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STRUCTURAL DEFORMATIONS IN THE METAMORPHIC ROCKS OF MT MEDVEDNICA (CROATIA)

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The aim of this work is a description of the basic geological structural forms in the metamorphic rocks of Mt Medvednica that originated during its tectonic formation, during discrete deformation events. Here their structural relationship is shown as well as the time of their origin. The conclusion is that the structural forms were made during three separate tectonic events, each with its own clearly recognisable structural characteristics. The newestz structural data and the consequent interpretation of the structural evolution of Mt Medvednica show the tectonic complexity of this part of the Pannonian Basin area. The tectonic events, on the basis of these data, can be attributed to the Palaeozoic, Mesozoic and Cenozoic.

Key words: tectonics, structural geology, folds, faults, fractures, Mt Medvednica

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Sadržaj rada je opis osnovnih geoloških strukturnih oblika u metamorfnim stijenama Medvednice koji su nastali tijekom njenog tektonskog oblikovanja, u vremenski odvojenim deformacijskim događajima. Prikazan je njihov međusobni strukturni odnos kao i vrijeme njihovog postanka. Zaključuje se da su strukturni oblici nastali u tri odvojena tektonska događaja, svaki sa svojim vrlo jasno prepoznatljivim strukturološkim karakteristikama. Najnoviji strukturni podaci a kroz njih i interpretacija strukturne evolucije Medvednice ukazuju na tektonsku složenost ovog dijela panonskog prostora. Tektonski događaji se na temelju tih podataka datiraju kao paleozojski, mezozojski i tercijarni.

Ključne riječi: tektonika, strukturna geologija, bore, rasjedi, pukotine, Medvednica

INTRODUCTION

Mt Medvednica belongs to the mountain range in the Pannonian area, the tectonic evolution of which can not generally be separated from the evolution of the rest of the mountain area. It is built of Paleozoic, Mesozoic and Tertiary rocks with tectonic records important for its structural formation. New structural data from metamorphic rocks of Mt Medvednica offer important information about intensity of deformation in the Pannonian area because so far there have been no systematic structural observations, descriptions, measurements and categorization.

There are different age data for the metamorphic rocks of Mt Medvednica. GORJANOVIĆ-KRAMBERGER (1908) considered them carbonic, but MIHOLIĆ (1958) on the basis of the absolute age method from green schists decided on the Ipper Archaean. Somewhat later CRNKOVIĆ (1963) wrote about the metamorphic complex as being of Upper Paleozoic age. By an analysis of conodonts from carbonaceous rocks, ĐURĐANOVIĆ (1973) showed a range from Lower Devonian to Upper Carboniferous, whereas with some others he demonstrated a range from Lower Triassic to Upper Triassic. According to ŠIKIĆ *et al.* (1979), the metamorphic rocks of Mt Medvednica belong to the Devonian-Carboniferous (?). The carboniferous origin of marble limestone from a quarry near Markuševac was proved by KOCHANSKY-DEVIDE (1981). The Paleozoic age is also shown by unmetamorphosed limestone from the Upper Permian (KOCHANSKY-DEVIDE, 1958). With some black shales from Marija Snježna village SREMAC & MIHAJLOVIĆ-PAVLOVIĆ (1983) demonstrate the Silurian in that part of the metamorphic complex. Recent accomplishments in the determination of the age of metamorphic rocks have shown a Triassic age for them. BELAK *et al.* (1995) assume that the basic rocks (?) of Mt Medvednica are a volcanic-sediment (?) formation of Middle Triassic to Upper Triassic age that underwent metamorphic changes during the period of the Lower Cretaceous. The age of metamorphism is determined on the basis of five isotopic analyses (K-Ar) from orthoschists and paraschists with values ranging from 115.5 to 122.5 million years.

Today's tectonic setting, with an approximate East-West strike of structures, was formed by the youngest tectonic events during the Tertiary and Quaternary (deformation phase ***F-III***) under the global stress which acts in the Pannonian area in a North-South direction (JAMIČIĆ, 1995a and b; PRELOGOVIĆ *et al.*, 1995). In the Mesozoic parts of Mt Medvednica the structures can be observed, as well as in the wider area between the rivers Sava and Drava (JAMIČIĆ, 1993), that are formed under stress along an East-West direction (deformation phase ***F-II***). The oldest deformation phase ***F-I*** caused some metamorphic changes in Paleozoic rocks, where complete transposition of primary bedding is often to be seen (TURNER & WEISS, 1963) along with the appearance of foliation. The orientation of main stress activity can only be assumed, that is, its activity in the North-West direction. This orientation and the time of the activities of all three basic stresses in the area of Mt Medvednica show the similarity with the tectonic shapes in the Slavonic mountains (JAMIČIĆ, 1995b) and to some extent, similarities with the area of Mecsek and Vilany in neighboring Hungary (BERGERAT, 1989; BERGERAT & CSONTOS, 1988).

