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Extensional Unroofing of the Veliki Jastrebac Dome (Serbia)

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Abstract. This paper presents the basic structural elements of the dome of Veliki Jastrebac, as well as the chronology and mechanisms of the deformational events responsible for its formation. It was determined that the dome of Veliki Jastrebac consists of two large sequences which are, in the vertical section, in the inverse position. The lower part is made of Late Cretaceous and Cretaceous–Palaeogene low-grade to medium-grade metamorphic rocks, which are intruded by Paleogene granitoid (probably the Vardar Zone), which are covered with a large overthrust consisting metamorphics of the Serbian-Macedonian Mass. The low-grade to medium-grade metamorphosed complex of Veliki Jastrebac, with the granitoid, represents a metamorphic core complex, exhumed by mechanisms of extensional tectonics in the Paleogene.

Key words: Serbia, Veliki Jastrebac, tectonics, syntectonic intrusion, extension, unroofing.

Апстракт. У раду су приказани основни елементи грађе Великојастребачке доме и хронологија и механизми деформационих догађаја одговорних за њено формирање. Утврђено је да дому изграђују два крупна навлачно-наборна ентитета која су, у вертикалној сукцесији, у инверсном положају. Доле леже горњокредне и кредно-палеогене ниско до средњометаморфисане стене у које је утиснут палеогени гранитоид (вероватно Вардарска зона), горе је као крупна навлака, кристалин Српско-македонске масе. Ниско до средње метаморфисан комплекс Великог Јастрепца са гранитоидом представља метаморфни core complex, ексхумиран механизмима екстензионе тектонике у палеогену.

Кључне речи: Србија, Велики Јастребац, тектоника, синтектонска интрузија, екстензија, раскровљавање.

-Introduction

The geological setting of Veliki Jastrebac and its immediate surroundings, particularly its tectonic setting, is very interesting and insufficiently defined. According to all previous concepts, this area was considered to be a part of the Serbian–Macedonian Mass. In the spatial sense, this is apparently correct. However, according to geological characteristics of the terrain of Veliki Jastrebac, this opinion should be revised. Namely, there are deposits in the area of Veliki Jastrebac which are, regarding their lithology and structural-tectonic characteristics, exotic in the Serbian–Macedonian Mass. Grubić (1999) was the first to suggest that the Serbian–Macedonian Mass is not a homogenous structure but is composed of several thrust-fold stacks with units in inverted stratigraphic positions (double window). The uppermost level of this pile is made of high-grade metamorphics, while the lower parts are made of Paleozoic, Mesozoic and Mesozoic–Palaeogene rocks, and medium to low-grade

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metamorphics. The geological setting of the area of Veliki Jastrebac has hitherto been explained: the Serbian–Macedonian Mass (gneiss and low-grade metamorphics) in the lower part and discordant Upper Cretaceous–Paleogene low-grade metamorphics with intruded Palaeogene granitoid of Jastrebac in the upper part (RAKIĆ *et al*. 1974, 1976; KRSTIĆ *et al*. 1978, 1980).

The model of the geological relations in the area of Veliki Jastrebac introduced by GRUBIĆ (1999), GRUBIĆ *et al*. (1999, 2005), has opened new problems related to the geology of the area:

a) more detailed division of the low-grade metamorphic formations;

b) reconstruction of the exhumation of the mechanism of the Veliki Jastrebac Dome (by surface erosion or by tectonic denudation?).

This paper is focused on solving these problems. For this purpose, a number of new data on the lithology, age and fabric of this terrain were collected. Preliminary results were obtained by these investigations, but detailed structural analysis and application of geochronology and thermochronology, the fission track method in the first place, are necessary for more reliable conclusions. Despite this, it is still possible to assume, on the basis of the obtained results, that the Veliki Jastrebac Dome was unroofed by tectonic denudation during the Palaeogene, coevally with an intrusion dome of the granite of Jastrebac.

Basic characteristics of the main tectono--stratigraphic units of Veliki Jastrebac

The structural setting of the Veliki Jastrebac Dome is a product of polyphase deformation, beginning with the Baikalian, through the Caledonian and Hercynian to the Alpine orogen. The Alpine Mesozoic–Cenozoic structural content is dominant today (Fig. 1). Two major tectono-stratigraphic units are recognized: the Jastrebac Unit and the Morava Unit, which are divided into several smaller subunits each of which being itself a complex thrust-fold pile. These units have different lithostratigraphic characteristics and structural pattern, which were the criteria for the tectono-stratigraphic divisions (GRUBIĆ 1999). He suggested that the Morava Unit is thrust over the Jastrebac Unit.

