GEOL. CROAT.	51/1	75 - 89	15 Figs.			ZAGREB 1998

The Two Stages of Structural Formation of the Coastal Belt of the External Dinarides

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Key words: Tectonics, Dinaride-striking structures, Hvar-striking structures, Mt. Velebit, External Dinarides, Croatia.

Abstract

Two successive stages of tectonism have been responsible for the formation of structures in the coastal part of the External Dinarides. As a result, Dinaride- and Hvar-striking structures formed, showing NW-SE and E-W strike orientation, respectively. Besides the great diversity in the geological and geophysical characteristics and intensive disruption, the coastal area represents a cohesive geotectonic unit, showing a uniform geodynamic evolution that is here confirmed by laboratory modelling.

1. INTRODUCTION

The coastal-island region of the External Dinarides, differently named and classified in papers dealing with tectonics and geotectonics of the region (e.g. HERAK, 1986, 1991), is defined as the subduction zone of three geotectonic units. To the NE these are: the Adriatic (mostly underthrusted), the Epiadriatic (consumed), and the Dinaric (surface dominant). All of these three geotectonic units show similar structural characteristics including predominately Dinaride-striking structures, except in the area of Central Dalmatia where Hvar-striking orientation becomes increasingly obvious (CVIJIĆ, 1924), and the predominance of tangential folded and faulted, southwest- to south-verging structural units.

There are no particular differences in the geological setting of a wider boundary zone between the Adriatic and the Dinaric units. Except for outcrops of the Epiadriatic at the southeastern and northwestern ends of the belt (i.e. extension of the Budva-Cukali zone and Vipava Valley, respectively), they both show the same development of the Mesozoic and Early Palaeogene carbonate platform units, and later flysch deposition during the Eocene and Early Oligocene.

However, the location and boundary of the subduction zone or its expression on the surface is debatable. Regarding the geological setting, this zone is dissipated within the wider contact zone between the aforementioned units. The width of this zone is defined by the width of the Eocene flysch zone. Structurally, this boundary zone may have the character of jointed underthrusting zones (BLAŠKOVIĆ & ALJINOVIĆ, 1981; BLAŠKOVIĆ, 1991). Even if this is true, it is, however, logical to expect that one major boundary contact would represent a subduction zone. The later is in part the subject of this paper.

It is easier to explain the observed structural characteristics of studied geotectonic units within a framework of a descriptive scheme of geodynamic processes and the arrangement of geotectonic units. However, some problems and open questions regarding geological relationships observed on the surface, as well as on seismic and gravity profiles and maps still remain. These are described below.

2. GEOLOGICAL AND GEOPHYSICAL CHARACTERISTICS

Following the strike of structures and orographic axes along the coastal belt towards the south-east (Fig. 1), there are particular regions which remain geologically and geotectonically still inconsistently defined:

- In the contact area between Mt. Velika Kapela and Mt. Velebit, i.e. approximately along the Senj-Ogulin line, there is a rapid change of geomorphological characteristics, and a sharp offset of Eocene flysch synclines. The same is observed to the southwest in the region of Rab Island.
- Within the huge massif of Mt. Velebit, as well as in the region of Gorski kotar, older, i.e. Late Palaeozoic and Mesozoic, rock complexes predominate.
- In the geological setting of Mt. Velebit three lineaments predominate: Alan Stinički-Kosinjski Bakovac, Baške Oštarije east of Karlobag, and the third in the area of Velika Paklenica that is weakly geomorphologically expressed.
- The southeastern end of Mt. Velebit, defined by the zone of outcrops of the Jelar Formation (Maslenica-Obrovac-Gračac); further on, in the spring area of the River Una and towards Drvar, this zone separates the Triassic-Jurassic anticline located north of Gračac from the one north of Knin.

