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The Role of Sinistral Strike-Slip Faults in the Formation of the Structural Fabric of the Slavonian Mts. (Eastern Croatia)

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Key words: Left-lateral faults, Transpression, Structural fabric, Wrench faults, Slavonian Mts., Croatia.

Abstract

This paper presents a simplified evolution for the Slavonian Mts. structural fabric during the Neogene, emphasising the importance of the sinistral wrench faults. These faults were formed under the influence of dextral displacements along the faults stretching through the Drava and Sava. They caused the uplift and compression of the general area of the Slavonian Mts. These events were accompanied by folding, reverse faulting and counter-clockwise rotation of the uplifted structures, typical for the transpression model and wrench tectonic processes.

1. INTRODUCTION

The Slavonian Mts. are an integral part of the Pannonian basin. From a tectonic point of view they represent intensively deformed structures composed of preserved Pre-Mesozoic and Mesozoic basement partially covered by Tertiary sediments. Pre-Mesozoic structures were formed by deformational processes which have also caused metamorphic changes. The Post-Cretaceous period of intensive tectonics (i.e. the Laramian phase of the Alpine Orogeny) was characterised by strong E-W compression, eastern vergence of the folded structural elements, clockwise rotation and dextral displacement of the structures (JAMIČIĆ, 1988, 1993). During this phase newly formed structures of N-S strike were uplifted, thus becoming the source area of the detritus incorporated in the Tertiary deposits.

The tectonic fabric of the Slavonian Mts., formed during the Tertiary and Quaternary, is characterised by the common presence of the sinistral faults and en-échelon folds (with approximately horizontal axis), of E-W strike, and northern vergence of their axial planes. The characteristics of the folds are variable, depending upon the stage of their evolution, depth of origin and comparent rock type.

The southern parts of the Pannonian basin have included in several recent tectonic studies (JAMIČIĆ, 1988; ROYDEN, 1988; BERGERAT, 1989; HORVÀTH, 1993). These studies indicate the importance of two regional dextral faults, stretching through the valleys of the Sava and Drava rivers. Under the influence of dextral tectonic displacement (JAMIČIĆ, 1988), several sinistral faults with NE-SW strike were formed between these faults (JAMIČIĆ, 1979), with movement of the SE blocks towards the NE.

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2. THE FORMATION MECHANISM OF THE SINISTRAL FAULTS

The general area of the studied structural fabric (shown simplified on Fig. 1) is characterised by numerous sinistral strike-slip faults. The orientation of the regional stress was determined by analysis of the linear elements on the fault surfaces. The approximate orientation of the compression was N-S (the greatest principal stress - σ_1), of the extension E-W (the least principal stress - σ_3), and the axis of the intermediate principal stress (σ_2) was vertical. Fault geometry, their relations with accompanying folds, as well as the reconstruction of the strike-slip deformation processes indicate the penecontemporaneous formation of plicative and disjunctive elements. Folds examined in the area of the Slavonian Mts. were displaced along the above mentioned faults under acute angles (between 30 and 45°).

Under the influence of the global stress (oriented approximately N-S in the Pannonian basin), and due to the migration of the Carpathian Arc towards the E and NE during the Neogene, two dextral strike-slip faults were formed, stretching through the valleys of the Drava and Sava rivers (ROYDEN, 1988; BERGERAT, 1989; HORVÀTH, 1993). In the area between these regional faults a conjugated fault set was formed. It is composed of synthetic faults with dextral displacement and NW-SE strike, and antithetic faults oriented NE-SW with sinistral displacement of the separated blocks (Fig. 2). Deformation processes were accompanied by extension along the E-W direction. Increasing regional stress caused the predominance of the sinistral faults, and led to their principal role in the formation of the structural fabric of the Slavonian Mts. region. Further increases of the displacement along the Drava fault additionally increased the greater angle γ (i.e. the angle between the sinistral faults and the Drava dextral fault, Fig. 2). In this way the faults were rotated clockwise around the vertical axis, similar to the examples of DIB-

