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Stratigraphy and Tectonic Relationships Along the Senj - Ogulin Profile (Velika Kapela Mt., Croatia)

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Abstract

Twelve lithostratigraphic units, representing a 5 km thick succession, have been determined from the Senj-Ogulin profile through the Velika Kapela Mt. This 45 km long sequence lies approximately normal to the Dinaric strike. Carbonate deposits ranging from the Middle Liassic to the Albian include laterally variable environments during the Kimmeridgian and Lower Tithonian. The deposits were deformed by compressive tectonics during the Tertiary tectonic cycle, and were consequently reshaped by weaker Neotectonic transpression. Therefore structures with the N-S strike, which are different to the common Dinaric strike (NW-SE), are interpreted as a consequence of syngenetic bending during the Tertiary cycle, rather than rotation during the Neotectonic cycle.

1. INTRODUCTION

Geological investigations of the Senj-Ogulin profile through the Velika Kapela Mt., were part of the project entitled "Geological analysis of part of the Primorje and Gorski Kotar", performed by the Institute of Geology, Zagreb, for the INA-Naftaplin company. Therefore, we are grateful to INA-Naftaplin for permission to publish some of the results.

The most important contributions to the geological knowledge of study area were obtained by systematic geological investigations performed during work on the Basic Geological Map 1:100,000 of the Ogulin sheet (VELIĆ & SOKAČ, 1981; VELIĆ et al., 1982) and parts of the Crikvenica (ŠUŠNJAR et al., 1970; GRIMANI et al., 1973) and Rab sheets (MAMUŽIĆ et al., 1969; MAMUŽIĆ & MILAN, 1973). In these works Mesozoic deposits were accurately subdivided, and the basic geological relationships in this part of the Dinarides were presented.

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2. STRATIGRAPHIC REVIEW

The investigated area is composed of shallow-water platform carbonates of Jurassic and Lower Cretaceous age (Fig. 1). Twelve lithostratigraphic units with an approximate total thickness of 5,000 m were established (Fig. 2). Since the study area has a very complex geological composition, especially due to the intense postdepositional tectonics, it was not possible to formalise the units; therefore, the units described in this paper represent informal lithostratigraphic units. Although determined fossil assemblages were very rich, only the most important index fossils are mentioned in this review. Data on the thickness of the stratigraphic units are based upon our investigation, as well as on comparisons with the results presented in the aforementioned sheets of the Basic Geological Map 1:100,000.

2.1. LITHOSTRATIGRAPHIC UNIT A

Deposits of Lithostratigraphic Unit A are represented by mostly 15-50 cm thick well-bedded dark gray to black mudstones with variable proportions of peloids and bioclasts. Beds containing light-coloured gastropods, oncoids, benthic foraminifera, echinoderms and ostracods are infrequent. In the uppermost part there are grainstones, scarce marly beds and beds containing molluscs of the genus *Lithiotis*. The thickness of Unit A is approximately 400 m.

On the basis of the fossil assemblage (*Orbitopsella praecursor* and *Lithiotis problematica*) it has been determined that deposits of Unit A are of Middle Liassic age. They were deposited mostly in the low-energy subtidal environments with sporadic shallowing.

2.2. LITHOSTRATIGRAPHIC UNIT B

Intense bioturbation, resulting in a mottled appearance of the rocks (their common name is "spotty limestones", or "*fleckenkalk*" in German) is the main characteristic of the Unit B. Deposits are represented by alternating 30-70 cm thick beds of gray to almost black