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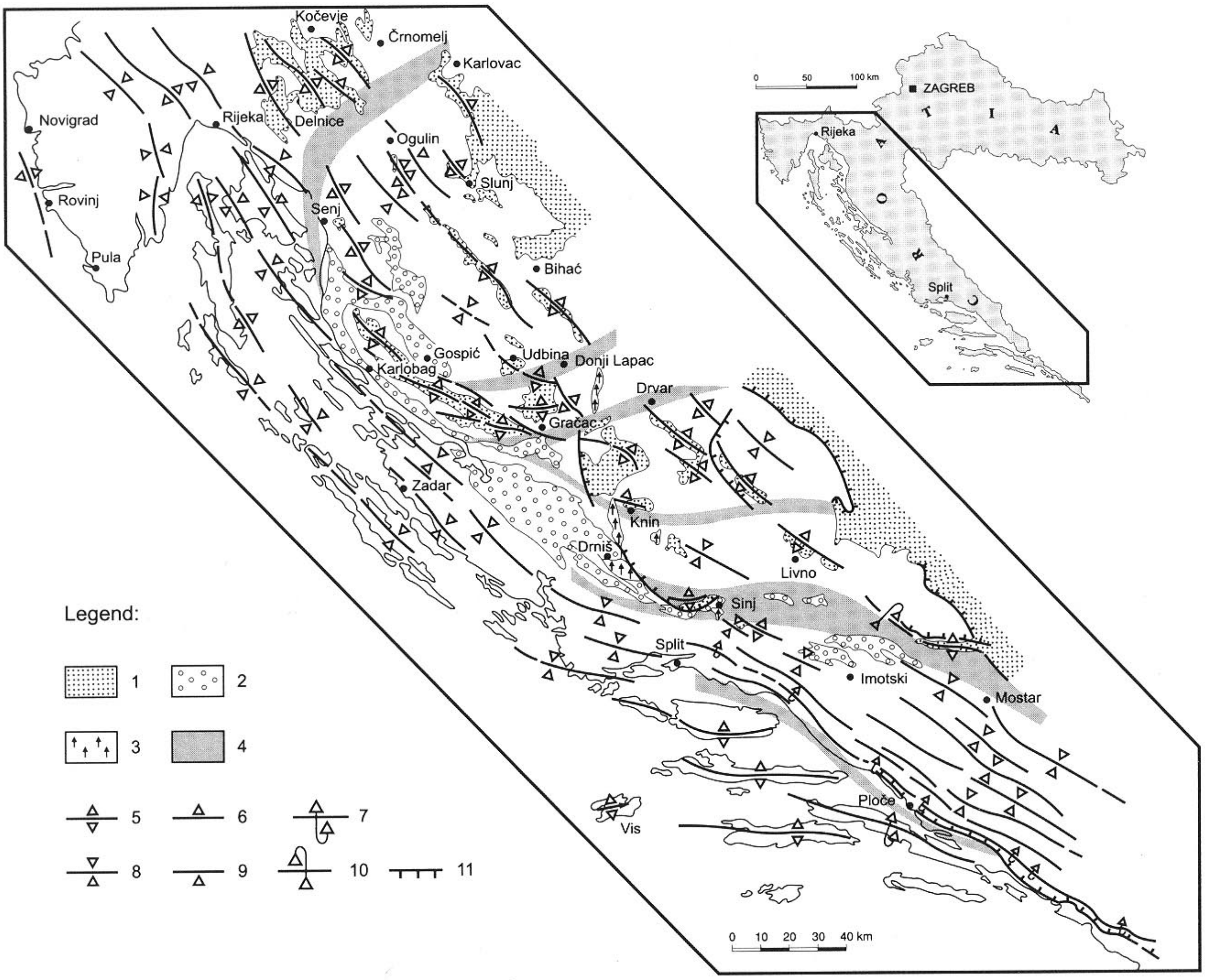


Fig 1 Simplified tectonic map showing distribution of the major folds and faults of the External Dinarides. Legend: 1) Late Palaeozoic - Triassic clastics and carbonates; 2) clastic rocks of the Promina and Jelar formations; 3) evaporites; 4) zones of strike discontinuity of structures and chronostratigraphic units; 5-11) main structures or their parts: 5) anticline; 6) anticline limb; 7) overturned anticline; 8) syncline; 9) syncline limb; 10) overturned syncline; 11) reverse fault.

Further similar uncertainties exist regarding the continuation of a generally Triassic antiform structure located north of Knin, as well as in the area of Vrlika and Sinj, where it is accompanied by the Jelar formation clastics.

At all these localities there is a clear divergence from the NW-SE Dinaridic strike orientation of the structures and main chronostratigraphic units. This is particularly clearly seen along the Sinj-Buško Blato-Duvanjsko Polje (Kongora)-Drežnica line, and further to the southeast.

From this line to the south and southeast, folds formed in the Cretaceous-Palaeogene rocks, again strike parallel to the Dinaridic strike. The Mosor-Biokovo and the Dubrovnik-Konavle Mesozoic carbonate massifs predominate, and are thrust onto the Eocene units towards the southwest. However, even in this part of the Adriatic coast the islands of Brač, Hvar, Korčula, and partly Pelješac peninsula, retain their Hvar-striking orientation of structures.

The same divergence from the common Dinaridic-striking orientation of structures, at almost the same localities, is also suggested and confirmed by seismic data (Fig. 2):

- The strike of the Rovinj-Novigrad seismic marker horizon (ALJINOVIĆ, 1984) diverges both from the Dinaridic strike and that of the West Istrian anticline (i.e. the Rovinj anticline). The later is commonly described as NE-SW oriented (POLŠAK & ŠIKIĆ, 1973; MARINČIĆ & MATIČEC, 1991; MATIČEC, 1994; MATIČEC et al., 1996).
- The coastal area of Istria and Kvarner is separated from Mt. Velebit and the Rab-Pag-Premuda area by a sharp seismic boundary trending along the Senj-Lošinj-Susak-Andrea I line (ALJINOVIĆ, 1984).

