development in various paleostress fields were determined. The features of the structure of the thrust and the faults that cut them, the relationships of folded and faulted deformation are established. Changes of the kinematic types of faults in time from the inverse to the strike-slip type have been established.*

Practical impact. *The obtained results complement the history of the formation of the Pieniny Klippen Belt and can be used to refine tectonic maps and select a geodynamic model of the region.*

Key words: Pieniny Klippen Belt, *paleostress, thrust, strike-slip, mélange.*

Introduction.

The area studied belongs to the Pieniny Klippen Belt (PKB) being very narrow tectonic structure between two huge parts of Carpathians: Inner and Outer ones. From geomorphologic point of view PKB represents a long (at least of 500 km) but narrow (1-20 km of width) belt of isolated solid klippens rising in relief and surrounding by softer rocks.

PKB represents a complex suture zone of the Alpine Tethys dividing the Cretaceous stack of the Central Western Carpathians from the Cenozoic accretionary complex of the Outer Carpathians. PKB was formed in front of ALCAPA terrain and at its SE ending wedges between ALCAPA and Tisza–Dacia terrains Fig.1, [1 - 6].

The PKB is an indicative object for studying the evolution of the sedimentary basin, the subsequent reduction of its sedimentary base, formation of a subduction-collisional orogen and its transformation into a giant megabreccia

The study area is located within the Pieniny Mountains in Southern Poland on the right bank of the river Dunajec near the Grajcarek mouth. The object of study is a large rootless block composed of Lower and Middle Jurassic rocks, which is located in the field of development of younger deposits of the Upper Cretaceous. The block has clearly manifested plastic and brittle deformations, which bear signs of various stages of formation and activation of deformation structures. Different segments of the upper rigid block (frontal, lateral, rear) are deformed in different ways, as well as different parts of the lower more plastic substrate.

How do the stress fields reconstructed by the kinematic method correlate with the structures of plastic deformation - folds and buddings? To what extent are the reconstructed stress fields regular and reflect regional or local tectonic and gravitational processes.

Overview of recent publications.

The PKB is interpreted as megabreccia resulted of several tectonic phases of deformation [4, 7 - 11].

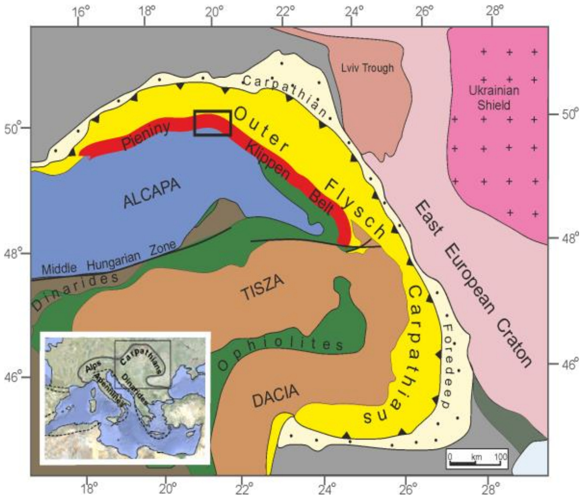

Fig. 1. Tectonic position of the PKB marked by bold red line, simlified after Schmid et al., 2008 [3]. The study area indicated by the black rectangle

The structural pattern of PKB reflectes the total effect of the spatial overlap of thrusting and gravitational flows resulting in chaotic breccias, olistoliths and olistostrome formation, which formed during the Maastrichtian to Early Miocene. Within the PKB the olistostromes form two belts related to the advancing of the accretionary prism and destruction of the Czorsztyn ridge separated the Magura and Pieniny basin [11].

The PKB is built during northward nappe thrusting at the turn of the Cretaceous to the Paleocene and then refolded in the Miocene during the formation of the Outer Carpathian overthrusts [7, 8]. The change in strike of the PKB from W–E to WNW–ESE associated with dextral strike-slip faulting in the North-European Platform [12].