Jastrebac pile of nappes

The Jastrebac pile of nappes – Jastrebicum makes the central part of the area of Veliki Jastrebac. It lies beneath the Morava pile of nappes, while its footwall remains unknown (GRUBIĆ 1999). He distinguished the following three subunits within the Jastrebicum: Lomnica, Boljevac and Vukanja. Detailed investigations showed that the Boljevac and Vukanja Subunits cannot be easily distinguished, because the formations from which these consist of are intercalated, particularly in the border area. Thus, these two subunits are thus presented as one unit.

The Lomnica subunit consists mostly of Cretaceous––Palaeogene low-grade metasediments, anchimetamorphosed rocks and, in places, also of non-metamorphosed rocks (PANTIĆ *et al*. 1969; RAKIĆ *et al*. 1972, 1974, 1976), Palaeogene granitoids and granodiorite-porphyrite and aplite (RAKIĆ *et al*. 1974, 1976). The Cretaceous––Palaeogene deposits are represented by psammites, psephites and most often by pelites, which are regionally metamorphosed up to greenschist facies ("black phyllite"). These rocks were subjected to contact-metamorphism (hornfels, dotted phyllite and micaschists) in the immediate surroundings of the Paleogene granitoid.

The granitoid of Jastrebac intruded into the Cretaceous–Paleogene deposits at 37 Ma (ČERVENJAK *et al*. 1963). Its periphery is made of fine-grained varieties, while coarse-grained varieties are in the central part.

The Cretaceous–Palaeogene deposits of the Lomnica subunit are intensely folded. At least two phases of folding can be distinguished. According to GRUBIĆ (1999), the older phase is characterized by intense folding accompanied by transposition and formation of axial-plane cleavage, therefore the primary sedimentary fabric can only be assumed in hinges of the intrafolial rootles folds (cm-dm, rarely of meter scale). The hinges of these folds plunge to NNW and SSE (Fig. $1D_1$).

The cleavage planes became the dominant S-surfaces which were deformed during the second phase of folding in such a manner that they periclinally encircle the Jastrebac granitoid, forming a rather symmetrical dome (GRUBIĆ 1999). Poles to the axial plane cleavage clearly mark such folds (Fig. $1D_2$).

The initial vergences of I phase old folds and therefore the tectonic transport could not have been determined because of the strong transposition and intense folding and subsequent refolding. According to the intensity of folding, the Lomnica Subunit could not be autochthonous, but it was most probably thrust over an unknown footwall. GRUBIĆ (1999) believes that transport in this unit was toward the east.

The Boljevac–Vukanja Subunit extends over the immediate periphery of Veliki Jastrebac and, in an arch shape, it surrounds the deposits of the Lomnica Unit and in places the Jastrebac granitoid. The Boljevac–Vukanja Subunit is made of two sequences of metamorphosed rocks of "greenschist facies" (Fig. 1).

The lower sequence is made up of epidote-actinolite, albite-chlorite and rarely chamosite schists with certain amounts of transposed rocks of the upper sequence. In the lower sequence of the crystalline schists, there are large and small lenses of metagabbro, particularly in the southern and southeastern parts of the Veliki Jastrebac Dome (RAKIĆ *et al*. 1974, 1976).

The upper part consists of albite-sericite schists, calcschists and marble with certain amounts of transposed rocks from the lower sequence (mostly in their bordering area) (RAKIĆ *et al*. 1974, 1976; KRSTIĆ *et al*.