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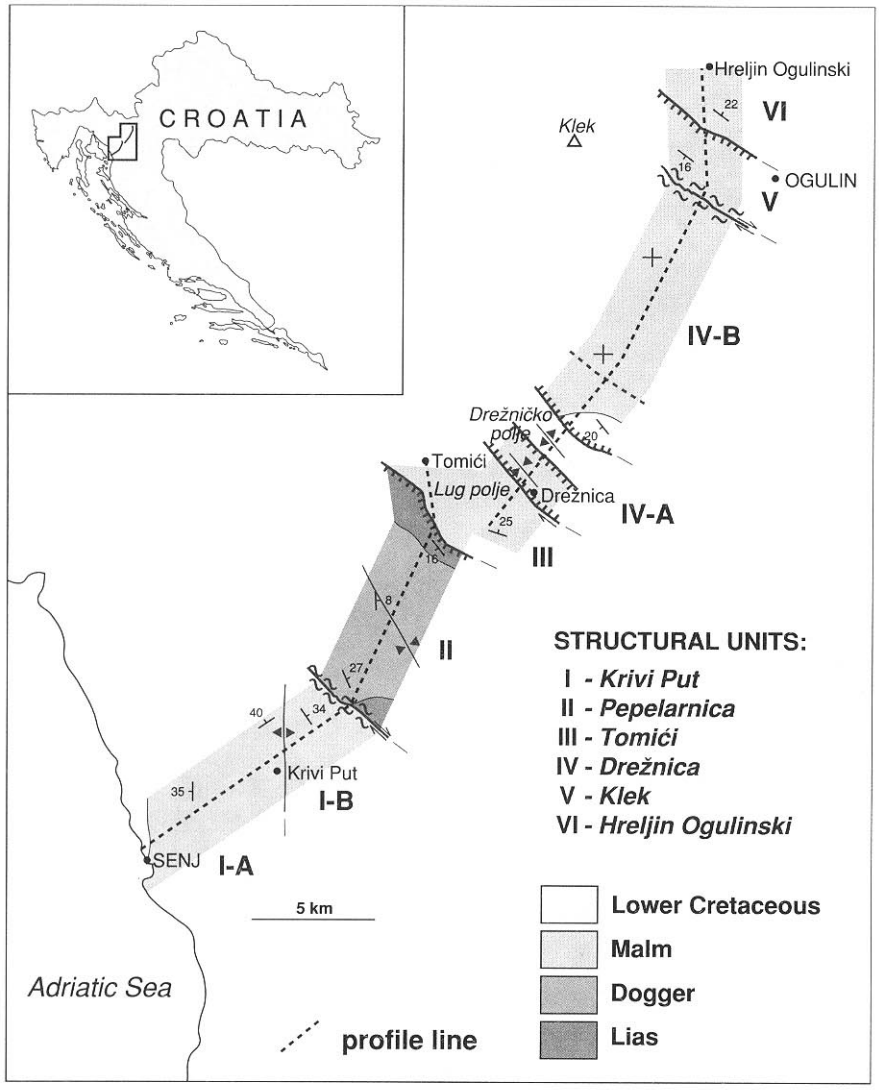

Fig. 1 Location map with simplified geological map and structural units described in the text.

mudstones and nodular peloidal packstones. Skeletal-peloidal grainstone beds with swaley cross-stratification sporadically occur, as well as ooid-oncoid-favreina packstones. At the top of the Unit, an approximately 15 m thick package of late-diagenetic dolomites occurs, which is a common characteristic of the uppermost part of contemporaneous deposits throughout the Dinarides. The complete thickness of Lithostratigraphic Unit B is approximately 130 m.

Deposits of this unit are of Upper Liassic age, and were deposited in somewhat deeper, lagoonal environments, near to or just beneath fair-weather wave base.

2.3. LITHOSTRATIGRAPHIC UNIT C

In the lowermost part of these deposits alternations of mudstones and hummocky cross-stratified peloid packstones predominates, while in the rest of the unit, only scarce massive beds of ooid-peloid packstones occur within the prevailing mudstones. Original grainstones are sporadically completely late-diagenetically dolomitized. The complete thickness of the Unit is approximately 400 m.

Based on the microfossil assemblage (*Mesoendothyra croatica* and *Selliporella donzellii*) a Lower Dogger age has been determined for this unit. The depositional environment was a low-energy subtidal lagoon with sporadic progradation of shallow-water sand bars.

2.4. LITHOSTRATIGRAPHIC UNIT D

In the lower 100 m of Unit D there are numerous beds of skeletal-oncoid-peloidal wackestones, intraclastic-oncoid-gastropod floatstones and ooid packstone/grainstones within the prevailing thick-bedded mudstones, as well as scarce beds indicating emersions. In the upper part 1-2 m thick beds of brown to gray-brown mudstones with interbeds of light-coloured intraclasts, oncoids and ostracods predominate. Lithostratigraphic Unit D is approximately 400 m thick.