METHODS

In this paper, data collected during the geological mapping of Zagrebačka gora within the framework of the preparation of a 1:50 000 geological map of Croatia are presented. During these investigations, detailed determination of outcrops on all structural elements presented was carried out, as well as their classification according to shape and genesis, along with all numerical measurements. Having in mind that the structures in the metamorphic rocks of Mt Medvednica were made in several kinematic events, it is clear that the relations between these events are masked. Because of that, the structural elements are systematized according to a somewhat modified method suggested by D. JAMIČIĆ (1988). The discontinuity planes are marked by *S*. The bedding is marked with *Ss*, foliation with *Sf*, and cleavage with *Sk*. Linear elements parallel to axes *b* are marked by *lb*. Tectonic transport on the discontinuity planes is marked with the angle size between the plane strike and left inclination of lineation by . The sequence of the creation of a particular structure is marked by a numerical index in addition to the basic mark. So a cleavage formed in the first deformation has the mark Sk_1, in the second Sk_2, etc. If the cleavage is defined as the cleavage of the axial plane created during the first deformation phase, it has the sign $Sk_1//Or$ with the pertinent index. Indices are added also in the determination of fold forming sequences (b1, b2, and b3).

The sequence of deformations in metamorphic rocks is determined on the basis of shape and genesis of structures, which are characterized by a particular deformation event. During the metamorphic changes (***F-1***) in the Paleozoic rocks of Mt Medvednica, in addition to planar and linear elements, there are occurrences of folded structures that are typical of processes during metamorphosis. These structures are formed mainly by the transposition of bedding planes. During the later deformations (***F-II*** and ***F-III***) these structures are reshaped (folded, rotated, or fractured) under the influence of new stress. But in this later phase some structures in Mt Medvednica were formed with a lower folding index and a different orientation of axis strike.

RESULTS

In Fig. 1 very simplified lithostratigraphical column of the Sljeme metamorphic formation, which built the central, south and southwest parts of Zagrebačka gora is shown.

The Sljeme formation (Fig. 1) includes six members: Brestovac, Mrzljak, Adolfovac, Medveščak, Bliznec and Markuševac. Members within the Sljeme unit are defined by lithological characteristics and they are metamorphosed at a low stage of regional metamorphism. The metamorphic stage corresponds to greenschist facies.

The member *Brestovac (1)* is presented by different varietes of green orthoschists. Protolitic rocks are basalts, diabases and tuffs metamorphosed by regional metamorphosis at lower temperatures. The footwall of this member is not found and the hanging wall is the member Mrzljak, in which the basaltic and diabasic rocks of the Brestovac member are intruded.

The member *Mrzljak (2)* consists of the following lithological varieties: ore-bearing quartz schists and sandstones, chlorite-calcite-magnetite-quartzic schists, quartz-magnetite schists, quartz-stilpnomelane schists and quartz-chlorite schists. Protolithic rocks are different varietes of quartzic sandstones, cherts and quartzic and carbonized pelites.

The member *Adolfovac (3)* consists of protolithic limestones with intercalations of pelites, which by the process of metamorphosishave been turned into cipolin marbles and marbled limestones with thin layers of metapelites (metatuffites?). Coarse-grained marbles and quarzic schists.

The member *Medveščak (4)* follows the Adolfovac member geographically. Dominantly, there are gray to dark gray marbled limestones, marbled dolomites and carbonate metaconglomerates.

The member *Bliznec (5)* is represented by calcitic slate-phyllites, metacalcarenites, slate-phyllites, metapsamites and metasiltites.

The member *Markuševac (6)* is the final member of the Sljeme formation. It consists of thicker bedded marble limestones. Within this member, younger intrusions of basitic rock are found, forming thinner or thicker veins.

Ductile deformations of listed members are characterized by metamorphic foliation (*Sf*) which is sometimes parallel to bedding (*Ss*), and various folded forms; monoclinal, flexures, »chevron« and conjugated folds. The relations of ductile characteristics between members (Fig. 1) also show the relation of deformation intensity

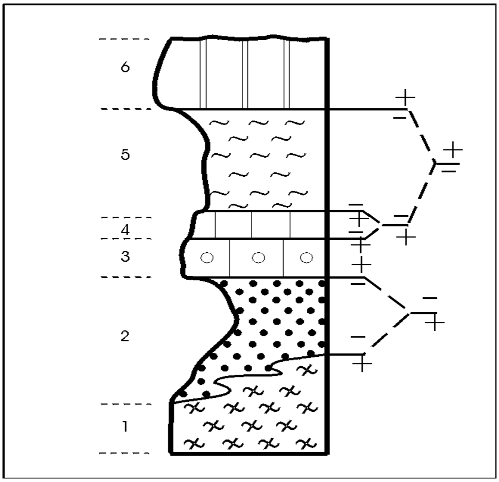

Fig. 1. Simplified lithostratigraphical column of Sljeme metamorphic formation. The symbol »plus« on the right hand side of the column indicates the competency, and a »minus« the incompetency of the presented members. See the text for the description of particular members.

of members, opposite orientation. Limestones and marble limestones are mainly less deformed than schists and clastites. The presence of important deformations in particular members is also marked in the position of the structure. So the same member in central parts of the folded structure can show full transposition of *Ss* bedding planes and in peripheral parts only fracturing.