Regionally, it is obvious that following the NE dip direction of the seismic marker horizon its angle of dip increases down to a depth in excess of 14 km in the coastal zone between Mts. Velebit and Biokovo. This

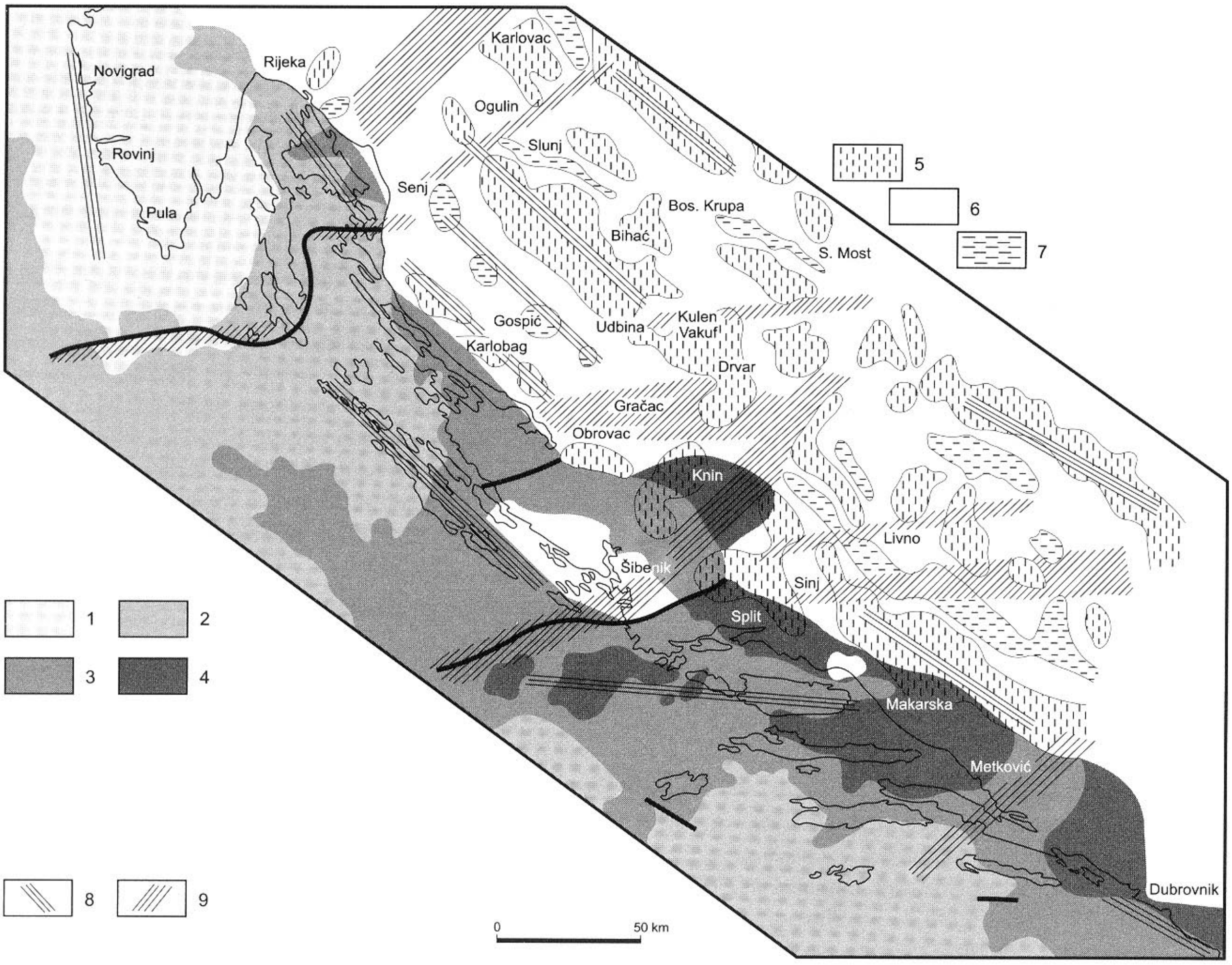


Fig. 2 Simplified and compiled sketch showing results of geophysical explorations in the Adriatic region and the External Dinarides. Isobath map of the deep marker horizons (after ALJINOVIĆ, 1984) and gravity anomaly map (after LABAŠ, 1987). Legend: 1-4) Isobath map of the deep marker horizons (shadings): 1) depths less than 5 km; 2) depths between 5 and 10 km; 3) depths between 10 and 13 km; 4) depths between 13 and 15 km. 5-7) Gravity anomaly map (white basis): 5) area of maximum positive anomaly; 6) medium anomaly values; 7) area of minimum negative anomaly. 8-9) Tectonic reinterpretation: 8) longitudinal zones marked by relative continuity of geophysical - tectonic characteristics; 9) transversal and diagonal zones marked by discontinuity of geophysical and tectonical characteristics.