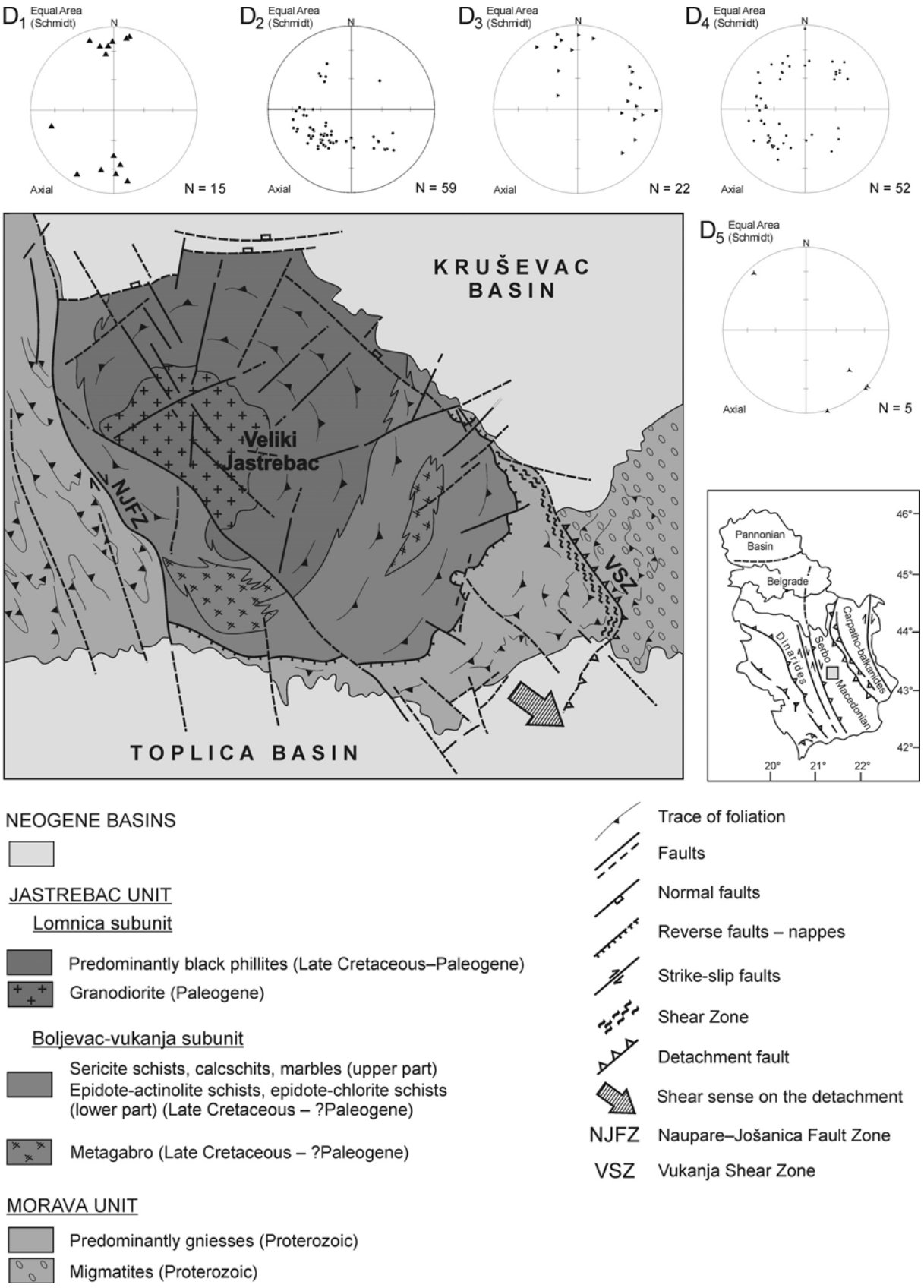

Fig. 1. Structural sketch of Veliki Jastrebac and an equal area lower hemisphere stereograms of: **D_1,** intrafolial folds of the Lomnica Unit; **D_2,** foliation of the Lomnica Unit; **D_3,** intrafolial folds of the Boljevac–Vukanja Unit; **D_4,** foliation of the Boljevac–Vukanja Unit; **D_5,** extensional lineation in the Boljevac–Vukanja Unit. Geological map (modified and simplified) after RAKIĆ *et al*. 1974; KRSTIĆ *et al*. 1978.

1978, 1980). The presence of calcschists and marble is rather conspicuous and it represents a criterion for the easier recognition of the upper package of metamorphites in the Boljevac–Vukanja Subunit.

The deposition age of the protolith of the metamorphic rocks of the Boljevac–Vukanja Subunit is the crucial question and the final explanation of the tectonic relations and events on these terrains depends on its solution. On the Basic Geologic Map, sheet Kruševac (RAKIĆ *et al*. 1974), these deposits were determined as Paleozoic, with the possibility of being younger. On the sheet Aleksinac (KRSTIĆ *et al*. 1978), these rocks were considered to be of Riphean–Cambrian age.