According to the microfossil content (*Paleopfenderina salernitana* and *Satorina apuliensis*) this Unit is of Upper Dogger age (Bathonian - Callovian). The depositional environment was a low-energy subtidal lagoon with infrequent shallowing.

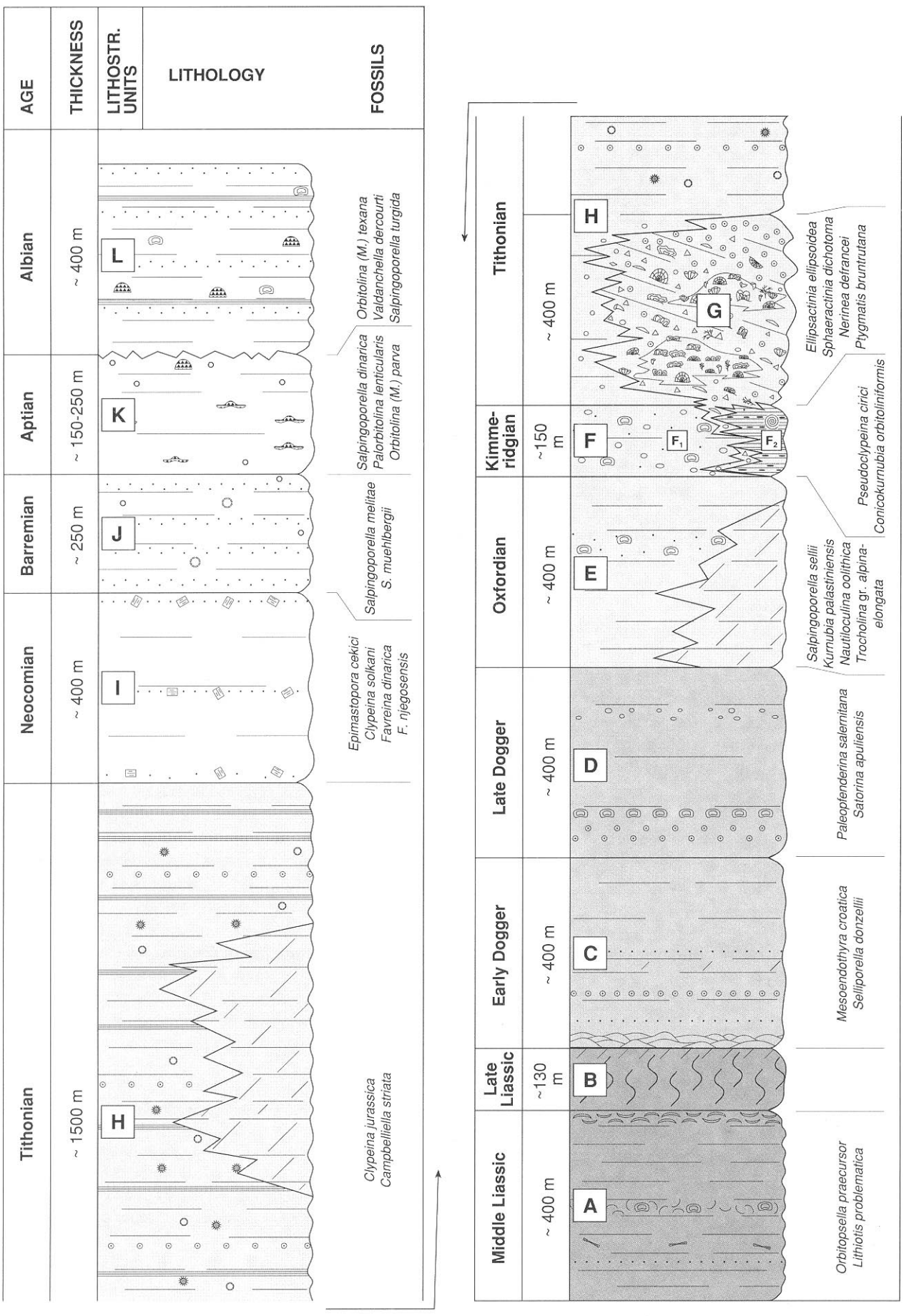

Fig. 2 Schematic geological column with determined lithostratigraphic units described in the text.