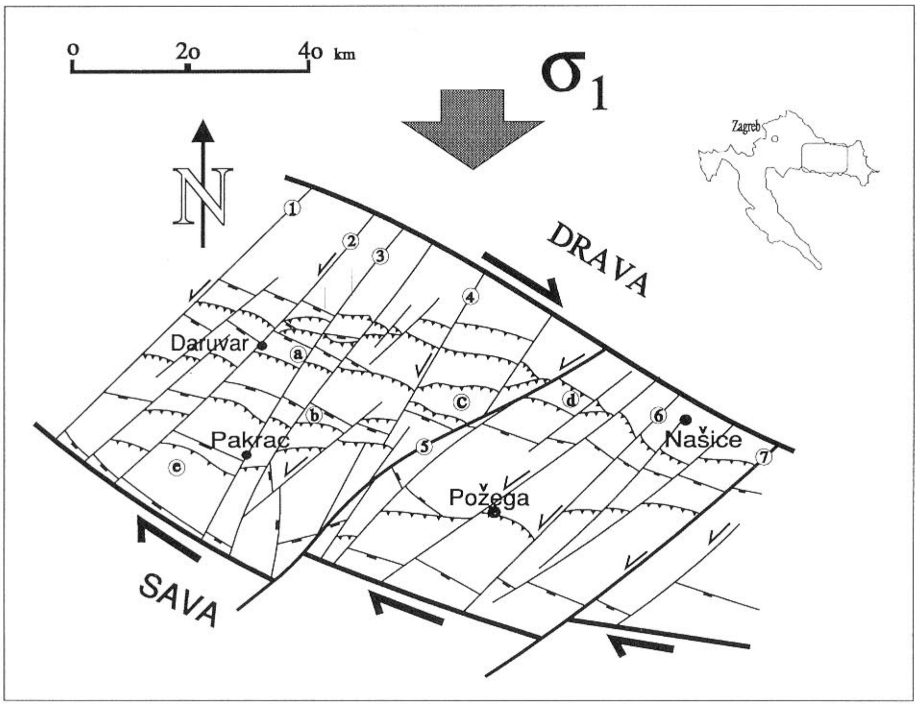

Fig. 1 Simplified structural map of the Slavonian Mts. with review of the Neogene tectonics. Faults and structures: 1) Ilova fault; 2) Daruvar fault; 3) Pakrac faults; 4.) Brzaja fault; 5) Radlovac fault; 6) Našice fault; 7) Dilj fault; a) Španovica structure; b) Pakrani structure; c) and d) Velince-Velika-Kapovac-Petrov Vrh structure; e) Bijela stijena-Kričke structure.

BLEE (1985) and SWANSON (1988, Fig. 11b). The supplementary angle β between the sinistral faults and the Sava fault (Fig. 2) was simultaneously decreased, resulting in convergence of the Sava and Drava faults and increased compression inside the separated blocks between the Sava and Drava rivers. Displacement of blocks along the strike-slip (wrench) faults during the initial stage of the formation of the Neogene structural fabric has generated the extensional processes in the Drava region and the formation of deep fractures accompanied by synsedimentary magmatism. As shown in Fig. 2, extensional zones (one is denoted by the A-B-C triangle) were mutually separated, which explains the discrete outcrops of volcanic rocks in this part of the Pannonian basin. The strongest displacement of blocks occurs between points B and C, connected to separate phases of deformation. Therefore, in this part of the Pannonian basin there are volcanic rocks of Otnangian-Karpathian age, and younger, Badenian rocks.

During further displacement along the dextral faults of the Sava and Drive rivers valleys with their mutual convergence, the distance between the point C and the line connecting points A and B decreased. The extensional processes were repleced by compression, resulting in closure of the former deep fractures and the interruption of volcanic activity. The conjugated set of the dextral faults striking NW-SE has mainly lost its characteristics of horizontal movement during these processes, mostly becoming faults with normal movement of the S and S-W blocks.

The increasing compression and narrowing of the area between the Sava and Drava rivers, also caused

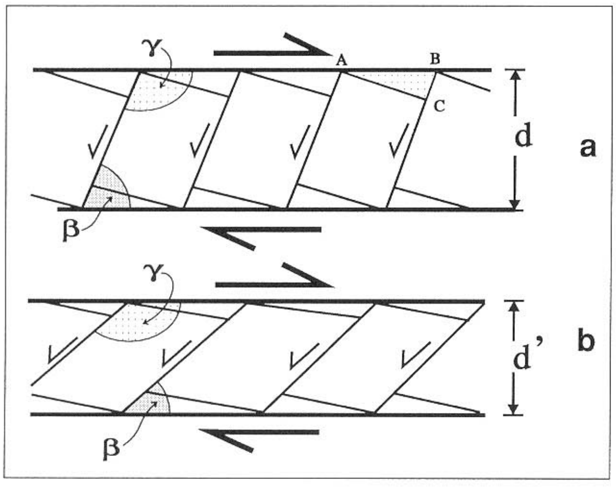

Fig. 2 Rotation of the sinistral strike-slip faults between two dextral strike-slip faults. See text for additional explanations.

