Acta Geogr. Croatica	Volumen 30	5-16	Zagreb, 1995.

UDK 551.4.07(497.5)
Primljeno *(Received)*: 15.12.1995.
Prihvaćeno *(Accepted)*: 20.1.1996.

Izvorni znanstveni članak
Original Scientific Paper

RELIEF REFLECTION OF STRUCTURAL RESGAPING DURING THE RECENT TECTONICALLY ACTIVE STAGE, IN THE NORTH-WESTERN PART OF THE OUTER DINARIDES MOUNTAIN RANGE

Darko Mihljević

Two principal directions of mountain ridge axes in the area of NW part of Outher Dinarides have been pointed out. They are consequence of the former and most recent tectonic active phase. Also, the kinematic model of counterclockwise rotation of structures has been outlined, and recognized as the fundamental cause of mainfold arc shaped mountain ridges. Due to the mentioned kinematic model, recent morphotectonic evolution of NW part of Outer Dinarides has been interpreted.

STRUKTURNO-GEOMORFOLOŠKA INTERPRETACIJA RELJEFA U NEOTEKTONSKOJ ETAPI NA PODRUČJU SJEVEROZAPADNOG DIJELA VANJSKIH DINARIDA

Izdvojena su dva pretežita pravca pružanja orografskih osi, povezana s prethodnom i najnovijom tektonski aktivnom fazom. Predočen je kinematski model retrogradne rotacije struktura u kojem je prepoznat temeljni uzrok lučno svinutih gorskih hrptova. Na temelju opisanog modela interpretiran je morfotektonski razvoj SZ dijela gorskog sustava Vanjskih Dinarida u najmlađoj tektonski aktivnoj fazi.

Keywords: structural geomorphology, Outher Dinarides, neotectonics, counterclockwise rotation, morphostructural evolution

Ključne riječi: *strukturna geomorfologija, Vanjski Dinaridi, neotektonika, retrogradna rotacija, morfostrukturna evolucija*

In the structural-geomorphological analysis of the Outer Dinarides mountain ridges, it is of vital interest to single out those relief forms where the origin and evolution is directly related to geological structures and tectonis movements. This includes the interpretation how the relief elements and the relief system in general, have developed in time, as well as the identification of characteristic sructural-geomorphological system as a result on the earth-surface of the former and of the present day active development stage of geological structures. In the present time relief we may see structures that developed during the former and particularly during the latest tectonically active period. A turnpoint in morphogenesis of the NW part of the Outer Dinarides mountain range occures with the change in shift of the Adriatic microplate northwards (McKenzie, 1974; Anderson & Jackson 1987). In this sense, in order to offer any explanation how the recent relief has developed, it is vital to identify the direction and situation of the earlier developed structures, related to the youngest stress direction ("structural original outline", Marinčić and Matičec, 1990) since the mutual position and internal properties of the earlier shaped structures have determined, concerning the newly appeared stress field, a type of their reshaping ("disintegration"), and thus they have affected the type of relief reshaping.

In the relief of the NW part of the Outer Dinarides mountain system we may notice, on a large sheme, two principal directions of mountain ridge axes. The first is related to the structures of approximate orientation NW-SE (Dinaric rectilinear direction of mountain ridge axes). This direction is characteristic for the mountain ridges of Ćićarija, Obruč and Veljun, SE-part of the island Krk and of the island Rab. Despite rather intensive shifts and denudation processes, the relief of this generation has more or less preserved its initial orientation within the regional context.

The second direction of the mountain ridge axes is related to the structures deviating in orientation some 30 degrees from the N-S direction to almost E-W direction (arc-shaped convex mountain ridge axis and expanded letter "Z" direction). The last one is a result of specific deformation kinematics which has developed during the latest, tectonically active stage, characterized by the counterclockwise structure rotation. This counterclockwise structure rotation on the area of the Outer Dinarides mountain system has been already recorded by Prelogović in 1989, and by Marinčić and Matičec in (1990, 1991)

The kinematic mechanism causing this counterclockwise rotation is of vital significance for the entire present day relief, and for the situation and orientation of mountain ridge axes conforming to structure deformations.