The palynological analysis performed during these investigations showed that the sericite schists, calcschists and marble are Late Cretaceous or maybe even Palaeogene. Less reliable data were obtained for the lower sequence, but they also imply Late Cretaceous age. These two sequences are probably of the same age because they are often interfingered and have similar structural characteristics.

Fig. 2. Intrafolial folds in calcshists of the Boljevac–Vukanja Unit.

The greenshists facies metasediments of the Boljevac–Vukanja Subunit were also folded during at least two phases, in a similar way to the Lomnica Unit. The first phase of folding is indicated by parts of the hinges of intrafolial rootless folds preserved to different degrees and, in places, by the whole folding sequences (Fig. 2). Hinges of these cm-dm and even meter-sized folds plunge generally to the east and NNW (Fig. $1D_3$). The bedding is transposed along the axial-plane cleavage; the primary fabric is mostly unrecognizable. The foliation along the axial plane cleavage of the first-generation folds is probably the result of flattening perpendicular to the planes. Foliation represents the dominant planar element. Foliation fabric is particularly well developed in the lower metamorphic sequence of this unit. It may be rather the strain than the rheology.

There are indications that folds on the eastern slopes of Veliki Jastrebac are west-vergent. Sericite schists, calcschists and marble appear in the cores of synforms, while epidote-actinolite and albite-chlorite schists appear in the cores of antiforms.

The cleavage and foliation of the Boljevac–Vukanja Subunit were folded into a dome structure during the second phase, similarly to the case of the Lomnica unit. This is clearly shown by the distribution of poles to foliation (Fig. $1D_4$).

Morava pile of nappes

The gneiss which surrounds the Veliki Jastrebac Dome, except in the southeast where it is probably covered by Neogene deposits, is considered to be a part of the Morava Unit (GRUBIĆ 1999).

On the western slopes of Veliki Jastrebac, along the Naupare–Jošanica Fault Zone (NJFZ), the gneiss is in tectonic contact with metasediments rocks of the Jastrebac Unit. In this part, it is mainly represented by fine--grained gneiss, mica-quartz-plagioclase schists, lenses of amphibolite and amphibolite-schists, as well as by small portions of quartzite. The composition of the rocks on the southern slopes of Veliki Jastrebac is similar. In the eastern part of Veliki Jastrebac, there are two groups of high-grade metamorphic rocks. From the tectonic contact between the gneiss and the Boljevac––Vukanja Subunit to the Vukanja Shear Zone (VSZ), there are mostly andesine gneiss, amphibolite and amphibolite gneiss. East of the VSZ, there is mostly migmatite with smaller portions of gneiss. The structure of the gneiss complex is extremely complex and in it was not studied during these investigations. Foliation, as the most distinct structural element is in the western part folded into cylindrical antiforms and synforms with the hinges trending in NNW–SSE, while it forms gentle open fold forms on the eastern side (Fig. 1).

The Morava Unit most probably consists of two nappes: the lower, consisting of various gneisses, overlays the Jastrebicum and the upper, represented by migmatites and subordinate gneiss, lays over the gneiss crystalline from which it is separated by the VSZ.

Exhumation Mechanism of Origin of the Veliki Jastrebac Dome

At the end of the Cretaceous and at the beginning of the Palaeogene, during the final phases of convergence between the Serbian–Macedonian Continental Plate and the Vardar Basin, intense folding of the deposits from the Vardar domain occurred. These deposits are exposed in the core of the Veliki Jastrebac Dome, overlain gneiss and schists of the Morava Unit. The complex fold-thrust sequence with an inverse succession of deposits was formed in the following manner:

Mesozoic–Cenozoic deposits are in the lower parts, while the Serbian-Macedonian Mass, i.e. the Morava Unit is in the upper part.

These deposits have been metamorphosed to greenschist facies grade and were folded during this metamorphic event at the end of the Paleogene. According to the lithological characteristics and by analogy to the certain parts of the Vardar Zone (north Bosnia and Croatia; PAMIĆ 1993; PAMIĆ *et al*. 2000, 2002), this could be a Vardar–Sava island-arc-back-arc-basin system.

During the final phases of convergence between the Serbian-Macedonian Continental Plate (as above) and the eastern part of the Vardar Zone, the Mesozoic–Palaeogene rocks were folded into tight, isoclinal folds, with the formation of an axial-plane cleavage with transposition. The hinges of the intrafolial folds in the Boljevac–Vukanja Subunit are generally plunging to the east, north-northwest and southeast.