seismic horizon marks the base of sedimentary cover and is concordant with the Moho discontinuity (ALJINOVIĆ & BLAŠKOVIĆ, 1984). Especially deep position of this seismic horizon is clearly seen in the area of Knin (>14 km) and the area of the Central Adriatic-Šolta-Split and Mosor (>13 km). The similar depths of the seismic horizon are observed in the area of Brač, Hvar and Biokovo, and the area of Šipan-Dubrovnik and Konavle, as well.

Its translation along the Žirje-Svilaja line is particularly clear, too.

Gravity data presented on a gravity anomaly map (Fig. 2; simplified from LABAŠ, 1987) confirms the field geological observations. Following the regional tectonic interpretations concerning the distribution of positive and negative anomalies in the karst area of the Dinarides, several different zones may be distinguished. Longitudinal zones of relative continuity strike predominately parallel to the Dinaride- and less to Hvar-strike orientation, while transversal to diagonal zones, cross-cutting the first ones, are characterised by the irregular distribution of anomaly values.

Two regions characterised by continuous longitudinal zones are the Velebit-Ličko Sredogorje-Mala Kapela-Plješevica zone, and the Split-Makarska-Dubrovnik coastal and hinterland zone.

Between these there is a broad diagonal to transverse belt of irregularly distributed anomalies in the area of Ravni Kotari, east to the Sanski Most, as well as the belt from Šibenik to Sinj and Livno that extends further east. The northwestern boundary of the Velebit-Plješevica longitudinal zone is represented by a wide transverse belt of relative discontinuity located in the area of Kvarner and Gorski Kotar, extending to Karlovac.

Therefore, it can be concluded that there is a clear correlation between the results obtained by three independent exploration methods (geological, seismic and gravity) in the delineation of surfaces and zones of the marked discontinuities.

3. RECONSTRUCTION OF KINEMATIC PROCESSES

Despite the generally accepted theories of formation of the Dinaridic structures of NW-SE strike orientation, there remains the question of which types of geodynamic processes were responsible for the evolution and formation of the studied discontinuities.

This paper reconstructs the kinematics of the geodynamic processes involved in the formation of the External Dinarides, without taking into account causes as well as the accurate timing of changes. This is part of a more complex geodynamic study on the Adriatic-Dinaridic and Pannonian Basin evolution. In this reconstruction, different models have been used to evaluate the different theories as well as to explain the kinematics. The recent geological setting, as well as the geomechanical characteristics of different chronostratigraphic units (e.g. ductility) served as a basis for modelling. Due to the characteristics of the modelling material (plasticene), the presentation of kinematic processes is overloaded by schematisation in the reconstruction of particular phases preceding the approximate recent structural setting.

There are two dominant and superimposed tectonic-structural elements in the External Dinarides that were used as a basis for modelling and reconstruction. These are firstly, the Dinaride-striking, tangential folded and faulted structures verging to the southwest, and secondly, Hvar-striking structures verging mostly to the south and less to the north.

According to the orientation of tangential structures the relative orientation of a collisional force is determined to be perpendicular to the b-axes of structures, whilst the dominant direction of movement induced by a continental slab-pull is toward northeast, i.e. in the opposite direction to the vergence of tangential structures. Therefore, the collisional movement that initiated formation of the predominate Dinaride-striking structures is directed along a NE-SW direction and formation of the Hvar-striking structures resulted from a subsequent, generally N-S or NNW-SSE to NNE-SSW directed collisional movement, which affected the same chronostratigraphic units as well as the previously formed Dinaridic-striking structures.

Two stages of structural formation can be defined. The primary stage of structural formation, and a later orthogonal stage of refolding (i.e. re-structuring). However, there remains a possibility for successive transition from the first into the second stage, i.e. with a partly simultaneous mutual action of forces related to the first and the second stage. Alternatively, two separate phases of kinematic process may be assumed. The first possibility is accepted here and simulated by modelling.

4. THE PROCESS AND GEOLOGICAL INTERPRETATION OF MODELLING

Separate modelling phases are recorded photographically from which simplified schematic diagrams are produced. Particular phases are described below following their order of formation.