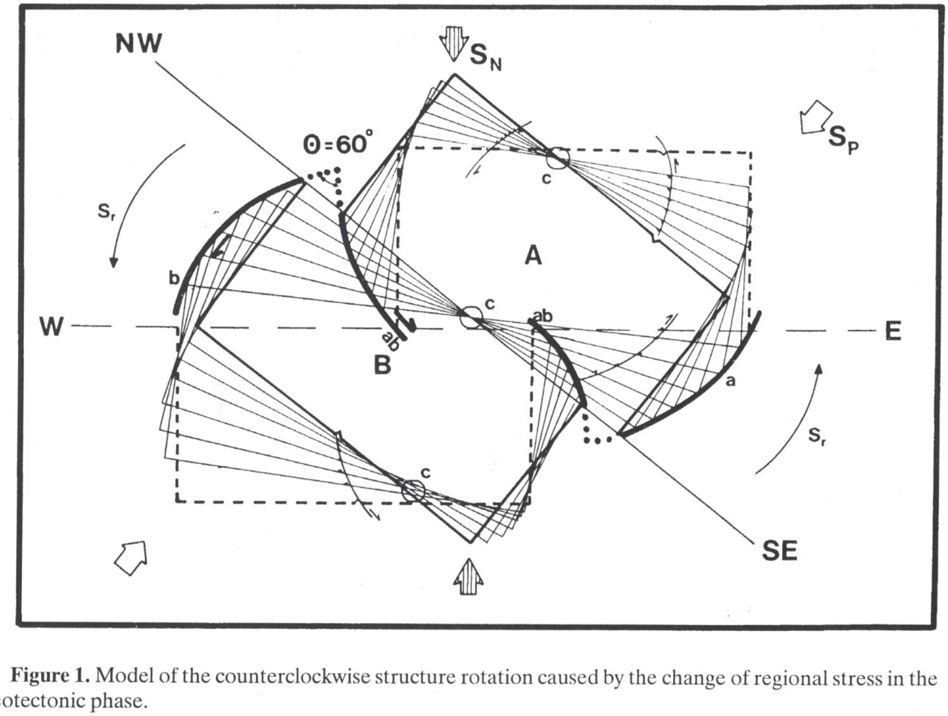

Figure 1. Model of the counterclockwise structure rotation caused by the change of regional stress in the neotectonic phase.

Slika 1. *Model retrogradne rotacije struktura uzrokovane promjenom globalnog stresa u najmlađoj tektonki aktivnoj fazi. Opis i značenje simbola u tekstu*

Fig. 1 shows a model of counterclockwise rotation, representing one of the mechanisms how arc-shaped faults and conforming to them, the arc-shaped mountain ridges, have developed. The mark S_P with hatched arrows, point to the approximate stress direction during the former tectonically active stage, which has shaped the structures of Dinaric orientation. They are characterized by the lineal, often overturned folds of SW vergency wich have, as compression has progressed, rotated around the intermedial stress axis (σ_2) changing into reverse faults. The principal orientation of structures developed during the former tectonically active stage is marked by full line and by NW and SE marks. Cross-hatched arrows marked by S_N indicate the stress direction during the youngest tectonically active stage. The hatched line marked by W-E represents the orientation when the right hori-

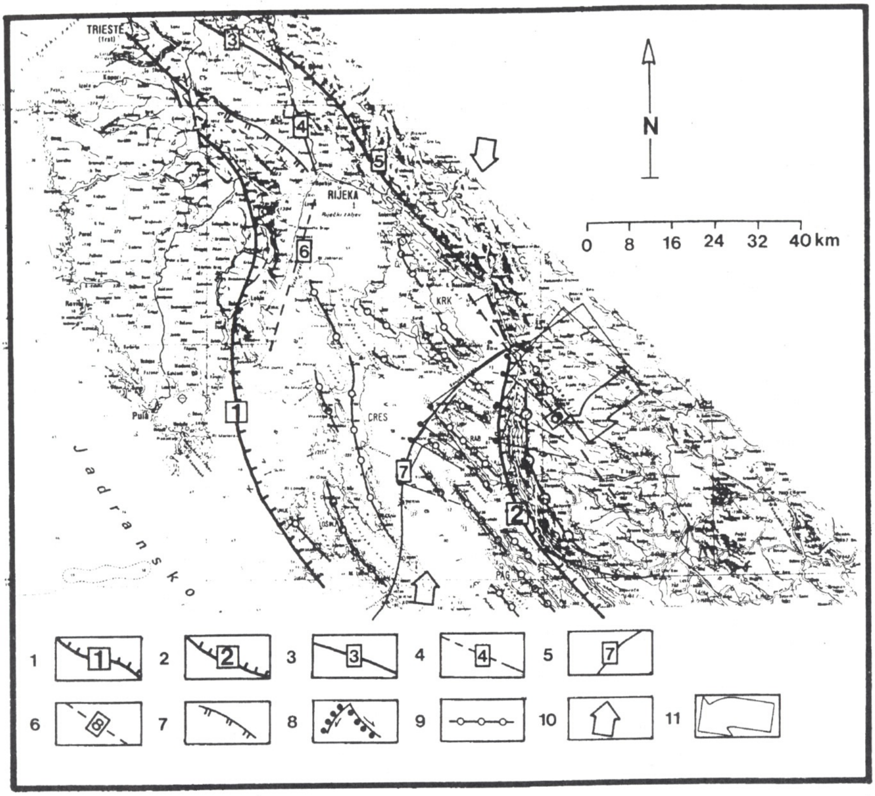

Figure 2. Key: 1 - reverse fault bordering the principle geotectonic units of the Istria and the Adriatic; 2 - reverse faults with right hand slip component bordering the principle geotectonic units of the Adriatic and the Dinaric, 2- Velebit fault, 5- Ilirska Bistrica-Rijeka-Senj fault; 3 - Kras fault; 4 - Postojna-Opatija fault, 6- Istrian fault; 5 - fault of Triassic basement (geophysically indicated); 6 - relict position of the Velebit fault; 7 - reverse faults with NE dip; 8 - trajectoies of counterclockwise rotated blocks along the new formed traces of discontinuity; 9 - strikes of the mountain ranges and ridges axses; 10 - approximate stress direction in the neotectonic period; 11 - direction of structure rotation.