The granitoid of Jastrebac originated in the Paleogene, at about 37 Ma (ČERVENJAK *et al*. 1963), by the melting of the crustal material which was buried into the deeper levels of the convergent Serbian–Macedonian–Vardar suture and subsequently intruded into the Cretaceous–Palaeogene complex.

Fig. 3. Extensional lineation in epidote-actinolite schists.

The emplacement mechanism of the granitoid into the higher levels and finally exhumation is still unknown. The explanation involving simple diapirism and erosion is hardly acceptable. The following indicators of extension, noticed in the gneisses and schists of the Jastrebicum, point to such events in the area of the Veliki Jastrebac Dome: stretching lineation (Fig. 3), s-type porphyroclasts (Fig. 4) and the wide mylonitic zones in the domains of the Naupare–Jošanica and Vukanja shear zones (particularly in the domain of the Vukanja fault) (SPAHIĆ 2006). The Vukanja Shear Zone (VSZ), which extends along the northeastern rim of Veliki Jastrebac, is bent toward south and southwest. The shear zone, marked by a several hundred meter-wide mylonite zone could represent a low-angle detachment normal fault along which extensional unroofing occurred. The stretching lineation (Fig. $1D_5$), shows the top-to-the south and southeast shear sense (SPAHIĆ 2006). It is also confirmed by the shape and orientation of the s-type porphyroclasts in the calcschists of the Boljevac–Vukanja Subunit (Fig. 4).

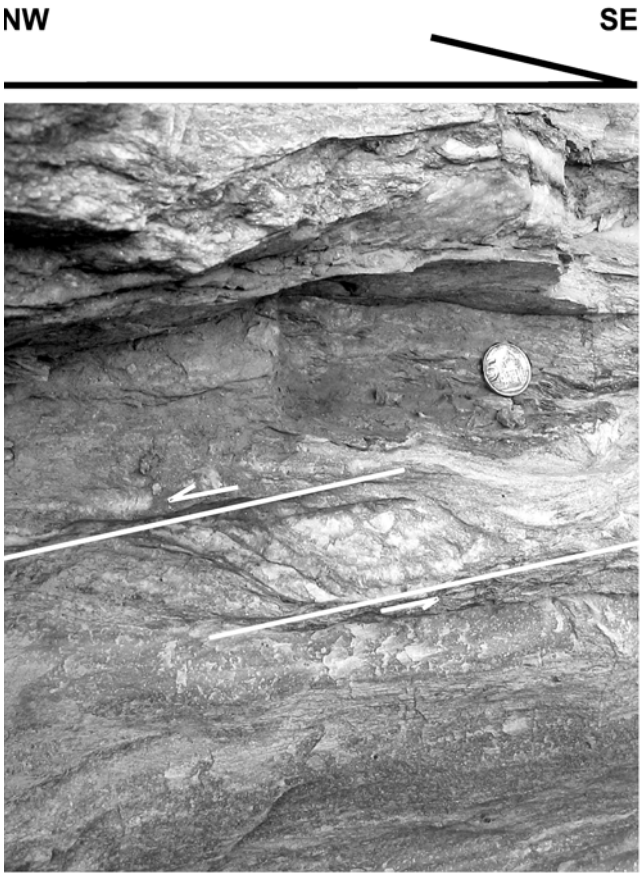

Fig. 4. Sigma -type porphyro clast in calcshists of the Boljevac–Vukanja Unit.

The process of extensional tectonic denudation probably induced decompression, uplift of geotherms and rock uplift of the granitoid body (isostatic adjustment?). Accompanied with erosion, the extension resulted in exhumation of the granitoid, together with the previously deeply seated metamorphic rocks. This resulted in a core complex-type map pattern of the area.

If the action of such an exhumation mechanism of Veliki Jastrebac is accepted, the problem of the tectonic denudation model and timing arise immediately. According to the age of the granitoid, the extension occurred most probably in the Palaeogene, during transtensional activity in the domain of the Naupare–Jošanica Fault Zone. In this case, there are two possibilities of activation of these extensional mechanisms:

• The Naupare–Jošanica and Vukanja shear zones represent a conjugate pair (NJFZ – dextral strike-slip, and VSZ – sinistral strike-slip) under conditions in which the axis of the maximum horizontal stress (SH) is

NE–SW oriented. In this case, the area between these two faults could escape towards the southeast and induce the extension and exposure of the deeper parts of the Jastrebicum. Such a lateral, crustal extrusion raises the problem of free space for the tectonic escape toward the south and southeast. However, in this particular case, no such space existed during the time of the extension.