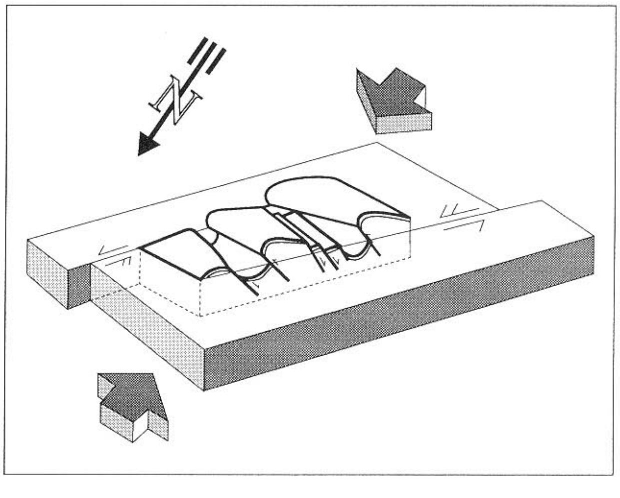

Fig. 3 Folding and uplifting of the structures between two blocks separated by the sinistral strike-slip faults. Block movements are indicated by single (slower movement) and double (faster movement) arrows.

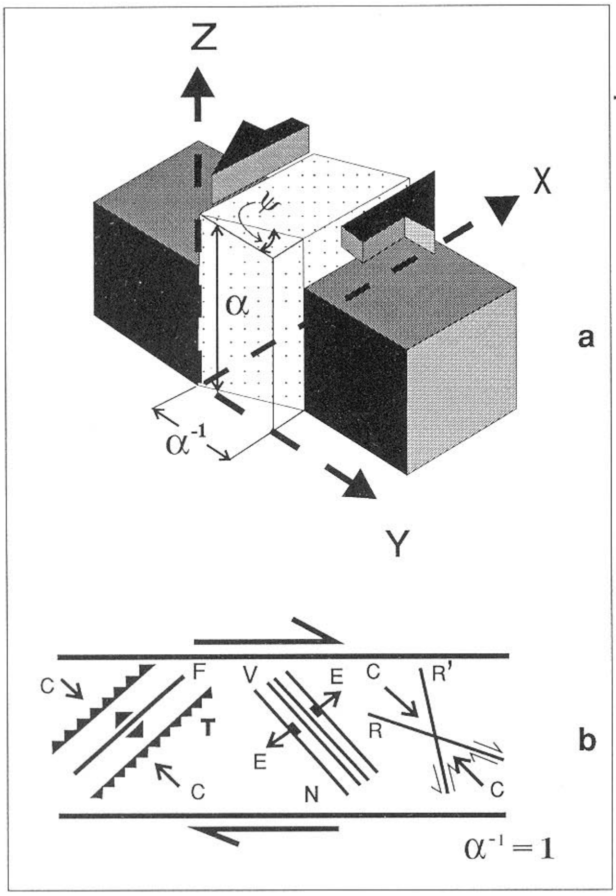

Fig. 4 a) Transpression model with vertical escape; b) Orientations of fractures corresponding to the wrench tectonics model: C - compression axis; E - extension axis; N - normal faults; T - thrust faults; R, R' - Riedel shears or wrench faults; V - veins, dykes or extension fractures; F - fold axis (after SANDERSON & MARCHINI, 1984).

blocks separated by sinistral faults to be folded and uplifted. The axis of the folds were oriented normally to the stress, i.e. E-W. During the initial phases, folding was the result of uplift along the normal faults. Later, during increased stress, faults with the normal movement in the N and N-E parts of the structures, have gradually increased their inclination: firstly to the flexural stage, and eventually they became reverse faults with northern vergence. The axial planes of the accompanied en-échelon folds have also assumed northern vergence, which is more strongly emphasised in the eastern parts of the folds (Fig. 3). This is the consequence of the anti-clockwise rotation of the structures, and greater uplift of their eastern parts during strike-slip movement along the sinistral faults. During a further stage of anti-clockwise rotation of the structural fabric, the eastern parts of the structures (both anti- and sinforms) closed further, and were transformed into overturned folds. These are more common in the central parts of displaced blocks, which are characterised by the strongest compression. Normal faults, formed during the initial stage of formation of the structural fabric in the S and SW parts of the uplifted structures, have kept the same characteristics of hanging-wall movement with a gradual inclination of the fault surfaces towards the N and NE.