2.5. LITHOSTRATIGRAPHIC UNIT E

Deposits of this unit are represented by thick-bedded (0.5-1 m), stylolitized dark-gray mudstones and oncoid-foraminiferal wackestones with abundant *Aeolisaccus* sections and oncoids. A large part of these deposits is completely late-diagenetically dolomitized, representing coarse-crystalline dark gray to almost black dolomites of massive structure. The complete thickness of Lithostratigraphic Unit E is approximately 400 m.

The Oxfordian age of this unit has been determined on the basis of a benthic foraminiferal assemblage (*Kurnubia palastiniensis*, *Nautiloculina oolithica*, *Trocholina* gr. *alpina-elongata*) and green algae (*Salpingoporella sellii*). The depositional environment was subtidal of predominantly low energy level.

2.6. LITHOSTRATIGRAPHIC UNIT F

In the central area of the Velika Kapela Mt., as observed in the Senj-Ogulin profile, deposits of the Middle and Upper Malm show important facies variability, as a consequence of the palaeogeographical differentiation caused by synsedimentary tectonics (VELIĆ et al., 1994). Consequently, in the Middle Malm two different lateral developments have been determined: the profile mostly comprises typical shallow-water deposits (F_1) - well-bedded gray to dark gray mudstones with oncoids, intraclasts and frequent benthic foraminifera, while in the area of Drežnica very restricted outcrops of limestones with chert (F_2) occur, representing a somewhat deeper, lagoonal equivalent of the contemporaneous F_1 deposits. On the basis of the available data, the thickness of Lithostratigraphic Unit F is estimated as 150 m.

The microfossil assemblage (*Pseudoclypeina cirici* and *Conicokurnubia orbitoliniformis*) and stratigraphic relations over a wider area indicate a Kimmeridgian age for these deposits.

2.7. LITHOSTRATIGRAPHIC UNIT G

The lowermost part of the Tithonian in the Krivi Put - Senj area is represented by rarely preserved hydrozoan-coral-bryozoan-gastropod reefs, and large amounts of peri-reefal material produced by their disintegration. The reefs were formed in the marginal areas of a lagoon, while in the deeper parts limestones with cherts were contemporaneously deposited. Therefore, in the progradational succession, peri-reefal - reefal deposits are always found overlying the limestones with chert (Lithostratigraphic Unit F_2), while this unit is completely missing in areas where shallow-water deposition during the Kimmeridgian, (as represented by Unit F_1), continued into shallow-water Tithonian sedimentation. Bioclastic material is mixed with ooids formed in shallows with agitated water in back-reef areas, with a progressively higher proportion of ooids towards the upper part of the Unit. The complete thickness of Unit G deposits is estimated at 400 m.

On the basis of biostratigraphic data, (mostly macrofauna including *Ellipsactinia ellipsoidea*, *Sphaeractinia dichotoma*, *Nerinea defrancei*, *Ptygmatis bruntrutana*), as well as regional geological relationships, this unit is determined as being Lower Tithonian in age.

2.8. LITHOSTRATIGRAPHIC UNIT H

In the southern part of the study area, between Krivi Put and Senj, Tithonian peritidal deposits concordantly overlie peri-reefal - reefal deposits of the Lower Tithonian (Lithostratigraphic Unit G), while in the northern area between Drežničko Polje and Ogulin they directly overlie Kimmeridgian shallow-water deposits.