Development of the Dinaride-striking folds that are modified through tectonic processes from upright to inclined and overturned fold provided the basic assumption (Figs. 3a & 3b) for the modelling experiments. Later, under the same orientation of collisional movement, overturned folds could become isoclinal, with a possibility for the development of reverse faults, imbricated and even nappe structures (Figs. 4a & 4b). Two phases of modelling described above correspond to the first stage of the structural formation characterised by parallel and relatively uniform folded and

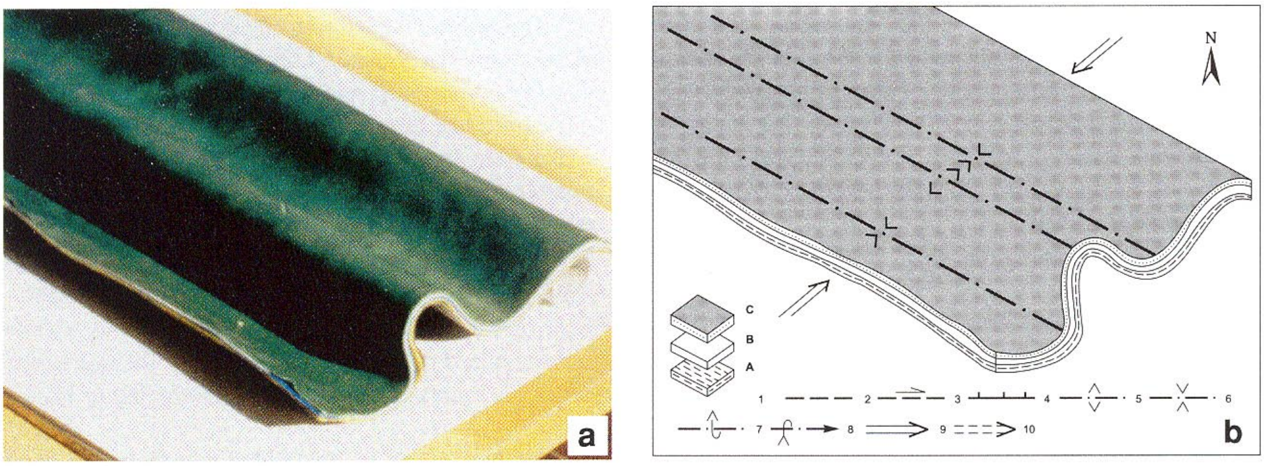


Fig. 3 a) Model. Isoclinal fold - early stage in formation of primary Dinaridic-striking structures. b) Geological and kinematic interpretation of the model. The same symbols are used for other figures and model interpretations. Not to scale, relative orientation. Legend for Figs. 3b-11b: 1) A, B, C - continuation of chronostratigraphic units; 2) fault; 3) strike-slip fault; 4) reverse fault; 5) upright and inclined anticline; 6) upright and inclined syncline; 7) overturned anticline; 8) overturned syncline; 9) orientation of compressional forces related to the primary stage I of structure formation; 10) compressional forces related to stage II of orthogonal refolding.

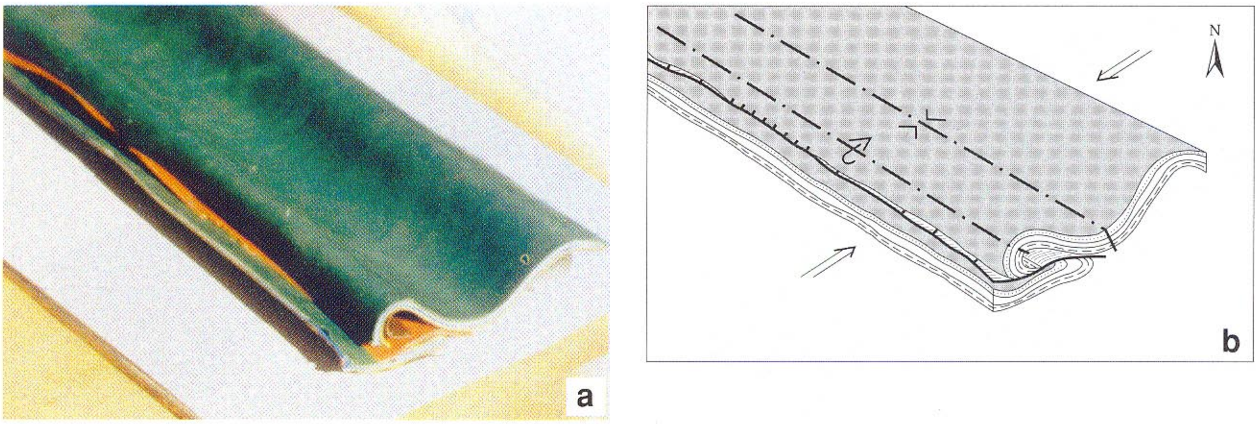


Fig. 4 a) Model. An isoclinal, overturned fold cut by a reverse fault. Continuation of process from Fig. 3. b) Geological and kinematic model interpretation.

faulted structures showing a Dinaride-striking orientation.