The PKB is separated from the Outer Carpathians by the Miocene sub-vertical strike-slip fault [7,13]. In modern literature [4, 8, 14] the present-day confines of the PKB are regarded as subvertical faults and shear zones.

The location of the study area in relation to regional tectonic structures is shown in Fig. 2. Within the PKB a number of lithofacies are recognized: Czorsztyn, Niedzica, Chertezik, Branisca and Pieninska, represented by Jurassic–Lower Cretaceous carbonate sediments overlain by Upper Cretaceous variegated marls and flysch deposits. These lithofacies have a common Middle/Upper Cretaceous sedimentary cover. Differences in sedimentary zonation remained during the Jurassic-Early Cretaceous [2, 7].

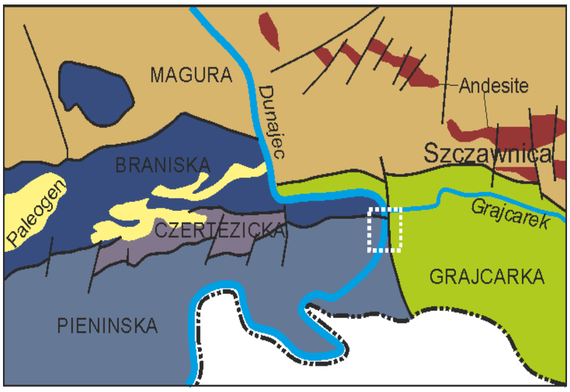

Fig. 2. Tectonic scheme of study area, scale 1: 30 000, fragment of [15]. The study area indicated by the white rectangle

The PKB is separated on the north from the Paleogene to Early Miocene flysch deposits of the Magura nappe by a narrow, strongly deformed belt known as the Grajcarek unit. The unit is composed of strongly deformed slices of Jurassic-Cretaceous sediments associated with synorogenic wild-flysch, breccias and olistoliths. In the study area the PKB and the Grajcarek Unit are separated by the Dunajec fault [7, 12, 16]. To the east of the Dunajec River the PKB gets narrow, while the Grajcarek unit gets wider (Fig.2). The relationship between the PKB and Grajcarek unit as well as its nature and position, have been the subject of many disputes and completely different interpretations. The Grajcarek unit was first defined by [7-8]) as a Peri-Klippen part of the Magura Basin, being back thrusted over the Klippen Belt as a cap, during the Maastrichtian-Paleocene phase. In [12] postulated that during the last phase of thrusting in the PKB the klippen units were gravitationally driven northward, overlapping the Grajcarek unit.

Purpose of the article.

The aim of the paper is a detailed study of faulted and folded structures, their relationships and the paleostress reconstruction in the outcrops of the PKB of the Northern Carpathians (Pieniny Mts., Poland). In Pieniny Mts., the PKB is much wider (up to 20 km) than in the Ukrainian Carpathians (1–2 km) and represented by a wider range of lithostratigraphic complexes and types of structural parageneses. The Pieniny Mts. area are more accessible for study from the point of view of well-developed infrastructure of the region.

Methods.

Methods of geological-and-structural analisys were used, including the method of structural paragenesis [17] and kinematic analysis, which was set up by J. Angelier [18]. We measured the dipping of wings, hinges and axial surfaces of the folds and relation of the latter with certain discontinuities to determine the mechanism of their formation.

When studying slicken-sides, their dimensions, kinematic type, and surface features were taken into account. The kinematic type of slicken-sides and faults was established based on the characteristic bends of layers, drug and S-type folds, furrows and slip strokes.

Paleostress reconstruction was performed using the program Win-Tensor, based on the principles of Right Dihedra method [19].

During the analysis of geological-and-structural data, we determined the positions of deformation structures in space, relationship of folding and faults, the kinematic sens of faults and its changes in reactivation.

The resultes.