In the Krivi Put - Senj area the transition from the underlying deposits is gradual. In the lowermost 280 m well bedded light gray mudstones and fenestral mudstones with beds of peloidal-algal wackestones (comprising *Clypeina* and *Salpingoporella*) predominate, although infrequent interbeds containing hydrozoan, and scarcer coral, gastropod and bryozoan bioclasts also occur. The proportion of ooids is highest in the lower part, and gradually, although somewhat irregularly, decreases towards the upper part of the Unit. The remainder of the Unit, (approximately 1,200 m), is characterised by mudstones with variable proportions of 0.5-1 m thick laminites of different origins: some lamination is caused by selective dolomitization and dedolomitization, some by fenestral fabric, and others by the alternation of mudstones and grainstones. The amounts of *Clypeina* bioclasts is very variable, and from the middle part towards the top of the Unit *Campbelliella striata* and *Favreina* pellets are frequent in some layers. In the uppermost part deposits are thin-bedded, and some beds with ostreid bioclasts were observed.

The peritidal succession in the northern area is generally similar, but is characterised by lesser amounts of ooids, and very infrequent bioclasts (as a consequence of the distance from the reefs).

Deposits of Lithostratigraphic Unit H are of Tithonian age. It is clear that deposition of the unit in the northern part of the study area commenced during the earliest Tithonian, while in the southern area peritidal deposition was established somewhat later. Therefore, the thickness of the unit is variable, but can be estimated at 1,500 m.

2.9. LITHOSTRATIGRAPHIC UNIT I

Lithostratigraphic Unit I is characterised by thick-bedded (>0.5 m), almost completely unfossiliferous brown mudstones with very rare beds of favreina wackestone-packstone, and, in the upper part, late-diagenetically dolomitized laminites. In the Senj area mudstones comprise variable portions of small voids formed by solution of the unstable mineral components. The complete thickness of this Unit is approximately 400 m.

It has been determined that the lower 200 m of this unit contains a fossil assemblage characteristic for the

uppermost Tithonian to Neocomian, while its upper part is definitely of Neocomian age (according to the assemblage characterised by *Epimastopora cekici*, *Clypeina solkani*, *Favreina dinarica* and *F. njegosensis*). Depositional environments were mostly characteristic of lagoonal conditions with infrequent shallowing to the upper subtidal/intertidal, especially in the upper part.

2.10. LITHOSTRATIGRAPHIC UNIT J

Deposits of Lithostratigraphic Unit J are very infrequent in the study area, and are represented by alternation of well-bedded (30-50 cm) gray-brown peloid-skeletal wackestone-packstones with rare mudstone laminae. The thickness of the Unit is approximately 250 m.

Common green algae (*Salpingoporella melitae* and *S. muehlbergii*) indicate a Barremian age for these shallow-water deposits.

2.11. LITHOSTRATIGRAPHIC UNIT K

Lithostratigraphic Unit K is represented by thick-bedded light-brown to brown-gray mudstones with a relatively rich fossil assemblage, dominated by palorbitolinids. Therefore, this Unit corresponds to the deposits which are in the Dinarides known as "the Lower Orbitolina Limestones". The upper 100 m of the Unit is thin-bedded, characterised by predominating peloid-intraclast-skeletal wackestones and packstones. The thickness of the unit is approximately 150-250 m.

The microfossil assemblage (*Salpingoporella dinarica*, *Palorbitolina lenticularis* and *Orbitolina* (*M.*) *parva*) indicates an Aptian age. Deposits of this Unit are characteristic of deeper lagoonal conditions with gradual shallowing, ending with the regionally known Aptian emersion in the upper part of the Unit.

2.12. LITHOSTRATIGRAPHIC UNIT L

Deposits of Lithostratigraphic Unit L are characterised by the alternation of well-bedded (30 cm) mudstones and peloid-intraclast-skeletal packstone/grainstones containing oncoids. Lamination was sporadically observed, characterised by the alternation of mudstone and packstone laminae. The most important fossils are mesorbitolinids, and the Unit corresponds to the level of "the Upper Orbitolina Limestones" in the Dinarides. The thickness of the unit is approximately 400 m.

On the basis of the determined fossil assemblage (*Orbitolina* (*M.*) *texana*, *Valdanchella dercourti*, *Salpingoporella turgida*) this unit is of Albian age. Depositional environments are mostly characteristic of shallow-subtidal conditions.

3. STRUCTURAL RELATIONS

Tracing of the determined lithostratigraphic succession along the profile resulted in the geological map (simplified in Fig. 1).