Slika 2. *Legenda: 1 - reversni rasjed graničan geotektonskim jedinicama Istre i Adrijatika; 2 - reversni rasjedi s prisutnom desnom komponentom kretanja, granični geotektonskim jedinicama Dinarida i Adrijatika, 2- Velebitki, 5- Ilirska Bistrica-Rijeka-Senj; 3 - Kraški rasjed; 4 - rasjed Postojna-Opatija, 6- Istarski rasjed; 5 - rasjed "trijaske granice", geofizički utvrđen; 6 - reliktni položaj Velebitskog rasjeda; 7 - reversni rasjedi sjeveroistočne vergencije; 8 - trajektorije točaka rotirajućih blokova duž novih trasa diskontinuiteta kojima se ostvaruje rotacija; 9 - pružanje gorskih hrptova i grebena; 10 - približan smjer stresa u neotektonskoj etapi; 11 - smjer rotacije struktura.*

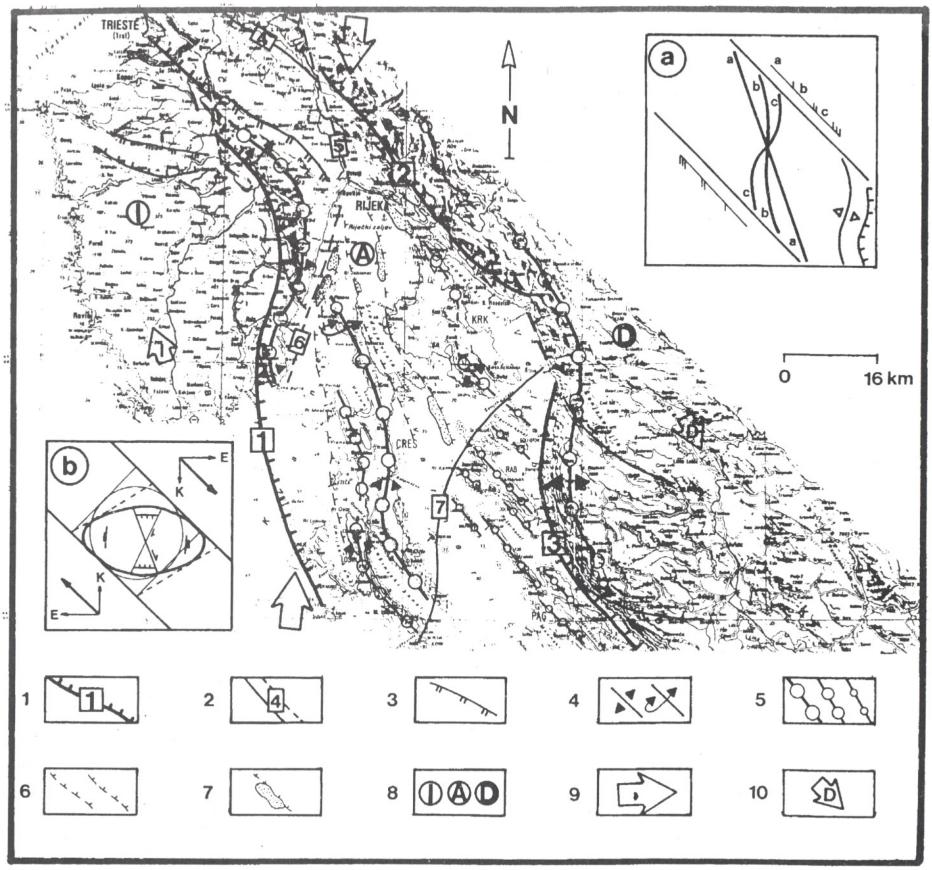

Figure 3. Key: 1 - reverse faults bordering the principal geotectonic units 1-Trieste fault, Ilirska Bistrica-Rijeka-Senj fault, 3-Velebit fault; 2 - regional faults bordering the principal structural units: 4-Kras fault, 5-Postojna-Opatija fault, 6-Istrian fault, 7-Senj-Lošinj fault (Triassic basementfault); 3 - reverse faults with NE dip; 4 - strike of the principle folds axis; 5 - strikes of the principal and secondary mountain ridge axis; 6 - reverse faults approximate located under the see level; 7 - lens of the Quarternary deposits under the see level; 8 - principle geotectonic units: I-the Istria, A-the Adriatic, D-the Dinaric; 9 - approximate neotectonic stress direction; 10 - opposite shift direction of the Dinaric and the Adriatic geotectonic units. (sketch "b" after Harding & Lowell, 1974).

Slika 3. *Legenda: 1 - reversni rasjedi granični geotektonskim jedinicama: 1-Tršćanski, 2-Ilirska Bistrica-Rijeka-Senj, 3-Velebitski rasjed; 2 - regionalni rasjedi granični pojedinim strukturama: 4-Kraški, 5-Postojna-Opatija, 6-Istarski, 7-Senj-Lošinj; 3 - reversni rasjedi sjeveroistočne vergencije; 4 - pružanje osi boranih struktura; 5 - pružanje glavnih i sekundarnih hrptova i grebena; 6 - reversni rasjedi u podmorju (približno locirani); 7 - izdužene zone zadebljanja kvartarnih naslaga u podmorju; 8 - glavne geotektonske jedinice: I-Istra, A-Adrijatik, D-Dinarik; 9 - smjer regionalnog stresa u neotektonskoj etapi; 10 - nasuprotno kretanje geotektonskih cjelina Istre i Dinarika. Skica "b" prema (Harding & Lowell, 1974).*

zontal shift component yields to the reverse overthrusting, with a tectonic transport towards south. Dotts named "c", mark the local rotation axis, mark S_r the counterclockwise rotation direction, and a thick arc-shaped line marked by a, b and ab - the discontinuity routes along which the rotation shifts occurs. "A" and "B" mark the rocky blocks involved in rotation. The angle Θ defines the angle between discontinuity routes, along wich the rotation of both blocks is performed. Under the approximately same stress direction, the initially rectalineal discontinuity route will assume the pronounced arc shape, convexly bulging towards direction of blocks rotation. The rotation of structure occurs around the axis-minimum stress (σ_3) to the moment until it reaches the optimum orientation - perpendicular to maximum stress direction (σ_1). The displayed mechanism of structure deformation is reflected in relief by the arc-shaped convex delineation of relief elements within the local and regional scheme.