In metamorphic rocks the presence of three deformation events (***F-I, F-II*** and ***F-III***) are proved as they have left records as structural forms. As mentioned earlier, the sequence of these tectonic events differs according to the shape and structures formed and the time of their activities. These tectonic events and structures are described below with references to concrete examples of outcrops of all the members of the Sljeme formation.

The first deformation event (***F-I***) is connected with metamorphic changes developed with stress orientation on the recent approximate North-South strike. It is characterized by the schistlike appearance of sediments and vulcanites as well as by occurrences of foliations formed parallel or subparallel to bedding, and it is to be found very often along the cleavage of the axial plane. In this phase of tectonic events, more ductile sediments, like different varieties of siltites and pelites, during the metamorphic changes and under the oriented stress underwent schistosity and folding, whereas less ductile sediments, limestones and sandstones, are just fractured and/or, like *r*-tectonites, fold into the more plastic sediment. Intensifying the stress, the transposition Ss of bedding plane occurs (Fig. 2). In addition to the appearance of this structural formation, the migration of squeezed quartz and calcite in the apical parts of folds formed, where the *r*-tectonites marking the fold axis are formed.

The transposition of *Ss* bedding planes along with the forming of foliation *Sf* appeared with the cleavage of the axial plane. It is frequent in the rocks of the Mrzljak

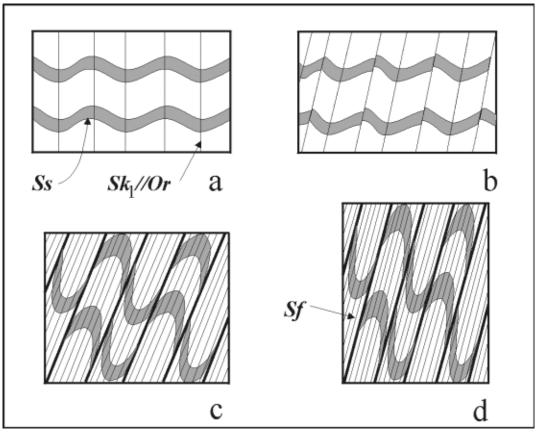

Fig. 2. The sequence of transposition of *Ss* bedding planes along the cleavage axis plane *Sk1/Or* (b_1) and the formation of foliation *Sf* in the metamorphic rocks of Mt Medvednica during the deformation events in ***F-I.***

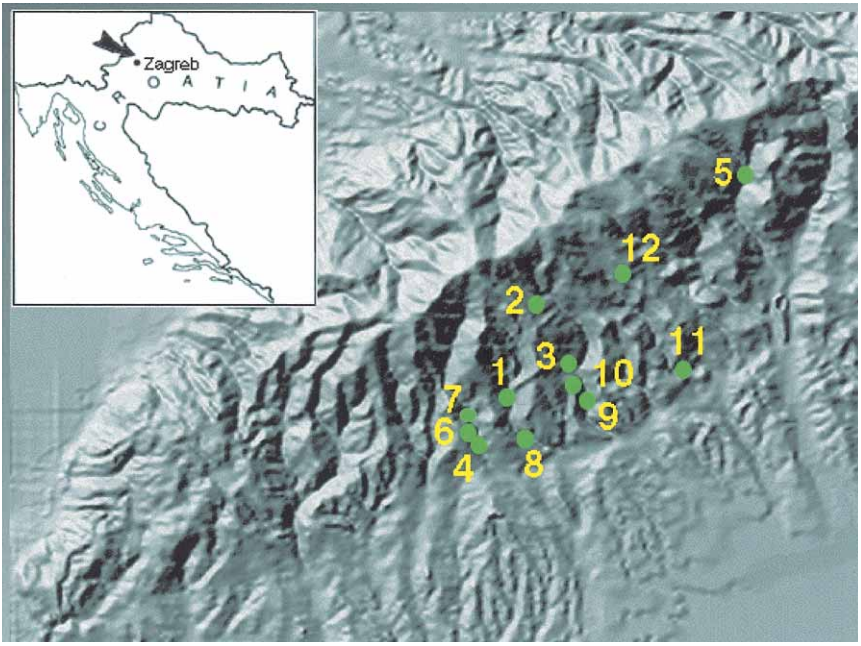

Fig. 3. Outcrop locations map

Fig. 4. Plava peć (Pusti dol). Albite-quartz-chlorite schists of the Mrzljak member. Fold axes *b1* (parallel to photography) are banded around the *b2* axis in the form of a monocline

and Adolfovac members and it characterizes the Medveščak and Bliznec members. It is not noticed in the Markuševac member.

Figs 4 and 5 show the rocks (albite-quartz-chlorite schists) of the Mrzljak member from the Plava peć location in the Pusti Dol stream (Fig. 3, location 1, coordinates X=5081520, Y=5574700, Z=420 m). The picture illustrates the results of transposition in part of that member. Foliation (*Sf*) is formed during the folding in the first deformation phase with a cleavage of the axial plane (*Sk1//Or*) with position 287°/72°. The folds with the b-axis with the position 205°/42°are formed, the apical parts of which are folded into monoclinale folds during further tectonic deformations. The folds (*b1*) are cm- to dm- dimensions and along their strike they disappear laterally along the axial plane cleavage. Elongated, elliptic forms (Fig. 5) belong to the folds and greater »pencil« structures, developed on the crosscut of axial plane cleavage and foliation. Envelope of the *b1* axis of these structures is parallel with foliation and the axial plane cleavage. On the outcrop the fracture system is noticed at a distance of a few meters from the zone perpendicular to the *b1* axis and the fractures are partly masked with younger fracture systems.