- The extension could have occurred in the domain of the dextral strike-slip of the Naupare–Jošanica Fault Zone in the area of the releasing band (Fig. 5). In this case, the Vukanja Shear Zone was activated as a major, low-angle normal detachment fault.

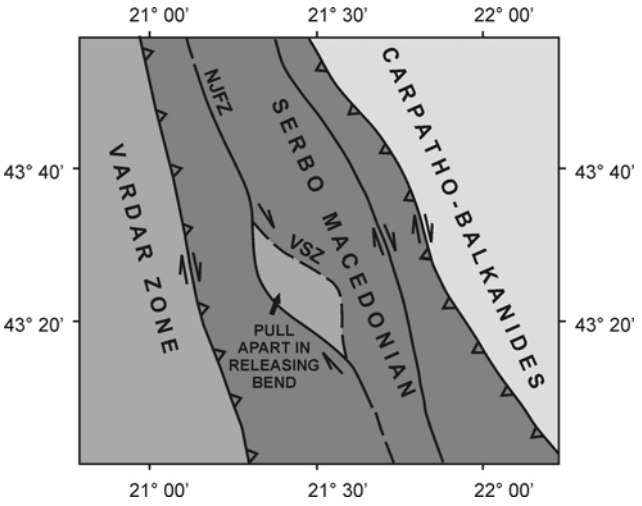

Fig. 5. Schematic diagram of extensional unroofing of the Veliki Jastrabac Dome.

The extension was probably followed by a quick uplift of the granitoid, accompanied by the consequential folding, i.e., refolding of the Mesozoic–Palaeogene folds of the first phase and development of the Veliki Jastrebac Dome (the second phase of folding of the Mesozoic–Palaeogene deposits).

Conclusion

The geological setting of Veliki Jastrebac, which was presented during the last several years and which have been partly obtained by investigations, point to the possibility that this area is a metamorphic core complex exhumed by extensional processes, i.e. by tectonic denudation during the Palaeogene. The extension could be related to the dextral transtension along the Naupare-Jošanica fault in the domain of the releasing band, with the Vukanja Shear Zone acting as a low-angle normal fault detachment. It remains necessary to obtain additional data for a more precise confirmation of this assumption. In this sense, data should be documented by structural and thermochronological analyses.

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Резиме

Екстензионо откривање доме Великог Јастрепца (Србија)

Дому Великог Јастрепца изграђују две крупне тектоностратиграфске целине које су у инверсном положају и у тектонском контакту. У доњем делу су горњокредне и кредно-палеогене нискометаморфне стене (вероватно Вардарске зона), преко којих су навучени кристаласти шкриљци високог степена метаморфизма Српско-македонске јединице. У мезозојско-палеогени метаморфни комплекс утиснут је палеогени гранитоид.

У склопу Великог Јастрепца доминира структура доме. Централно место у њој заузима гранитоид около којег су елиптично распоређене остале формације: прво, мезозојско-палеогене и на крају кристаласти шкриљци Српско-македонске јединице.

Истраживања су показала да су мезозојско-палеогени метаморфити претрпели две фазе убирања. У првој фази, крајем креде и почетком палеогена са навлачењем кристалина Српско-македонске масе преко горњокредних и кредно-палеогених творевина, ове стене су деформисане у дуктилним условима. Овакав догађај означен је регионалним метаморфизмом, формирањем изоклиних набора и кливажа аксијалне површи дуж којег се одвијала транспозиција и генерисала фолијација. Други деформациони догађај је последица испољене екстензионе активности и тектонске денудације у палеогену. То је омогућило рађање и премештање гранитоида ка површини, ексхумацију ниско до средње метаморфисаних горњокредних и кредно-палеогених творевина и пренабирање доњег и горњег навлачно-наборног пакета у дому Великог Јастрепца. Екстензија је обављена у условима декстралне wrench-тектонске активности раседа Наупаре–Јошаница и са Вукањском дислокацијом као главним low-angle detachment гравитационим раседом.