The presented model of retrogradee rotation is most clearly reflected in the morphostructure of Velebit (Fig. 2). Discontinuity route (7) indicates a geophysically determined fault (in direction: Senj-Rab-Lošinj) interpreted as a difference in "triassic border" depth (Aljinović 1984; Aljinović and Blašković 1981), from wich there is a pronounced parallel orientation of isles' mountain ridges (Grgur, Goli, Prvić, Rab, Pag, the extreme southern part of Lošinj and of Dugi otok) in SE direction. Northwestwards of the mentioned fault there is a radial divergency of mountain axes, noticed as early as in 1906, by Waagen. Obviously, the fault (7) defines the border of a different kinematic mechanism of structures, reflected in the described morphographic relief properties. In connection to this, it is very important to note the following relief characteristics:

- an abrupt break in orientation of the NE ridge of the island Krk towards SE, in front of the fault route (7)
- orientation of the island Rab immediately in front of the convexly bent SW ridge slopes of Velebit, whereof its SE part has no logical relief continuity in the morphostructure of North Velebit
- southern or northern termination of the island Grgur and Goli, marked by steep cliffs (probably, the once unique block of rocks wich was a continuation of the SW ridge on the Island Krk and wich is cut through by the accompanying left horizontal fault, developed due to counterclockwise block rotation towards SW, from the Velebit fault)
- an arc-bent ridge of the central and southern part of the island Cres and Lošinj
- coincidence in delineation of the island's Cres east shores with the island's Krk SW shores.

The present day orientation of the above described morphostructures may be explained in terms of a shift, conforming to the shifts shown in the model on Fig. 1. The fault routes (7) and (2) on Fig. 2 show an identical arc-shaped delineation and a shift direction of blocks, as on the displayed model. Even the angle closed by the routes of two mentioned faults is identical to the angle Θ on the model displayed on Fig. 1 (about 60^{o}). The assumed orientation of the Velebit fault route, as well as of the entire Velebit structure, during the former tectonically active period ran NW-SE. The mountain axes of the Kvarner islands (wich were the land at the time) were mutually parallel to the NW-SE orientation. By the change in stress during the latest tectonically active stage, the rotation of morphostructures started, followed by the gradual arc-bending of the Velebit fault route, bordering the tectonic entities of Adriaticum and Dinaricum. Quite significant is that the Velebit fault paraclase, running from SW towards NE gets abruptly perpendicular towards depth (Prelogović 1991, A, B; 1995), so the rotation is followed by transport and stuffing of rock masses mainly towards SE. In the relief of the NW part of the Outer Dinarides mountain system, this is generally reflected in an increase of the mountain ridge heights, in this very direction. As rotation has been prograding, a differentiation between single submorphostructural units of Velebit occurred. Structural-geological relation on the area of the Northern and Southern Velebit was described by Prelogović in 1989, and structural-geomopgological relations by Bognar in 1992, 1994; by Faivre in 1992, 1993 and by Prelogović in 1994. Rotation of the Velebit structure together with the gradual redistribution of rock passes and with bending of the bordering fault (2) should have also been accompanied by the rotation of the SW oriented blocks, along the fault route (7). A break in continuity of the structure orientation towards the SE from the fault route (7) and their counterclockwise shift (towards SW conforms to the above mentioned fault route. In relief, it is reflected as a break in parallel and continuous orientation of island ridges. We also come across accompanying faults of the left shift, along which the once unique block has been broken in two pieces and on wich the present day islands Grgur and Goli have been formed. The rotation of the SW block (within which the present day islands Rab, Prvić, Grgur and Goli have been formed) presses the structure Cres-Lošinj overthrusting westwards and therefore arc-bending, too. Shifting is performed probably by the footwall horizontal fault of decollment type with pronounced lamellar structures. An initial orientation of this morphostructure comprising also the present day island Krk, ran NW-SE, conforming to the orientation of other lineal elongated structures which developed under the stress regime of the former tectonically active stage.

The structures in wich the mountain ridge of Učka has been shaped, are more or less of meridional orientation. Quite justified is the question why the orientation of the Učka mountain axis and of the nortern island Cres completely deviates from the "Dinaric" orientation of mountain axes in the surrounding relief forms. Also, how could we interpret the genesis, orientation and direction of the structure and of the mountain ridge shaped on this structure, since in order to shape such a structure, the stress direction should have been at least N90^{o}, and the "b" axis of the structure is sigmoidaly bending towards the generally meridional direction? Especially because on basis of the past research works, by field measurement of structural elements and by geophysical research, the direction of tectonic forces in the stress field, as a result of the earlier tectonically active stages, was N125^{o} for Laramian and N50^{o} for Pyrenean stage (Marinčić and Matičec, 1991) and during the youngest tectonic stage about N0^{o} (Anderson & Jackson, 1987; Del Ben et al., 1991; Matičec, 1994; Prelogović, 1994).