The schistlike appearance and development of foliation in the Brestovac member rock (green schichts) also occur along the axial plane cleavage (*Sk1//Or*). In the photograph of Fig. 6 which is taken by the main road, SE of Brestovac (Fig. 3, location 2, coordinates X=5083280, Y=5575060, Z=790 m) the sliding fracture systems are no-

Fig. 5. Plava peć (Pusti dol) location. »Pencil« structures on the cross section of axial plane cleavage and foliation

Fig. 6. Brestovac location. Boudinage structure in green schists of the Mrzljak member.

a)

b)

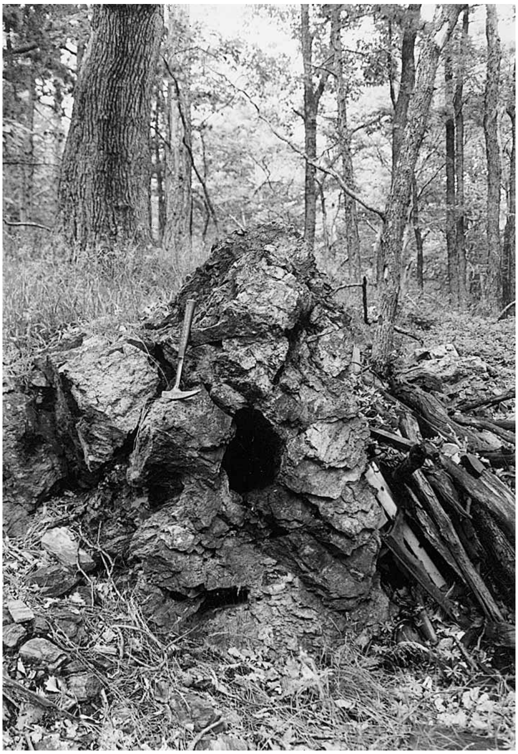

Fig. 7. Obrtanjak location. a) one meter fold (*b1*) in quartzitic schists with magnetite

ticed at a distance of between 10 and 50 cm, along which basalt rocks schistlike texture. Discontinuity planes, primarily formed by basalt effusion, are folded and occur schistlike with the cleavage *Sk1//Or*. Quartz was drained out in lens forms, marking with their longer axis the axis parallel to *b1*. In the picture the gentle inclination of the cleavage *Sk1//Or* is visible, which implies that the green schist outcrop belongs to an overturned part of a bigger structure.

The less ductile parts of the Mrzljak member, quarzites and quartz-schichts, during the main stress activity in the first deformation phase were folded without transposition of the *Ss* planes. The bedding wass disturbed between layers, but is preserved. In Fig. 7a and 7b taken at the Obrtnjak location, NW of the Adolfovac house (Fig. 3, location 3, coordinates X=5082565, Y=5575490, Z=650 m) there is a one meter fold (b_1) in quartzitic schichts with magnetite. Interlayer sliding with foliation developing during the folding, brought to mm/cm lineation parallel to the *b1* axis. Simultaneously with the folding, conjugated fractured systems (*h0l*) were developed with the angle on the *b1* axis, and along them gentle left and right shifts of separated lithons are observed. More remarkable are the fractures from the zone perpendicular to the *b1* axis. On the crosscut of the conjugated fractured system from the axial plane zone, a stronger crushing of the central parts of the fold occurred (Fig. 7b). This caused the formation of a little cavern the longer axis of which is parallel to the b1 structure axis. The strike of the structure is N-S (9°/3°) and it belongs to a bigger structure like the aforementioned forms (Fig. 4, 5, 6). The tectonic processes rotated the structure into the present position by the influence of stress in the E-W direction.

The marble limestones of the Adolfovac and Medveščak members, of which the protolith is plate-bedded and thinner-layered limestones, behaved differently during the deformation processes. That essentially depended not only on their ductile characteristics, but also on their position in the structure and index of folding (the relation between the fold amplitude and the distance between the folds). In the case of isoclines with a large index of folding, the change of orientation of the *Ss*-plane during the mechanical shaping led to the transposition and new orientation of this discontinuity planes. In the central parts of the folded structures, the thinner layered (3–10 cm) limestones of the Medveščak member underwent full transposition of bedding along with the axis plane cleavage (*Sk1//Or*) and the formation of »pencil« structures. In Fig. 8, taken on the right side of Kraljevec stream (Fig. 3, location 4, coordinates X=5080360, Y=5574040, Z=330 m), the »pencil« structures in the marbled limestones of the Medveščak member are shown. The sticks are oval in cross section and they are from 0.5 to 3 cm and 20 cm thick. The length of the »pencil« forms is laterally defined with a fracture system from the zone perpendicular to the b axis. Parallel to the »pencil« structure axis the mm-lineation is noticed, which together with the longer axis of the sticks mark the *b1* fold axis. During later structural deformation in ***F-II*** these structural forms were folded along the younger cleavage of the axial plane (*Sk2//Or*), in the forms of flexures and sigmoidal folds (Fig. 9).