It is, however, inevitable to suppose that the structures may have undergone variable deformation along their strike. This implies that competent rock complexes may be raised to the same level as non-competent ones; this will invoke greater and lesser resistance to changes, respectively, and simultaneously, will have a slight influence on the character and type of changes in continuation of the process. Unfortunately, due to the characteristics of the modelling material this could not be tested.

The current geological situation and gravity data allow separation of several regions that behaved as relatively more rigid or homogeneous units when compared with other areas along strike. These are wider area of Gorski Kotar with outcropping Palaeozoic rocks versus the area of Mt. Velebit with a smaller volume of corresponding rocks, and the area of Southern Dalmatia and Herzegovina characterised by Mesozoic and Palaeogene rock complex and continuous structural characteristics.

This arrangement of rock complexes showing different geomechanical characteristics is of particular importance during the second stage of tectonism, when the NE-SW collisional movement of primary stage is accompanied by the almost predominant, compressive force of the orthogonal stage, which is parallel with the b axes of previously formed structures inducing their refolding and faulting (Figs. 5a & 5b). This is simulated by the model in Figs. 6a and 6b.

The compressive force of stage II resulted in the formation of structures that strike almost perpendicular to the Dinaride-striking structures (the transverse and diagonal zones of discontinuity delineated by field mapping (Fig. 1) and geophysics (Fig. 2)). The locations of these zones are predetermined by the greater resistance of the more rigid rock complexes. In modelling, this is roughly simulated through a sequence of images showing topography as well as the horizontally and vertically orientated sections on different levels.

Consequently, within a belt characterised by the diagonal and transverse Hvar-striking structures, the model supposes two complicated zones of thrusting under the rigid complex of Mt. Velebit, the Central mountain range of Lika and Mt. Mala Kapela. Moreover, within a contact zone between Mts. Velebit and Velika Kapela, the model predicts thrusting of Mt.

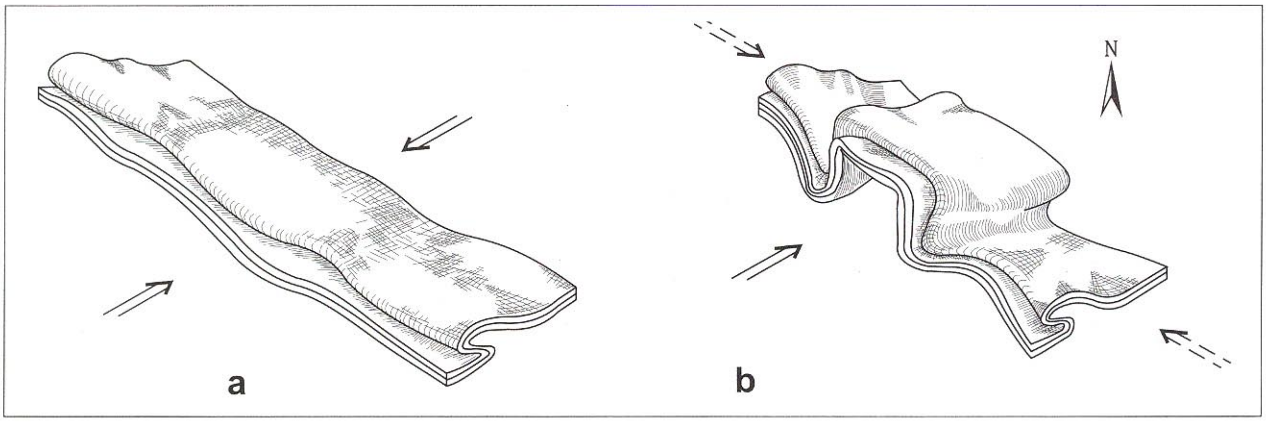


Fig. 5 Graphical sketch illustrating formation of primary stage I structures (a) and structures related to secondary stage II of orthogonal refolding, i.e. re-structuring (b).