The simplified geological map and stratigraphic log reflect main rock complexes of the study area (Fig. 3) [9]. The oldest rock are the dark oxygen-reduced spotty limestones and marls of the Pliensbachian-Lower Bajocian age. These rocks are visible in the lower block of the thrust system. The upper plate is composed by cherty limestone of maiolica-type (Biacone) facies. It is one of the most famous wide spread Tethyan facies of Upper Jurassic-Berriasian in age well known both from Alpine and Apennine regions. These white-grey, micrite well bedded calpionellid-bearing limestones built now highest part of the Pieniny Mts.

We have identified different types of folding and kinematic types of faults and built a structural scheme of the study area (Fig. 4). In the southwestern part of the research area, a south-dipping 60° thrust fault 1 was found (see Figs. 4, 6), which is accompanied by a series of near-fault folds in the hanging wing. The axial surface of Gothic fold 2 is subparallel to thrust surface 1 and is interpreted as a thrust fold of longitudinal bending.

The lines on the slicken-sides indicate the displacement in two different directions - by the inverse and sinistral strike-slip types. In the zone of the thrust surface, there are friction clays and drag folds, which indicate a left-hand shift (Fig. 7). The changes of stress fields over time occurred from the thrust type to oblique normal and strick-slip ones.

The study of fault 3, which dips to the northeast at an angle of 60°, was carried out in the cave, in the central part of the outcrope (Fig. 5). On the surface of the sliding mirror, the directions of movement according to the kinematic type of left-hand strike-s[ip are established. This fault displaces the surface of the main thrust 4 to the type of left shift. This is indicated by the bending of the layers of schistose clay rocks in the thrust zone and the upward extrusion of the plastic substrate along the fault 3 (Fig. 8).

The main thrust 4 has a northeast direction with a dip to the southeast at angles of 35-45° (Fig. 5). The zone is represented by shaly clay rocks with inclusions of limestone boudins. Rocks in the recumbent wing are crumpled into discordant inverted and recumbent folds with arcuate bends of the axial surfaces, which may reflect rotational movements of the blocks (Fig. 8).

From above, the zone of plastic deformations of the main thrust is limited by a slicken-side, on which, in addition to thrust-type furrows, strike-slip -type ones are observed, which indicates changes in paleostress fields during the development of deformations over time. From the north, thrust 4 is cut by a northeast 65°dipping left-hand strike-slip 5. In the north-eastern corner of the cave there is a tectonic mirror dipping to the north at 65° with friction clay and sliding grooves (Fig. 5).

Within the outcrop, we measured the parameters of 77 sliken-sides and reconstructed paleostress fields using the Win-Tensor program (Fig. 9). The directions of the compression axes and the directions of movements along the faults in accordance with the orientation of the stress axes are also shown in Figure 5.

At the first stages, thrust faults and plastic deformations were formed. At the second stage, the surfaces of the thrusts shifted along the left-hand faults of the north-west trend. The second stage was also accompanied by plastic deformations. The third stage of development has the youngest age and is well manifested by the massive distribution of slicken-sides of strike-slip types.