From previous knowledge it was already possible to assume that the geological structure of this part of the Dinarides represents the consequence of two periods of tectonic activity, characterised by different orientations of the regional stress. During the Tertiary tectonic cycle, which lasted from the Eocene to the end of the Miocene, compressive movements oriented NE-SW reached their cumulative maximum with orogenesis of the Dinarides. During the later, Neotectonic period, the main stress changed to N-S, resulting in further uplift and transpressive deformation of the older structures. Namely, faults of the Dinaric strike (NW-SE), which were favourably oriented structures towards the new stress regime (approximately under the angle of 45°), were reactivated into faults with dextral strike-slip movement. Therefore, during the investigation of the Senj-Ogulin profile special attention was paid to the contacts of the established structural units, in order to define their mutual relations.

Investigation of the field relationships of the different lithostratigraphic units, and structural analysis of the tectonic fabrics, has resulted in determination of six different structural units, divided by significant faults with a relatively high component of vertical movement (in some cases more than 1,000 m).

3.1. THE KRIVI PUT STRUCTURAL UNIT

The Krivi Put Structural Unit encompasses the southwesternmost part of the study area (Figs. 1 & 3, I). It represents a large anticlinal structure composed of Tithonian carbonates (Lithostratigraphic Units G & H), with a b-axis orientation (N-S) very different from the Dinaric strike. The almost undisturbed western limb of the structure, (Fig. 1 & 3, I-A), including the continuous transition into the Lower Cretaceous deposits (Lithostratigraphic Unit I), shows no signs of rotation. Furthermore, common traces of reverse interlayer movements indicate exclusively compression normal to the structure. Considering the intensity of the deformation during the Tertiary tectonic cycle, when elements of the older tectonics were more or less destroyed, it is not probable that this structure is inherited from the older, Cretaceous tectonic cycle. This structure probably resulted from deviated local stress during the Tertiary tectonic cycle. The apical parts of the structure, as well as its eastern limb (Figs. 1 & 3, I-B) were destroyed by faults of Dinaric strike with traces of dextral movement. These faults represent the structures which are inherited from the Tertiary cycle, and were subsequently reactivated by the Neotectonic activity.