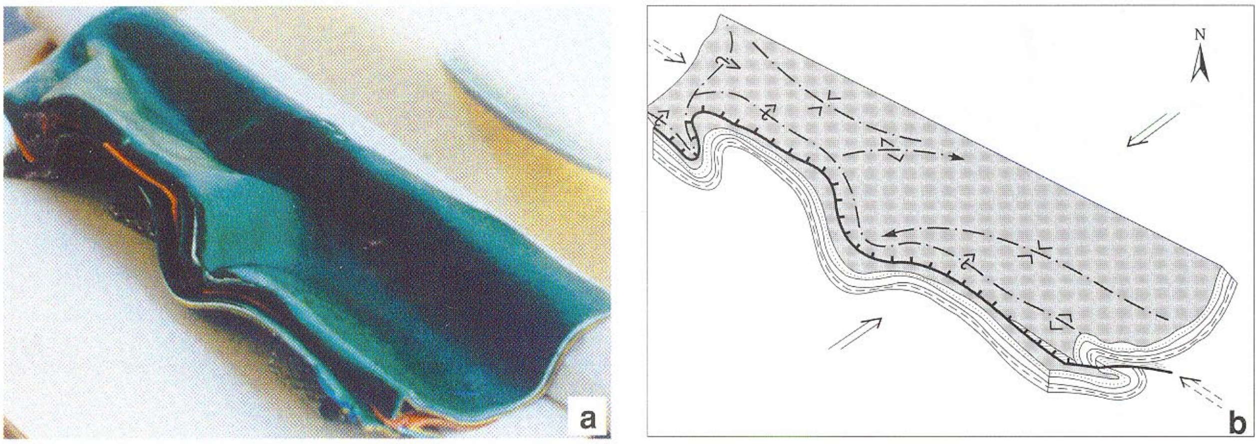
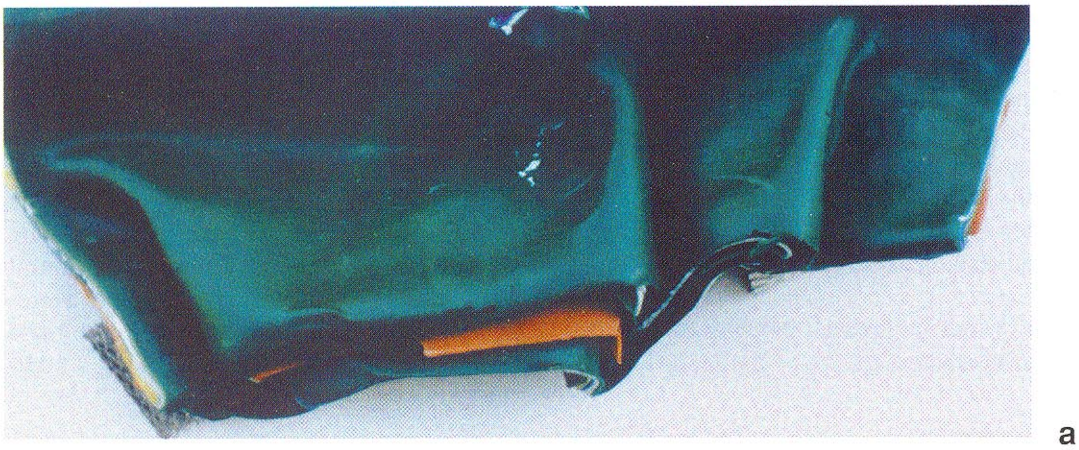


Fig. 6 a) Model. Simplified simulation of the early stage of orthogonal re-structuring of Fig. 5b. b) Geological interpretation of model structures.

Velebit massif onto the rocks of Velika Kapela leaving behind the relatively rigid complex of Gorski kotar (Figs. 7a & 7b). These particular locations or areas are generally shown and marked on figures accordingly.

Direct correlation between the presented model and actual geological setting is not possible. The model is used to understand the very essence of the refolding process. Therefore, two south verging antiforms presented by the model could be positively correlated with partly similar, although fragmentary preserved anticlines: the Sinj anticline and the Knin - Sučević - Bosansko Grahovo anticline or with the Southern Velebit - Donji Lapac antiform. Two well marked reflection seismic boundaries, i.e. AB and X, observed northwest of Knin (PRELOGOVIĆ et al., 1995 - fig. 7) confirm the supposed process. The reflection boundary AB is considered here as corresponding to the zone of underthrusting related to the primary stage of structural formation (stage I), and the reflection boundary X as the base of orthogonal refolding stage (stage II).

Moreover, an opposite verging antiform located more to the northwest, between Mt. Velebit and Gorski



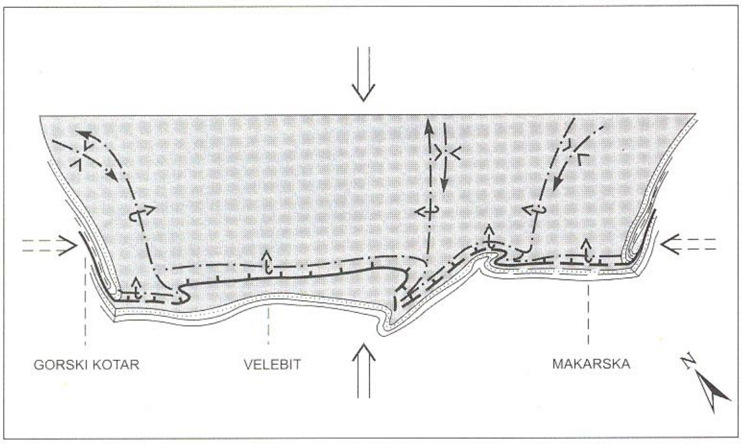


Fig. 7 a) Model. Orthogonal refolding of a Dinaride-striking structure. b) Geological interpretation of the model.