Fig. 3 renders basic morphotectonic relief elements of the NW part of the Outer Dinarides mountain system. The folowing facts may be observed:

- There are three faults bordering the geotectonic units: (1) Ćićarija-Učka-Lošinj (Triest fault, Del Ben et al., 1991) (2) Ilirska Bistrica-Vinodol-Senj (Rijeka fault, Del Ben et al., 1991) (3) Velebit fault (Prelogović, 1989, 1994) bordering Istria, Adriaticum and Dinaricum. The fault (7) has been geophysically determined (Aljinović and Blašković, 1991) and is marginal to the north and central part of the Adriatic platform. Istria and Dinaric are composed of solid limestone deposits, while Adriatic is composed solid - limestones and elastic deposits - flysh, marked by ductility (plasticity) contrast.

- Orientation of structures and of ridges shaped on these structures within Adriaticum display a pronounced divergency (or a virgation - radial expansion towards south, Waagen 1906) in following directions: WNW-SSE (130-310^{o}) Draga-Bakarac-Bakar, NW-SE (150-330^{o}) Omišalj-Malinska, NNW-SSE (157-337^{o}) preluka-Cres (Benac, 1994) and NNW-SSE (165-345^{o}) towards NNE-SSW (20-200^{o}) the Učka ridge.

- Along the faults routes bordering the Kvarnerian submarins structures and struc-

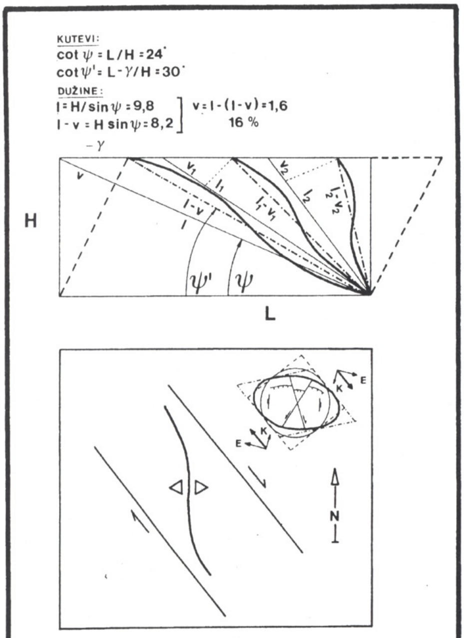

Figure 4. Arc-benting of primary linear structural elements in the shear zone

Slika 4. *Svijanje ravnocrtnih elemenata ruptura i plikatura u zoni smicanja* tural blocks, we have evidences of lentil-like elongated, rather thick Quarternary deposits (Benac, 1994) (Fig.3)

- By geophysical methods (Anderson & Jackson, 1987; Del Ben et al., 1991) as on basis of horizontal striation on the open/uncovered planes of reverse faults in the hinterland of Rijeka, the right horizontal shift component is indicated.

Due to the active tectonic forces in the stress field, which during the youngest tectonically active stage have been directed (with local deviations) northwards, there occurs along the faults bordering geotectonical units the opposite mass movement of Istria i.e. of the NE-part of the Adriatic and of structures within Dinaric. The entire zone of Adriatic is in that sense exposed to pronounced shear stress (Fig.3 sketch a) followed by progressive arc bending of regional fault routes in an expanded letter "Z" shape, as well as by the arc bending of structures and of lineal relief elements shaped on these structures. Such movement is on one hand supported by lithological contrast between limestone and flysh, and on the other hand by subhorizontal inclination of footwall thrust of decollment type, with branching of reverse faults getting more perpendicular towards surface, and shaping an imbricate fan; thus enabling quicker and easier tectonic transport of rock masses, in comparison to the area where the plane of overthrust is getting abruptly perpendicular towards depth (zone of the Rijeka and Velebit faults). The regime of pressures within the shear zone, as soon as it reaches the critical limit, gets released by the right slip component along horizontal faults that may also terminate by a thrust. (Fig. 3, sketch b). Since the routes of right horizontal and reverse faults due to the compressed space within the shear zone, may also be manifoldly bended, the tension release by the right shifts could be followed by transpressure and transtension zones, which reflects in relief in a succesion of basins (an example to this are thick Quarternary deposits in the submarine area of the Kvarner Bay, most probably related to transtensional local depressions).

In terms of the above quoted facts, it may be concluded that the present day mainly meridional orientation of this structure and of the Učka ridge formed on this structure is the result of specific movements marked by such distribution of tensions in a shear zone leading to the progressive bending of ruptures and plicatures (Fig.4) and in connection to this, to a redistribution of rocky masses within and along the arc-bent fault routes. The compression occurs, which is of essential importance, not as a consequence of a "pure shear" - when axis rotation does not take place, but due to unhomogeneous "simple shear" - with rotation of axis, leading to abbreviation and to sigmoidal bending of linear elements "unfavourably" oriented to the stress direction in the shear zone (Fig.4).

The discribed kinematic deformation, is characterized by the development of different relief forms of meso and macro rank size (Mihljević 1995) depending on type of accompanying structures (transpressure, transtension, domino, pop up, snake head, imbricated fan, duplex, horse).