Similar »pencil« forms almost identical to those in the Medveščak member are found (Fig. 10) on the left side of the Bidrovec stream (Fig. 3, location 5, coordinates

Fig. 8. Kraljevec stream. Pencil structures in marble limestones of the Medveščak member.

Fig. 9. Selected pieces of pencil structure sticks from Fig. 8. Folding of axis *b1 around new axis b2* is visible.

Fig. 10. Bidrovec location. Pencil structures in marble limestones of the Medveščak member

X=5080000, Y=5579425, Z=380 m). Here it can also be noticed that the *b1* axes of the »pencil« structures are fractured and folded along the axis plane cleavage (*Sk2//Or*) during the latest tectonic events in ***F-II,*** when the monoclines which characterized this deformation phase were shaped.

The thicker-bedded limestones of Medveščak member were also folded along the axial plane cleavage (*Sk 1// Or*) during the transposition of layers (*Ss*) when similar folds were shaped. In Fig. 11 (Fig. 3, location 6, coordinates X=5080485, Y=5574040, Z=340 m) is the fold on the left side of Kraljevec stream, which is in the marbled limestones of Medveščak member. The fold has all the characteristics of the similar fold type. The pressed limbs of the fold contain linear elements b_1 parallel to the hammer. The fold is cut with fractures from the zone *Sk2//Or* that appear at distances of approximately 40 cm by deformations that occured after the shaping the structures in the phase ***F-II***. The main stress ($_1$) that led to the occurrence of these fractures was active nearly parallel to axis *b1*. With fractures *Sk2//Or,* separation and folding of the older linear elements parallel to *b1* in the form of flexures appears (seen above and under the hammer). In the following phase ***(F-III)*** the structure comes under the influence of the basic stress *(* $_1$*)* in the approximate direction N-W when the fold inclines (with other structural elements) by app. 50°, that is, the structure rotates around the horizontal axis with an E-W strike.

Upstream and downstream of this location in the Kraljevec stream some similar structures are found. Important structures are formed in thicker bedded limestones

Fig. 11. Kraljevac stream. Fold in marble limestones of the Medveščak member

of the Medveščak member as shown in Fig. 12 (Fig. 3, location 7, coordinates: X= 5080475, Y=557440 and Z=335 m). The completely round shapes created are elongated marbled limestone *r*-tectonites, which have by transposition been inserted into the metasiltites of the Bliznec member. The longer axes of the *r*-tectonites mark axis *b1*. These are the transitional levels between the Medveščak and Bliznec members.

As mentioned earlier, the creation of different structures in metamorphic rocks of Mt Medvednica is defined by their position in macro-structure. In the Adolfovac and Medveščak members in ***F-I***, interbedded folds in slightly folded layers are found. In the Pusti dol stream (Fig. 3, location 8, coordinates X=5080100, Y=5575495, Z=285 m) in the close vicinity of the retention some interbedded folds can be noticed. One of these is presented in Fig. 13. Linear elements parallel to fold axis *b1* are visible, and fracture systems at the distance of 10–50 cm from the zone perpendicular and at an angle to *b1*. The axial fold plane (*Sk1//Or*) is parallel to the bedding.

In the following deformation phase, ***F-II,*** these interbedded structural forms are reshaped around a new regional axis B_2. A good example of the folding of the older structures is shown in Fig. 14 taken around 250 m upstream of the retention on the right side of Pusti Dol stream (Fig. 3, location 8, coordinates X=5080278, Y=5575185 and Z=295 m).The bending of the beds of the Medveščak member and interbedded folds b_1 are noticed around the younger axis b_2. The following fracture systems developed during the folding formed a fanlike cleavage from the axial plane zone.

Fig. 12. Kraljevac stream. Rounded *r*-tectonites of the Medveščak member (marble limestones) in metasiltites of the Bliznec member

Fig. 13. Pusti dol location. Interlayered fold (*b1*) in marbles of the Adolfovac member.