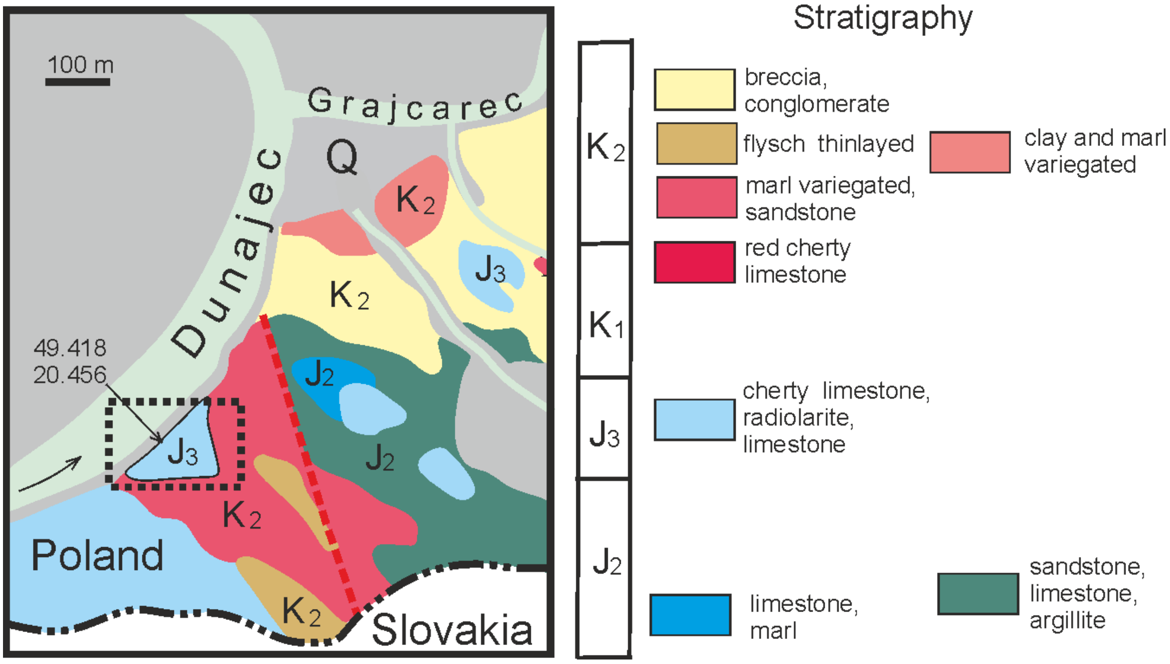

Fig. 3. Geological map of the study area, scale 1: 25 000, fragment of Mapa, 2013 [15]

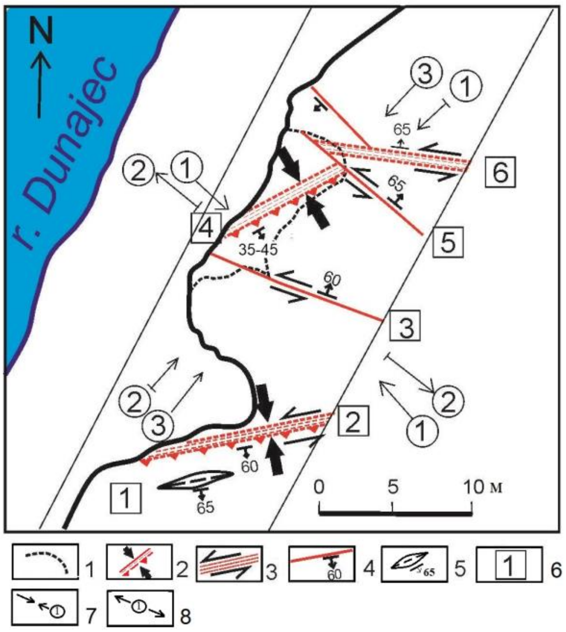

Fig. 4. Structural and tectonic scheme of the study area with paleostress axis: 1 – inverse type, 2 – normal-strike-slip type, 3 – strike-slip type

1 – contour of the cave; 2 – thrusts with zones of shale detachment and directions of movement in the inverse-type field; 3 – kinematics of strike-slip movements at the stage of activation; 4 – fault dipping; 5 - Gothic fold and dipping of its axial surface; 6 – numbers of folds and faults mentioned; 7 –direction of compression and numbers of related paleostress fields; 8 – direction of extension and numbers of related paleostress fields.