CONCLUSION

Evolution and development of single relief forms at the meso and macro-morphological level within the NW part of the Outer Dinarides mountain range is a result of compression marked by shearing and by retrograde structure rotation in the youngest tectonically active period. The retrograde rotation occurrs along reverse faults paraclases, marginal o the main geotectonic units which have been abruptly inclined towards the lithosphere depth. In he former tectonically active phase, linearly elongated structures and rectilinear fault routes of the NW-SE direction begin, due to the unsuitable orientation towards the newly appeared stress direction, to rotate in retrograde direction in order to take an optimal (vertical) position concerning the stress direction. The consequence is a gradual arc bending of fault routes and tectonic transport towards SE which is reflected in arc bending of the once linearly elongated mountain ridges. In this way, the bent ridge of Velebit has been gradually shaped. Rotation of blocks occurs along the routes of the bent pair of faults shifting to the right, lying under the angle of 60 degrees. Within them, there are accompanying left faults. Along one of them, the once unique block has been out through and the islands Goli and Grgur have been shaped. Rotation of the Velebit structure was followed by the rotation of the SW oriented block; so, along the "Senj-Rab" fault the continuity of the once rectilinear insular ridges is broken. Rotation of the SW block presses the "Cres-Lošinj" structure which gets overlapped towards the west along the most probably footwall fault, of horizontaly laid paraclase (decollement), affecting the radial expansion of orographic axes of the Kvarner islands.

SAŽETAK

STRUKTURNO-GEOMORFOLOŠKA INTERPRETACIJA RELJEFA U NEOTEKTONSKOJ ETAPI NA PODRUČJU SJEVEROZAPADNOG DIJELA VANJSKIH DINARIDA

Darko Mihljević

U reljefu SZ dijela gorskog sustava Vanjskih Dinarida prepoznaju se na krupnom planu dva pretežita pravca pružanja orografskih osi. Prvi je povezan sa strukturama približnog pružnja SZ-JI (dinarski smjer orografskih osi ravnocrtnog pružanja). Navedeno pružanje obilježava gorske hrptove Ćićarije, Obruča i Veljunskog hrpta, jugoistočni dio otoka Krka i otok Rab. Unatoč intenzivnim pomacima i procesima denudacije, reljef ove geogeneracije, uglavnom je sačuvao, na regionalnom planu, svoje inicijalno pružanje.

Drugi pravac pružanja orografskih osi povezan je sa strukturama, čije današnje pružanje varira oko tridesetak stupnjeva od pravca sjever - jug do pravca gotovo istok - zapad (lučni konveksno ispupčen ocrt orografskih osi i ocrt u obliku razvučenog slova "Z"). Potonji je posljedica specifične kinematike deformacija nastale u najnovijoj tektonskoj aktivnoj fazi, obilježenoj retrogradnom rotacijom struktura. O retrogradnoj rotaciji struktura na području gorskog sustava Vanjskih Dinarida pisali su Prelogović 1989, te Marinčić i Matičec 1990, 1991.

Kinematski mehanizam koji dovodi do retrogradne rotacije od prvorazrednog je značaja za današnji oblik reljefa u cjelini te položaj i pružanje orografskih osi planinskih hrptova, sukladno deformacijama struktura.

Na slici 1 prikazan je model retrogradne rotacije, koji reprezentira jedan od mehanizama pomoću kojeg nastaju lučno svijene trase rasjeda i sukladno s njima, lučno svijeni planinski hrptovi. Sa S_p uz neispunjene strelice označen je približno smjer stresa prethodne tektonske aktivne faze koji je oblikovao strukture dinarskog pravca pružanja. Obilježene su linearnim, često prebačenim borama jugozapadne vergencije koje su, kako je kompresija prostora napredovala, rotirale oko osi intermedijalnog osnovnog stresa (σ_2) prelazeći u reversne rasjede. Pretežita orjentacija struktura nastalih u prethodnoj tektonskoj aktivnoj fazi označena je punom linijom s oznakama NW i SE. Šrafirane strelice s oznakama S_n pokazuju smjer stresa u najmlađoj tektonskoj aktivnoj fazi. Isprekidana linija s oznakama W-E, predstavlja položaj kad komponenta desnog horizontalnog kretanja ustupa mjesto reversnom navlačenju s tektonskim transportom usmjerenim prema jugu. Točke "c" označavaju lokalne osi rotacije, oznake S_r retrogradni smjer rotacije, a podebljana, lučno svijena linija s oznakama a, b i ab trase diskontinuiteta duž kojih se ostvaruje rotacioni pomak. S A i B označeni su rotacijom zahvaćeni stijenski blokovi. Kut Θ definira kut između trasa diskontinuiteta duž kojih se ostvaruje rotacija oba bloka. Pod približno istim smjerom stresa, inicijalno ravnocrtna trasa diskontinuiteta zadobit će naglašeno lučni ocrt, s konveksnim ispupčenjem u smjeru rotacije blokova. Rotacija strukture napreduje oko osi minimalnog stresa(σ_3) sve do trenutka dok ne dostigne optimalni položaj - okomit na smjer maksimalnog stresa (σ_1).