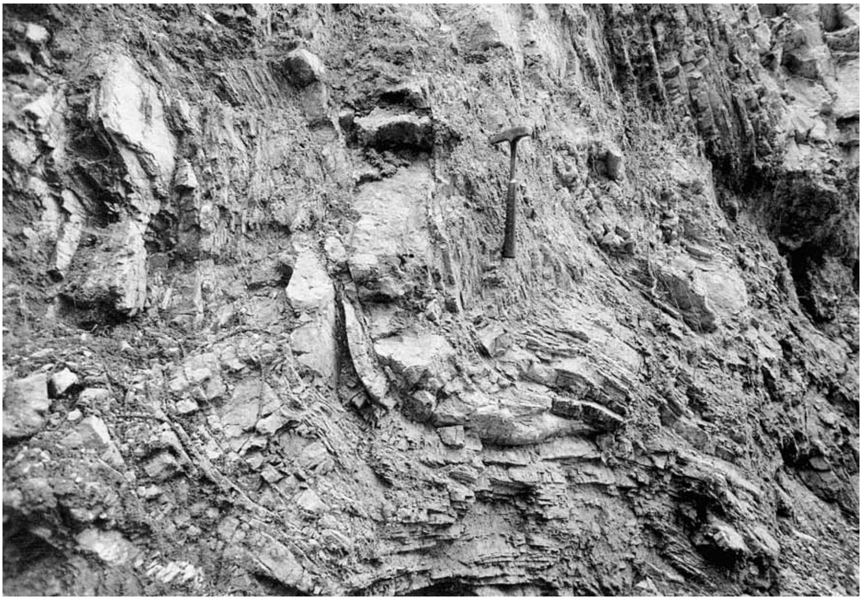

Fig. 14. Pusti dol. Folding of beds and folds around new axis *b2* in marble limestones of the Medveščak member.

Fig. 15. Rusinski breg location. Fold *b1* (parallel to the hammer) and fold *b2* of »chevron« type in marble limestones of the Medveščak member

Phase ***F-II*** in the metamorphic rocks of Mt Medvednica is also characterized by »chevron« folds. In Fig. 15 (Fig. 3, location 12, coordinates X=5084025, Y=5577305 and Z=610 m) taken on the woodland lane to Rusinski breg in the marbled limestones of the Medveščak member, the relationship between the folds created in phases ***F-I*** and ***F-II*** is visible. The older fault the crest of which is parallel to the hammer was developed by the transposition of the bedding along $Sk_1//Or$. The axial plane is horizontal. Fracture systems from the zones perpendicular and angled to axis *b1*. Younger folds the b_2 axes of which are horizontal and perpendicular to the photo, have developed from monoclines (»kink folds«) by stress intensification, during phase ***F-II***. The vergence of these folds is eastern.

In the rocks forming the Bliznec member, schistose and foliation shaping is also developed along the axial plane cleavage (*Sk1//Or*). Because of limitations of length, below only a selection of the characteristic structures of this member will be shown with photos of outcrops. According to its ductile features (slate-philites, metacalcarenites, metapelites and metapsamites), the Bliznec member is suitable for the shaping of different structures. These structures show that they are developed by the transposition of the *Ss* bedding planes, which have rarely been preserved. One such metapelitic outcrop (Fig. 16) with preserved bedding is found in the Bliznec stream valley by the sawmill (Fig. 3, location 9, coordinates X=5081605, Y=5576155 and Z=430 m). With a relatively thick (cm to mm) cleavage of axial plane, during the folding in phase ***F-I***, foliation was created, so that *Sf*-foliation planes on this outcrop became peripheral structural elements that had the main role in defining

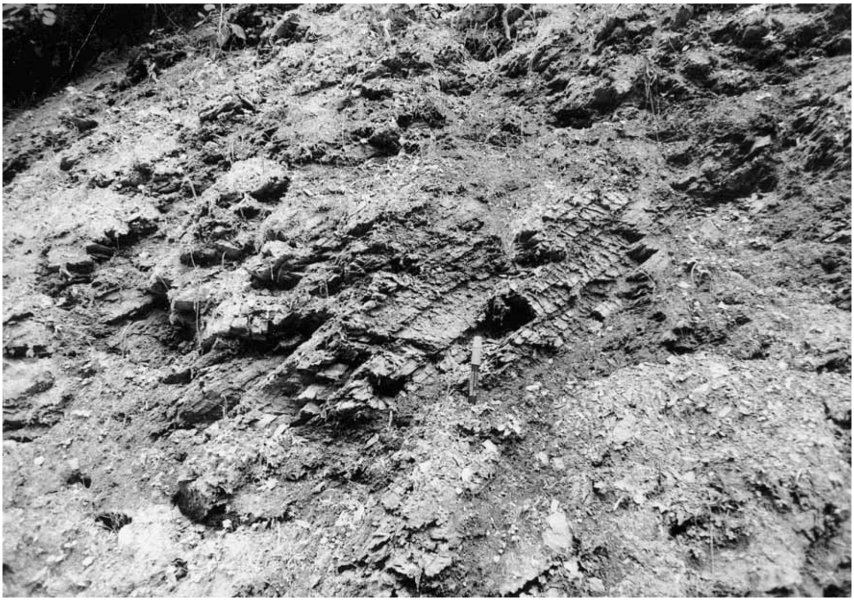

Fig. 16. Bliznec stream (sawmill). Metapelites of the Bliznec member. Description in text.

the further tectonic structures. The primary bedding is certainly visible at the cross-section level or is clear (on photo to the right of the marker) as a discontinuity plane at an angle of approximately 90° to the foliation. The bedding planes envelope the elements of which were measured on the outcrop and in the broader area gives the overturned fold the axis of which coincides with the axis b_1.