This simplified view of the evolution of the Slavonian Mts. during the Neogene indicate that their tectonic fabric exhibits characteristics of the transpression model (SANDERSON & MARCHINI, 1984). This model, schematically shown on Fig. 4a, represents transformation of the unit cube during reduction along the y-axis, with simultaneous displacement along the x-axis. The preservation of volume is enabled by elongation along the z-axis. Deformation between these two faults with horizontal displacement is accompanied by the formation of en-échelon folds. The angle between the fold axis and fault surfaces is mostly below 45°.

Besides the presented model with vertical elongation of the unit cube, there are several other transpression models which possibly explain horizontal elongation (DIAS & RIBEIRO, 1994). Figure 4b represents the orientation of the structural forms related to this model, depending on the values of $α^{-1}$. The factor $α^{-1}$ represents the ratio between the deformed unit cube and its original width, and has a value ranging from $α^{-1}<1$ to $α^{-1}>1$. The value 1 indicates deformational processes known as wrench tectonics. This term was introduced by KENNEDY (1946) for faults in general, and by WILCOX (1973) for large faults accompanied by horizontal displacements of several tens of kilometres. Displacement of blocks is accompanied by the set of en-échelon folds, whose orientation depends on the direction of movement along the strike-slip fault. WILCOX (1973) has experimentally demonstrated on the clay model that the left movement resulted in the left orientated set of en-échelon folds, while the right one produced the right orientated set of folds. The angles between the fold axes and the fault zone along which the displacement is performed, are always acute, usually approximately 30° (in the clay model). By increasing the stress, deformation and movement along the sinistral faults, the angle between the folds axis and the faults is decreasing. Its value depends upon the thickness and ductility of the rock complex. Accompanying conjugate faults belong to the Riedel shears type, and are characterised by an angle of 10 - 30° (synthetic faults) towards the dextral faults (Fig. 5, Sf). Their conjugate faults (Fig. 5, Af) have angles from 70-90° (antithetic faults) towards the main dextral faults.

3. TECTONIC SETTING

BERGERAT (1989) has concluded that along the dextral strike-slip faults, stretching through the valleys of the Sava and Drava rivers, there was important right displacement under the influence of the N-S compression during the Miocene and the Pliocene. Also, the author also stated that there was some extensional process (oriented E-W), resulting in continuous subsidence along the NNE-SSW faults, which were perpendicular to the Drava valley. Along these faults separated

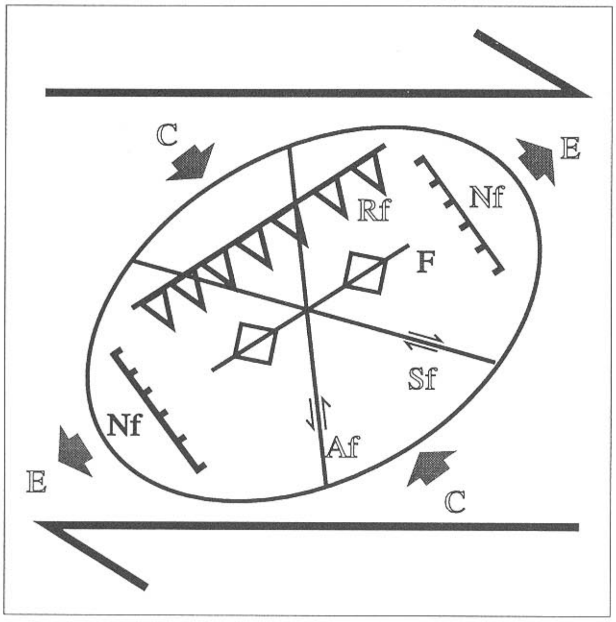

Fig. 5 Orientation of the structural elements formed under the influence of the dextral displacement: C - compression; E - extension; Rf - reversed faults; Nf - normal faults; Sf - synthetic faults; Af - antithetic faults; F - folds.

blocks subsided stepwise towards the SE, with the contemporaneous filling of associated depressions.