Prikazani mehanizam deformacija struktura reljefno se izražava lučnim konveksnim ocrtom reljefnih elemenata na lokalnom i regionalnom planu. Predočeni model retrogradne rotacije najjasnije se izražava u morfostrukturi Velebita (sl. 2). Trasa diskontinuiteta (7) označava geofizički utvrđen rasjed (na liniji Senj - Rab - Lošinj) protumačen kao razlika u dubini "trijasne granice" (Aljinović 1984; Aljinović i Blašković 1981), od kojeg je prema jugoistoku prisutan izraziti paralelizam pružanja otočnih hrptova (Grgur, Goli, Prvić, Rab, Pag, najjužniji dio Lošinja te Dugog otoka). Sjeverozapadno od spomenutog rasjeda prisutna je zrakasta divergencija orografskih osi koju je još 1906 uočio Waagen. Očito je da rasjed (7) definira granicu različitog kinematskog ponašanja struktura, koje imaju odraz u opisanim morfografskim svojstvima reljefa. Pri tome je važno uočiti slijedeće značajke reljefa:

- nagli prekid pružanja SI hrpta otoka Krka prema JI, ispred trase rasjeda (7),
- položaj otoka Raba neposredno ispred konveksno svijenih JZ padina hrpta Velebita čiji JI dio nema logičan reljefni nastavak u morfostrukturi Sjevernog Velebita,
- južni odnosno sjeverni svršetak otoka Grgur i Goli, obilježen strmim liticama (vjerojatno nekad jedinstveni blok stijena koji je bio nastavak JZ hrpta otoka Krka, a presječen je pratećim, lijevim horizontalnim rasjedom nastalim uslijed retrogradne rotacije bloka JZ od Velebitskog rasjeda),
- lučno svijeni hrbat srednjeg i južnog dijela otoka Cresa i Lošinja
- podudarnost u ocrtu istočnih obala otoka Cresa s JZ obalama otoka Krka.

Današnji položaj opisanih morfostruktura može se tumačiti kao rezultat pomaka koji su sukladni pomacima prikazanim u modelu na slici 1. Trase rasjeda (7) i (2) na slici 2 pokazuju identičan lučni ocrt i smjer pomaka blokova kao na prikazanom modelu. Čak i kut Θ koji zatvaraju trase dvaju spomenutih rasjeda identičan je kutu Θ u modelu na slici 1 (cca 60^{o}). Pretpostavljeno pružanje trase Velebitskog rasjeda kao i cjelokupne Velebitske strukture, u prethodnoj tektonski aktivnoj fazi bilo je SZ-JI. Orografske osi Kvarnerskih otoka (koji su tada bili kopno) bile su međusobno paralelne i pružale su se pravcem SZ-JI. Promjenom stresa u novoj tektonski aktivnoj fazi započinje rotacija morfostruktura praćena postupnim lučnim svijanjem trase Velebitskog rasjeda graničnog tektonskim cjelinama Adrijatika i Dinarika. Važna je činjenica da se paraklaza graničnog Velebitskog rasjeda idući od JZ prema SI naglo ustrmljuje prema dubini (Prelogović 1981, A, B, 1995) pa je rotacija praćena transportom i natiskivanjem masa pretežito prema JI. U reljefu SZ dijela gorskog sustava Vanjskih Dinarida to se u pravilu izražava u povećanju visina gorskih hrptova upravo u tom smjeru. Napredovanjem rotacijskog kretanja dolazi do diferencijacije pojedinih submorfostrukturnih jedinica Velebita. Strkturno geološke odnose u okviru Sjevernog i Južnog Velebita opisao je Prelogović 1989, a strukturnogeomorfološke Bognar 1992, 1994; Faivre 1992, 1993 i Prelogović 1994. Rotacija velebitske strukture uz postepenu preraspodjelu masa te svijanje graničnog rasjeda (2) morala je biti praćena i rotacijom JZ položenog bloka duž trase rasjeda (7). Dolazi do prekida u kontinuitetu pružanja struktura JI od trase rasjeda (7) i njihovog retrogradnog pomaka (prema JZ) sukladno trasi spomenutog rasjeda. Reljefno se to odrazilo u prekidu paralelizma i kontinuiteta pružanja otočnih hrptova. Javljaju se prateći rasjedi lijevog pomaka duž kojih je razlomljen nekad jedinstven blok na kojem su oblikovani današnji Goli otok i Grgur. Rotacija JZ bloka (u okviru kojeg su oblikovani današnji otoci Rab, Prvić, Grgur i Goli) pritišće strukturu Cres-Lošinj koja se navlači u smjeru zapada i pri tom lučno svija. Pomaci se ostvaruju vjerojatno podinskim horizontalnim rasjedom dekolmanskog tipa uz izrazito ljuskanje. Inicijalno pružanje ove morfostrukture u koju je bio uključen i današnji otok Krk bilo je SZ-JI, sukladno pružanju ostalih linearno izduženih struktura nastalih pod režimom stresa prethodne tekonski aktivne faze.

Strukture u kojima je oblikovan gorski hrbat Učke, pokazuju uglavnom merdionalno pružanje. Opravdano se postavlja pitanje, zašto smjer pružanja orografske osi Učke i sjevernog dijela otoka Cresa, potpuno odudara od "dinarskog" pružanja orografskih osi okolnog reljefa? I drugo, kako interpretirati postanak, položaj i pružanje strukture, i na njoj oblikovanog gorskog hrpta, za čije bi oblikovanje smjer stresa trebao biti približno N90°, i čija "b" os sigmoidalno svija u generalno merdionalnom pravcu? To tim prije što je na temelju dosadašnjih istraživanja, mjerenjem strukturnih elemenata na terenu i geofizičkim istraživanjima, smjer tektonskih sila u polju stresa, koje su rezultat prethodnih tektonskih aktivnih faza bio N125^0 - za Laramijsku i N50^0 za Pirinejsku, (Marinčić i Matičec, 1991), a u najnovijoj tektonskoj fazi približno N0° (Anderson & Jackson, 1987; Del Ben et al., 1991; Matičec, 1994; Prelogović, 1994).