In the close vicinity (Fig. 3, location 9, coordinates X=5081720, Y=5576225 and Z=405 m) of the previous outcrop (Fig. 17), a photo was taken and is shown in Fig. 14. Planes of the vertically placed axial plane *Sk1//Or* cleavage (parallel to marker) and *Ss* plane is slightly plisse (*b1*) and at an angle of approximately 50° to the west. The inclination of the *b1* axis occurred through stress activity in the E-W direction in phase F-II, when the axis sloped to the west. During the youngest deformation event (***F-III***) the foliation was folded forming folds parallel to the regional axis B_3 and with a gentle slope of approximately 8° to the east (to the right of the marker and directly by it).

On the left side of the Bliznec stream, at the same location, (Fig. 3, location 9, coordinates X=5081725, Y=5576254 and Z=410 m), dark, almost black metasiltites (Fig. 18 and 19) with a strongly pronounced millimetre transposition of bedding planes (Ss) along the axial plane cleavage *Sk1//Or* occurred. Along the cleavage the foliation was developed in deformation phase ***F-I***. The cleavage planes on the outcrop

Fig. 17. Bliznec stream (sawmill). Vertical cleavage of axial plane (*sk1//Or*) and slightly plisse (*b1*) bedding plane.

Fig. 19. Detail from Fig. 18. Thick cleavage of axial plane (*Sk1//Or*) (mm in dimension) and primary bedding is apparent (parallel to scale).

Fig. 18. Bliznec stream (sawmill). Transposition of bedding along the axial plane cleavage (*Sk1//Or*) and formation of foliation in metasiltites of the Bliznec member

are almost placed vertically (parallel to hammer). The measured orientations of the bedding envelopes inside particularly the bigger (dm in size) lithons rimmed by strong cleavage feature folds the axes of which are parallel to b_1. These folded shapes disappear laterally, parallel to the fold axis, and reoccur along the axial plane cleavage. During the tectonic processes of folding and transposition, fracture systems appear from the zone perpendicular to axis b_1.

Large scale transposition of *Ss* is visible on the outcrops on the right slope of Bliznec stream along the main road crossing Mt Medvednica (Fig. 3, location 10, coordinates: X=5081720, Y=5576165 and Z=420 m). Here, the Bliznec member (Fig. 20) is characterized by a primary interchange of siltites and finely bedded carbonate rocks. During the folding in phase ***F-I***, there are more ductile elements (siltites), strongly schistlike in appearance, along the mm-cleavage of the axial plane (*Sk1//Or*) forming the foliation (*Sf*). Carbonate intercalations were, through an intensification of the transposition processes, separated in lens-like forms, the longer axes of which mark the strike of the structure of the *b1* axis, together with the corresponding linear elements. On the basis of this outcrop and structures shown in Fig. 16, it is concluded to be an overturned limb of a bigger antiform by defining structural forms and the envelope of separated carbonate intercalations.

The final member of the Sljeme formation consists of the thicker-bedded (app. 0.5–3m) recrystallised limestones of the Markuševac member, which is according to ductile characteristics and deformation susceptibility, different to the other members. This member, in deformation phase ***F-I***, does not show the presence of struc-

Fig. 20. Bliznec stream. Transposition of *Ss* planes in transient levels of marble limestones of the Medveščak member and metapelites of the Bliznec member.

Fig. 21. Markuševac quarry. Reverse faults and *R1* fracture system in the slightly metamorphosed limestones of the Markuševac member.

tural forms of bigger fold index as do the earlier described members. Linear elements, formed in the interlayered movements along the bed planes and parallel to axis *b1*, are noticed very rarely. Of more important fracture systems, conjugated fractures from zone b_1 are noticed. They led to fracturing of the thicker beds. Thinner-bedded marble limestones are schistlike, whereas the measured elements of schistosity statistically show the contemporaneous formation with foliation (*Sf*) in the younger members.

In Markuševac quarry (Fig. 3, location 11, coordinates: X=5082025, Y=5577940 and Z=350 m) the strong cataclasis of weakly marbled limestones is visible, along with a couple of sub-parallel reverse faults (Fig. 21) formed in the F-I deformation phase. Intensive cataclasis of rocks is also caused by development of relatively thick R1 (RIEDEL, 1929) fractures between two reverse faults. In the younger deformation phase (***F-II***), the rocks of this member were at Markuševac and Baèun (observed in the S part of quarry) folded in the form of a broken antiform with axis *b2* and strike N-W. The following deformation phase (***F-III***) under the influence of transpression tectonics (JAMIČIĆ, 1995) during Tertiary and Quaternary left the sequence of reverse faults with strike E-W and northern vergence.