On the basis of detailed structural investigations JAMIČIĆ (1978, 1983, 1988) has concluded that the predominant characteristic of the Slavonian Mts. structural fabric is the presence of the sinistral faults striking NNE-SSW and en-échelon folds with axes striking approximately E-W. The folds are characterised by displacement along the sinistral faults (sporadically up to 10 kilometres), and by the anti-clockwise rotation of the youngest structural forms (in Pre-Tertiary and Tertiary rocks). Tectonic reduction and the counter-clockwise rotation of the structures during the youngest period of structural fabric formation took place along the reverse faults. These faults are parallel with the axial planes of the plicative structures.

Like many others (Fig. 1), examples of such structures include the overturned synclines of Španovica (Novo Selo syncline in JAMIČIĆ, 1988) and Pakrani in the western part, and the overturned anticline Velince-Velika-Kapovac-Petrov Vrh in the eastern part of the Slavonian Mts.

In the western part of Španovica the overturned syncline is represented by an approximately 3 km wide outcrop of Helvetian to Quaternary rocks. In the eastern part, near the village of Mijači, the width of the same zone is tectonically reduced to 250 m, due to overthrusting of the southern limb over the northern one. The axis of the syncline was displaced along the numerous NNE-SSW striking sinistral faults, and is inclined towards the W. The axial plane was curved: in the eastern part it has a northern vergence of approximetely 40 degrees, while in the western part its northern vergence is very weakly expressed.

The overturned anticline Kapovac-Petrov Vrh (Krndija Mt.), composed of Mesozoic and Precambrian rocks, is characterised by a similar tectonic fabric, but the influence of numerous parallel reverse faults is much more important. In the easternmost part the structure is completely tectonically reduced along this set of faults. This reduction was accompanied by the gravitational sliding of some blocks, and anti-clockwise rotation of the structures, which eventually lead to the overthrusting of the southern parts of the structures over the northern ones. Tectonic reduction is also the very important consequence of the displacement of the Velinca-Velika-Kapovac-Petrov Vrh structure along 10 km of the ENE-WSW striking Radlovac. Curving of the Radlovac fault (Fig. 1) from an NE-SW to ENE-WSW strike indicates its clockwise rotation around the vertical axis. The rotation, which is more important in its NE part, led to increased compression in the SE block of this fault, due to the tectonic reduction of the area. The index of folding and reverse faulting was significantly increased during the further increases of compression. The Velince-Velika structure represents the extension of the Kapovac-Petrov Vrh structure towards the West, and is characterised by the same tectonics. Its westernmost part is stretched to the Brzaja sinistral strike-slip fault, where it is in the contact with the Palaeozoic rocks of Papuk Mt.

Displacements of parts of the structures along the sinistral wrench faults were very important in the formation of the marginal contacts of Metamorphic-Mesozoic complexes and Tertiary sediments, as well as in the gradual disappearence of the Pre-Tertiary rocks towards the E and W, where they are covered by Pliocene and Quaternary deposits. Above mentioned transpression model (SANDERSON & MARCHINI, 1984), together with the formation of the left oriented en-échelon folds, can explain the uplift of the central parts of the Slavonian Mts. in comparison to their E and W slopes during the evolution of their structural fabric. Lateral movements along these faults led to compression inside the blocks, and their subsequent upliftment. Stronger movements led to uplifting of a larger scale. The left-lateral separation of blocks along the Pakrac fault (JAMIČIĆ, 1993) has resulted in the uplifting of the Psunj metamorphic complex, and its thrusting over the overturned Španovica structure. Between the Pakrac and Ilova faults there are several faults of the similar features. Towards the W they are characterised by a gradual decrease in uplift, as well as by a gradual decrease in horizontal displacement. In the same direction, this decreased amount of the vertical and horizontal tectonic transport is accompanied by the gradual disappearence of the en-échelon folds and a transition from reverse faults to normal faults with uplifted southern blocks.