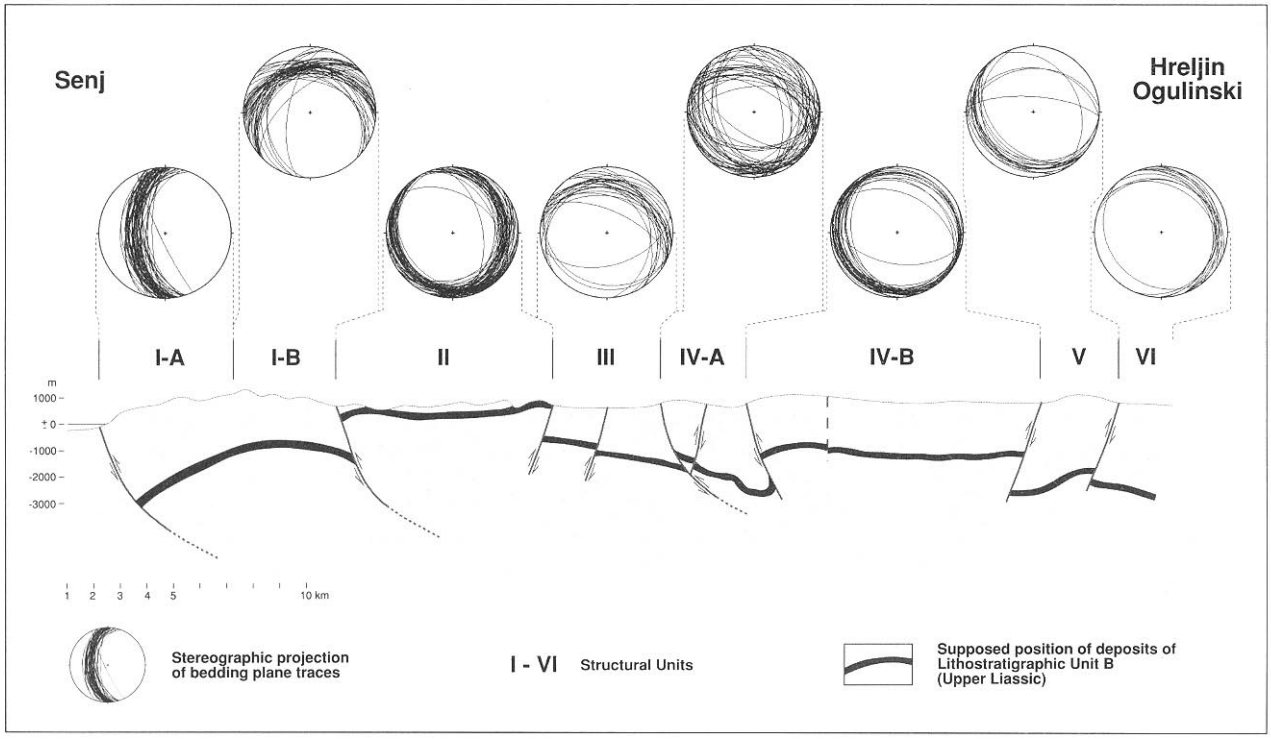

Fig. 3 Schematic geological cross-section representing structural units and diagrams of bedding traces.

3.2. THE PEPELARNICA STRUCTURAL UNIT

The Pepelarnica Structural Unit (Figs. 1 & 3, II) is separated from the Krivi Put Unit by a wide crushed and dolomitised zone. Such a wide zone probably resulted from Neotectonic reactivation of the inherited reverse fault of Dinaric strike into the dextral strike-slip fault. This structure is only peripherally encompassed by the profile, in the part where it appears as a gentle syncline. However, northwestward it outcrops as a distinct structure. In its central part it is composed of the Dogger deposits, i.e. Lithostratigraphic Units C & D, while in the marginal parts Upper Liassic carbonates (Lithostratigraphic Unit B) outcrop. It is probable that the Krivi Put and Pepelarnica Units originally represented a single anticline-syncline structure, which was subsequently destroyed by the reverse movement along the listric fault of SW vergence, with the vertical component exceeding 1,000 m (Tithonian and Upper Liassic deposits are in contact).

3.3. THE TOMIĆI STRUCTURAL UNIT

The Tomići Structural Unit (Figs. 1 & 3, III) is also in reverse relation to the Pepelarnica unit, but with the opposite vergence. Along this backthrust, the vertical component of movement also exceeds 1,000 m (NW of the Tomići village a contact between Tithonian and Upper Liassic deposits also occurs). Deposits of this Unit, comprising Malm carbonates (Lithostratigraphic Units E, F & H) uniformly inclined towards the NE, are, in the area of the Lug polje, in a similar situation to the Drežničko polje area in the neighbouring Drežnica Unit as they are compressed between a reverse listric fault with a large vertical movement from NE and a strong backthrust from SW. Both poljes are characterised by numerous large-scale sinkholes, which resulted from Neotectonic reactivation of inherited Tertiary faults. This reactivation, in the form of transpression, formed the new faults, the orientation of which (E-W strike) corresponds to the *P* ruptures in the newly established ellipsoid of deformation. Dextral movements along their fault planes caused opening of deeply penetrative axial plane cleavage of the inherited Dinaric structures.

3.4. THE DREŽNICA STRUCTURAL UNIT

The Drežnica Structural Unit (Figs. 1 & 3, IV) could be divided into two parts. The southwestern part (Figs. 1 & 3, IV-A) is strongly tectonically disturbed, since the Oxfordian deposits (Lithostratigraphic Unit E) in its frontal part are uplifted in the form of an imbricated listric fan towards the west for approximately 650 m (the Oxfordian and Tithonian deposits are in contact). The backthrust along the southwestern margin of the Drežničko polje has a vertical component of movement of approximately 700 m (uppermost Tithonian deposits of Lithostratigraphic Unit H are uplifted to the level of Aptian sedimentary rocks in the footwall). The polje represents a deformed syncline composed of Lower Aptian and Albian deposits (Lithostratigraphic Units K & L), pushed from the northeast along the fault with approximately 700 m of vertical movement (lowermost Neocomian and Albian are in the contact). This fault forms a boundary with the northeastern part of the