Fig. 5. The gothic fold (deformation structure 1) – subparallel to the thrust 2

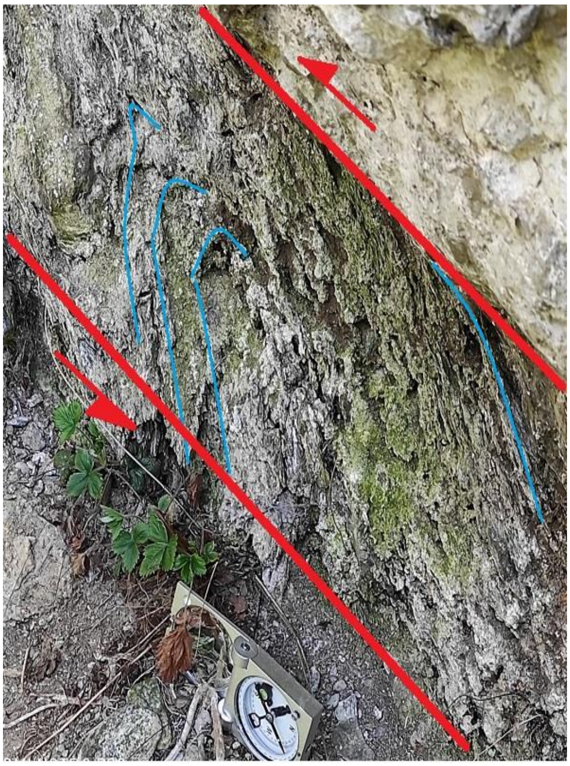

Fig. 6. The thrust 2 with related drag folds and S-structures indicating sinistral strike-slip movement

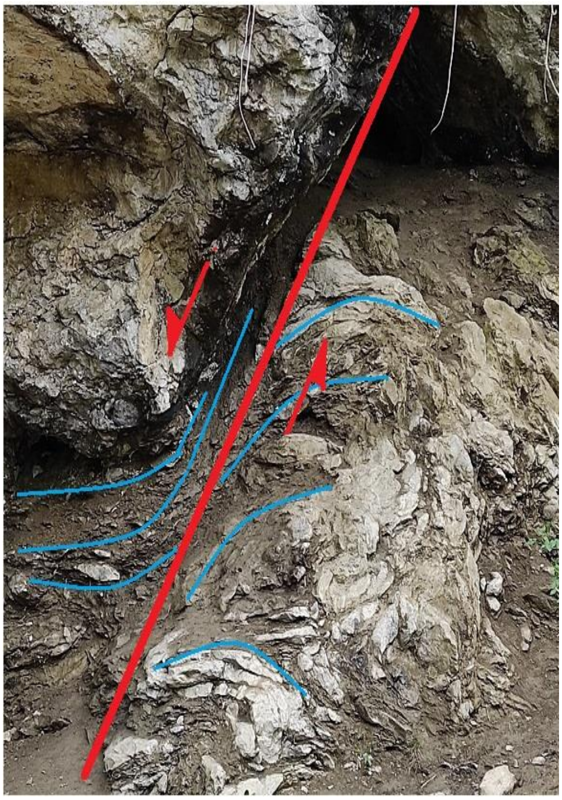

Fig. 7. The drug-fold, S- structures, boudinage, and of tectonic flow in the area of normal-sinistral strike-slip fault 3 cutting the thrust fault 4

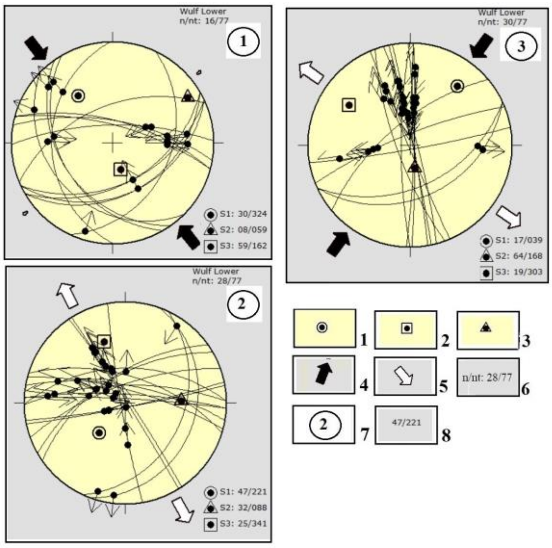

Fig. 8. Paleostress fields reconstructed using Win-Tensor program

1 – axis of compression; 2 - axis of extension; 3 ¬ intermediate axis; 4 – compression direction; 5 – extension direction, 6 – number of sliken-sides (28 – corresponding to this field, 77 – total number of measurements); 7 – stress field number according to Fig. 4; 8 – parametrs of the main axes of the paleostress field: (221 – dip azimuth, 47 – dip angle).