Na slici 3 prikazani su osnovni morfotektonski elementi reljefa SZ dijela gorskog sustava Vanjskih Dinarida. Uočavaju se slijedeće činjenice:

- Prisutna su tri rasjeda granična geotektonskim jedinicama: (1) Ćićarija-Učka-Lošinj (Tršćanski rasjed, Del Ben et al., 1991) (2) Ilirska Bistrica-Vinodol-Senj (Riječki rasjed Del Ben et al., 1991) (3) Velebitski rasjed (Prelogović, 1989, 1994) granični strukturama Istre, Adrijatika i Dinarika. Rasjed (7) utvrđen je geofizički (Aljinović i Blašković, 1991) i graničan je sjevernom i srednjem dijelu jadranske platforme. Istra i Dinarik građeni su od kompetentnih (čvrstih), vapnenačkih naslaga, dok je Adrijatik građen od kompetentnih (čvrstih) - vapnenci i inkompetentnih (podatnih) naslaga - fliš, obilježenih konastom duktilnosti (plastičnosti).

-Pružanje struktura i na njima oblikovanih hrptova u okviru Adrijatika pokazuje izrazitu divergenciju (ili virgaciju - zrakasto širenje prema jugu, Waagen 1906) i to smjerovima SZJ-JJI (130-310°) Draga-Bakarac-Bakar, SZ-JI (150-330°) Omišalj-Malinska, SSZ-JJI (157-337°) Preluka-Cres (Benac, 1994) i SSZ-JJI (165-345°) do SSI-JJZ (20-200° hrbat Učke.

- Duž trasa rasjeda graničnih strukturama i strukturnim blokovima u podmorju Kvarnera, evidentirana su lećasto izdužena, znatnija zadebljanja kvartarnih naslaga (Benac, 1994) (sl.3).

- Geofizičkim metodama (Anderson & Jackson, 1987: Del Ben et al., 1991) kao i na osnovi horizontalne strijacije na otkrivenim plohama reversnih rasjeda u zaleđu Rijeke, indicirana je desna horizontalna komponenta pomaka.

Zbog djelovanja tektonskih sila u polju stresa, koje su u najnovijem tektonski aktivnom razdoblju usmjerene (uz lokalna odstupanja) prema sjeveru, duž rasjeda graničnih geotektonskim jedinicama dolazi do nasuprotnog kretanja masa Istre tj. sjeveroistočnog dijela Jadranske mikroploče i struktura u okviru Dinarika. Zona Adrijatika u tom smislu izložena je izrazitim naponima smicanja (Sl 3, skica a), praćenim progresivnim lučnim svijanjem trasa regionalnih rasjeda u obliku razvučenog slova "Z", kao i lučnim svijanjem struktura i na njima oblikovanim linearnim elementima reljefa. Takvo kretanje potpomognuto je, s jedne strane, litološkim kontrastom između vapnenca i fliša, a s druge, subhorizontalnim nagibom podinske navlake dekolmanskog tipa, od koje se odvaja niz reversnih rasjeda koji se ustrmljuju prema površini, oblikujući ljuskavu strukturu (imbricate fan) čime je omogućen brži i lakši tektonski transport masa, u odnosu na područje gdje se ploha navlake naglo ustrmljuje prema dubini (zona Riječkog i Velebitskog rasjeda). Režim pritisaka unutar zone smicanja, kad dosegne kritičnu granicu, oslobađa se desnom komponentom kretanja duž horizontalnih rasjeda koji mogu završiti i navlakom. (sl. 3 skica b). Kako trase desnih horizontalnih i reversnih rasjeda, zbog kompresije prostora unutar zone smicanja, mogu biti i više struko zakrivljene, oslobađanje napona desnim pomacima može biti praćeno zonama transpresije i zonama transtenzije, što se u reljefu izražava u sukcesiji potolina (primjer su zadebljanja kvartarnih naslaga u podmorju Kvarnera, koje su vjerovatno povezane s trastenzijskim lokalnim depresijama).

Na osnovu iznesenog može se zaključiti da je današnji, pretežito merdionalni položaj strukture, i na njoj oblikovanog hrpta Učke posljedica specifičnih pokreta u vremenskom slijedu, obilježenih takvom raspodjelom napona u zoni smicanja koja dovodi do progresivnog svijanja ruptura i plikatura (sl.4), i s tim povezane preraspodjele stijenskih masa unutar i duž svinutih trasa rasjeda. Kompresija nastaje, što je od osobite važnosti, ne kao posljedica "pure shear"-a (izostaje rotacija osi), već nehomogenog "simple shear"-a, (rotacija osi) koji dovodi do skraćivanja i sigmoidalnog svijana linearnih elemenata "nepovoljno" orijentiranih na smjer pritisaka u zoni smicanja (sl.4).

Opisani kinematski čin deformacija, obilježen je razvojem raznovrsnih oblika reljefa mezo i makro reda veličine (Mihljević 1995) ovisno o tipu pratećih struktura (transpresijske, transtenzijske, domino, pop up, snake head ombricated fan, duplex, horse).

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