Drežnica Structural Unit (Figs. 1 & 3, IV-B), which represents a gentle, spacious anticline-syncline composed mostly of Tithonian deposits (Lithostratigraphic Unit H), disturbed by a fault of uncertain characteristics. Northeastward of this fault, the uppermost Kimmeridgian outcrops (Lithostratigraphic Unit F_1), but approximation of the amount of vertical movement is very difficult. Namely, the major problem in the estimation of the vertical component of movement in the northeastern part of the profile lies in the fact that the Tithonian deposits, which were observed in the contacts along all faults, are very thick and lithologically homogeneous. Therefore, it is very difficult to determine which part of the Tithonian succession is exposed along the relatively narrow area investigated by geological mapping along the profile line.

3.5. THE KLEK STRUCTURAL UNIT

Along the profile the Klek Structural Unit (Figs. 1 & 3, V) begins with a strongly tectonically disturbed zone. Neotectonic activity caused reactivation of the older reverse faults of Dinaric strike into the dextral strike-slip faults, which resulted in obscureness of the primary tectonic contacts. However, from the sporadically visible relationships between the tectonic boundary and the morphology it is clear that this is the inherited reverse fault of NE vergence. The area near the fault is characterised by strong crumbling of the footwall and a wide zone of tectonic breccia. With the exception of a narrow zone of Neocomian deposits (Lithostratigraphic Unit I) outcropping in the mentioned tectonic zone, this Unit is composed of the almost completely dolomitized Tithonian deposits (Lithostratigraphic Unit H). Beds in the Klek Structural Unit are uniformly inclined towards the southwest.

3.6. THE HRELJIN OGULINSKI STRUCTURAL UNIT

The boundary between the Hreljin Ogulinski Structural Unit (Figs. 1 & 3, VI) and the Klek Structural Unit is characterised by a reverse fault caused by movement of the Klek Unit towards the northeast. However, because of the aforementioned problem with the estimation of the thickness of the Tithonian deposits, it is not possible to determine precisely the amount of vertical movement along the fault. However, the vertical component of movement is important, since the deposits of the footwall are of the uppermost Tithonian age (as indicated in the vicinity by outcropping of the Lower Cretaceous in the continuous succession).

4. REVIEW OF THE RESULTS

Some results of the present study contribute to a better knowledge and understanding of the geological relationships in this part of the Dinarides:

- The basic characteristics of 12 informal lithostratigraphic units, ranging in age from the Middle Liassic to the Albian have been determined, including their fossil assemblages, lithology and depositional environments.

- The existence of laterally different environments during the Kimmeridgian and Lower Tithonian is proven, as a consequence of palaeogeographic differences probably caused by synsedimentary tectonic activity.

- The tectogenesis of the Dinarides is the cumulative effect of two tectonically active periods - Tertiary and Neotectonic. During the Tertiary tectonic cycle structures were formed by the NE-SW orientated compressional tectonics (structures of the Dinaric strike). Subsequently these structures were reshaped by the transpressional Neotectonic activity, when the older faults were reactivated into the dextral strike-slip faults by the change of regional stress direction to the N-S.

However, in the study area traces of the Neotectonic activity are very common, and are mainly represented by gentle striae, but the inherited Tertiary structures are still well preserved. Therefore, it may be concluded that the influence of the Neotectonic activity in the area of the investigated profile should not be overstated.

- The structures of the N-S strike (i.e. the Krivi Put Structural Unit), which are different from the Dinaric strike, show no signs of subsequent rotation. This fact, together with other indicators of Neotectonic activity, indicate that these structures are the result of the syngenetic bending along the strike, probably caused by the local deviation of stress during the Tertiary tectonic cycle.

Since the presented results were obtained on a single profile through the Dinarides (although investigated in detail, and almost 45 km long) they do not allow comprehensive conclusions to be drawn about the relationships of a regional area. However, they complement additional data, including seismic investigation and study of other profiles, and certainly represent a contribution to a more complete knowledge of the structure of the Dinarides.

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