Similar tectonic pattern was discovered at the easternmost slopes of the Slavonian Mts., being characterised by more frequent wrench faults. Along these faults Pre-Tertiary rocks were more significantly rotat-

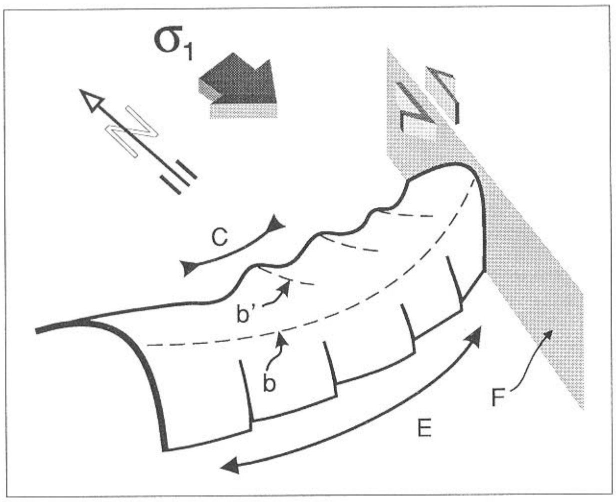

Fig. 6 Bending of the Bijela stijena - Kričke anticline structure along the sinistral Pakrac fault: C) compression; E) extension; F) Pakrac fault; b) structure axis; b') secondary folds.

ed anti-clockwise, as shown on the example of the Kapovac-Petrov Vrh structure (JAMIČIĆ, 1988).

Transpressional structures shown on Fig. 1 and block-diagram (Fig. 3) were formed between the Carpathian and Quaternary. At the end of this paper two further examples will be presented, illustrating formation of the structural fabric of the Slavonian Mts. according to the transpression model.

Example 1. Intensive stretching of separated blocks along the sinistral Pakrac fault (Fig. 1/3), during the last phases of its activity caused bending of the E-W oriented Bijela stijena - Kričke anticline structure along the vertical axis (Figs. 1c and 6). As a result the northern limb was folded due to the compression, and the southern one was stretched because of the extension, with the appearance of faults oriented approximately normal to the structural axis. Concave bending of the structure towards the North was caused by the larger index of tectonic transport of the Psunj (eastern) block, and also by its counter-clockwise rotation, leading to the aforementioned reduction of deposits in the eastern parts of the Španovica structure.

Example 2. As already mentioned, along the Radlovac fault (Fig. 1/5) the structures of Papuk and Krndija are stretched for approximately 10 km. Although this fault is visible almost along its complete surfacial occurrence, the best, 50 m wide outcrops have been found in the Hercegovac quarry WNW from Našice (Fig. 7). Stretching of blocks of Papuk and Krndija Mts. along the Radlovac fault caused very intensive milonitisation and foliation of metamorphic rocks of the Krndija Mt., at the contact with the Mesozoic carbonates. The fault is oriented 50°-230°, with the fault surface inclined between 84°-90°. Linear marks of 160° angle indicate sinistral transport. From these data the following information concerning the orientation of the regional stress can be stated: 187/11 - compression (σ_1), 281/17 - extension (σ_3) and 66/69 - the intermediate axis (σ_2). Corresponding tectonic data, indicating tectonic transport along the sinistral faults, have also been obtained for the other faults shown on the Fig. 1.

4. CONCLUSION

According to the data presented in this paper the following conclusions have been drawn.

The mechanism of the structural fabric formation of the general area of the Slavonian Mts., during the Neogene kinematics of this part of the Pannonian basin, was controlled mainly by the transpression model, which is characterised by displacements along the strike-slip faults.

Under the influence of the approximately N-S oriented regional stress, characterised by N-S compression and E-W extension, dextral strike-slip faults were formed stretching through the Sava and Drava river valleys. During the initial phase of horizontal displacements a set of sinistral strike-slip faults was formed in the area between these main faults. Displacement of blocks along the faults corresponded to the transpression model, wich was also characterised by folding and uplifting of separated blocks. Clockwise rotation of the

a

b

Fig. 7 a) The Radlovac fault in the Hercegovac quarry; b) a detail of the right part of the outcrop.

sinistral strike-slip faults around the vertical axis and their mutual convergence led to the compression and narrowing of the area between the Sava and Drava rivers. These processes were accompanied by the anticlockwise rotation of the folded forms with an approximate E-W strike, and the important tectonic reduction of the eastern parts of structures.

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