DISCUSSION AND CONCLUSION

The analysis of the structural elements in the metamorphic rocks of Mt Medvednica shows the following. In the first deformation event (***F-I***), under the influence of tangential global stress σ_1 in the N-S direction, a structural setting of monoclinal symmetry was formed. Along with the transposition of *Ss* bedding planes, folded structures with horizontally oriented regional axes *B1* (Fig. 22a) with E-W strike were formed. In phase ***F-II***, the axes of *B1* structures rotated (Fig. 22b) from a horizontal position around the axis of the N-S strike by approximately 40° and inclined towards W. Following fracture system from the zone perpendicular to axis *b1*, in this phase, inclines towards E from its vertical position. Global stress, in the next tectonically active period (***F-III***) was active (Fig. 22c) along the N-W direction,

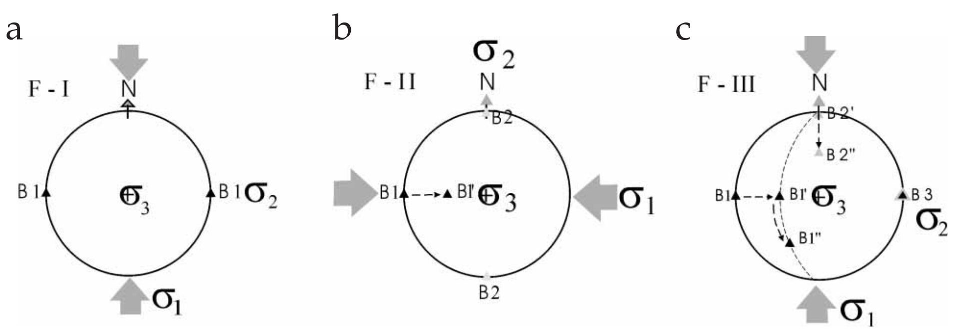

Fig. 22. Orientation of main stress activity according to deformation phases and migrations of *b1* and *b2* axes in the metamorphic rocks of Mt Medvednica

when the axes of *B1* structures, together with other structural elements, bent and rotated around the axis with E-W strike and plungde into N or S for different angle values. The gentle folding of fractures from the zone perpendicular to axis *b1* (Fig. 18) is the outcome of stress activity in the youngest tectonic phase.

The sequence of tectonic events described, which was influential for the structural shaping of the metamorphic rocks of Mt Medvednica, divided in three deformation phases, is also characteristic of the broader structural setting of Mt Medvednica area. For determination of a particular tectonic event duration, it is significant that the structures found in metamorphic rocks were formed in all three deformation phases. The description of tectonic deformations and their evolution in younger, Mesozoic and Tertiary formations will be considered in a subsequent paper. So far, it can be said that the deformations formed in the second and third phases (***F-II*** and ***F-III***) are preserved in Mesozoic rocks (Lower, Middle and Upper Triassic, Upper Cretaceous-Palaeogene), whereas in Tertiary rocks only the third phase has remained recorded (***F-III***).

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SAŽETAK

Strukturne deformacije u metamorfnim stijenama Zagrebačke gore (Hrvatska)

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U radu se iznosi opis i analiza geneze karakterističnih i izabranih strukturnih oblika iz jednog dijela metamorfnih stijena Zagrebačke gore. Ishodišne stijene, koje su procesima regionalne metamorfoze dovedene na današnji stupanj metamorfizma, protolitno čine razni varijeteti bazalta, dijabaza, tufova, kvarcnih pješčenjaka, rožnjaka, pelita, karbonatnih pelita, psamita, siltita, vapnenaca i dolomita.

Današnji strukturni sklop prikazanog područja, formiran je tijekom tri odvojena deformacijska događaja koji su, svaki za sebe, ostavili u metamorfnim stijenama jasno prepoznatljive strukture. Tijekom prve deformacije (*F–I)*, koju prate i metamorfne promjene do nivoa facijesa zelenih škriljavaca, došlo je do intenzivnog boranja i uškriljavanja sedimenata i vulkanita te postanka folijacije. Folijacija je rjeđe oblikovana paralelno ili subparalelno sa slojevitošću. Duktilniji sedimenti su uz klivaž osne ravnine, procesima transpozicije ploha slojevitosti, izgubili svoju primarnu orijentaciju uz nastanak milimetarske folijacije. Ove procese prati iscjeđivanje kvarca i kalcita u tjemene dijelove bora. O intenzitetu procesa transpozicije svjedoče i česte pojave »pencil« struktura i drugih oblika *r*-tektonita u karbonatnim i klastičnim tvorevinama. U metamorfnim stijenama susrećemo razne tipove boranih oblika; monoklinalne, koljeničaste, »chevron«, slične i konjugirane bore. Prateći pukotinski sustavi su, uz milimetarski do centimetarski klivaž osne ravnine, i pukotine koje stoje pod kutom i okomito na os struktura.

U drugom deformacijskom događaju (*F-II)*, koji je datiran kao postkredni (laramijski), zatečene strukture u metamorfnim stijenama dolaze pod utjecaj stresa koji djeluje na pravcu I–Z. U ovoj fazi dolazi do rotacije ranije stvorenih struktura oko osi pružanja S–J i oblikovanja novih. Međutim, indeks boranja je u ovoj fazi manji u odnosu na ranije tektonske događaje.

Sljedeći tektonski događaj *(F–III)*, uvjetovan djelovanjem stresa u smjeru S–J tijekom tercijara i kvartara, vezan je za tektonske procese po modelu transpresije. Ti procesi dovode do stvaranja boranih oblika pružanja I–Z i sjeverne vergencije, a prate ih pukotine i reverzni rasjedi. Strukturni elementi, nastali u prethodnim tektonskim fazama oblikovanja sklopa Zagrebačke gore, u ovoj fazi rotiraju oko osi I–Z za različite iznose.