Conclusions.

In the outcrops of the rootless block of the PKB, numerous folded and faulted dislocations were studied, which were formed in different kinematic types of stress fields. Three types of fields and three stages of formation and activation of fault zones are established. In the first field, there are thrusts and associated fault folds and mélange zones.

At the second stage, the thrusts shifted by north-west trending strike-slip of sinistral type. The surfaces of the former thrusts were activated as sinistral strike-slips. At the same time, drag folds were formed in incompetent rocks and tectonic mirrors with sliding furrows in competent rocks , which indicate an oblique normal displasement with a left-hand component of strike-slip movement. At the third stage, numerous tectonic mirrors are formed in the shear-type field, and the surfaces of previous faults are reactivated. The stage is characterized by the predominance of brittle deformations.

The identified features of the formation and development of deformation processes in the investigated rootless block may reflect the general trend of the tectonic evolution within the PKB. The obtained results can be used to clarify the history of formation of deformations and to choose a geodynamic model of the PKB.

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ФОРМИ ТЕКТОНІЧНИХ ДИСЛОКАЦІЙ ТА ПОЛЯ ПАЛЕОНАПРУЖЕНЬ В ПОРОДНИХ КОМПЛЕКСАХ ЗОНИ П'ЄНІНСЬКИХ СКЕЛЬ НА ДІЛЯНЦІ МІСТА ЩАВНИЦЯ (ПОЛЬЩА)

Мета. *Дослідження розривних і складчастих структур та реконструкція полів палеонапружень в породних комплексах Зони П'єнінських Скель Північних Карпат (район міста Щавниця, Польша).*

Методика. *Використовувалися методи польових структурно-геологічних та тектонофізичних досліджень з обробкою польових структурних даних та реконструкції полів палеонапружень в комп'ютерній програмі «Win-Tensor».*

Результати. *На правому березі річки Дунаєць підено-західної околиці міста Щавниця (Південь Польщі) у відслоненнях великого блоку порід Зони П'єнінських Скель вивчені численні складчасті та розривні дислокації, їх кінематичні типи та взаємовідносин. Визначено поля палеонапружень підкидового, скидового та зсувного кінематичних типів. В першому полі формувалися насуви на границі компетентних і некомпетентних порід. В більш пластичних породах нижнього блоку утворювались приразломні складки та потужні зони меланжу. В скидовому полі напружень поверхні насуви активізувались як скиди та зміщувалися по лівому типу зсувами північно-західного простягання. Напрям переміщень в крилах насувів змінювався на косий скид з компонентою лівого зсуву, в шовних зонах активованих розломів формувалися складки волочіння. В наймолодшому за віком зсувному полі палеонапружень поверхні насувів активувались в якості зсувів. Зсувні деформації зафіксовано і по обмежуючих насуви ортогональних та косих розривах. Кінематичні типи тектонічних порушень та складчасті структури в шовній зоні насуву свідчать про обертання крил розломів в горизонтальній і вертикальній площині. Хвиляста форма поверхні руху блоку порід може бути причиною одночасного існування поля стиснення та розтягу в різних його сегментах.*

Наукова новизна. *В результаті досліджень визначені кінематичні типи розривних дислокацій, їх взаємовідносини і особливості розвитку в різних полях палеонапружень. Встановлені особливості будови шовних зон насувів та розломів, які їх зрізають, взаємовідносини складчастих та розривних дислокацій. Встановлено зміни напрямів переміщень крил розломів і їх кінематичних типів у часі від підкидового до зсувного типу.*

Практичне значення. *Отримані результати можуть бути використані при побудові геологічних та тектонічних карт П'єнінської структурної зони та доповнюють її історію формування та розвитку.*

Ключові слова: *Зона П'єнінських Скель, палеонапруження, насуви, зсуви, меланж.*

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