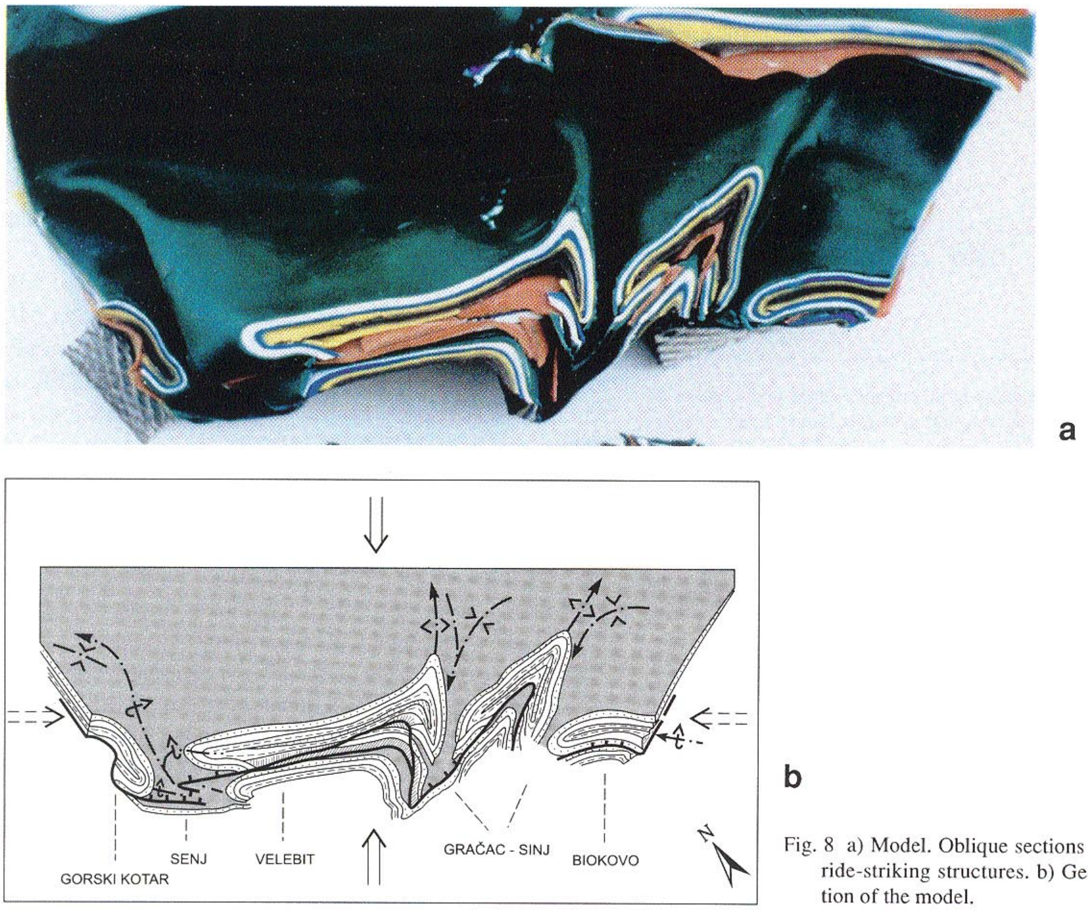


Fig. 8 a) Model. Oblique sections of Hvar- and Dinaride-striking structures. b) Geological interpretation of the model.

Kotar (Figs. 7a & 7b) could be considered as representative of the geological-structural relations along the contact between Mts. Velebit and Velika Kapela, approximately following the Senj-Ogulin line or Alan Stinički-Kosinjski Bakovac line on northern Velebit.

The different strike of the newly formed antiforms and synforms is clearly seen on Figs. 7a and 7b. Kinematic processes controlling formation of the Hvar-striking structures or those diverging from the Dinaride strike is more obvious, and was also responsible for the formation of the observed geological and geophysical discontinuities.

This is even more clearly seen on horizontal, vertical or variously dipping sections following the successive modelling phases. These sections help in the reconstruction of basic geological map elements (horizontal and differently dipping sections of the model) as well as in the perception of geological profiles (vertical model sections; Figs. 8a & 8b).

A section through the model which corresponds to a very complicated topographic sequence seen in the study area, allows correlation with the recent structural assemblage. This is especially apparent if the possibility of reverse faulting for the second generation Hvar-striking folds is taken into account, leading to the reduction of particular syncline structures or the destruction of previously formed folds.

According to the presented kinematic model, the possibility for transformation of relatively simple, first-stage folded structures, (e.g. an antiform eventually dislocated by reverse fault) into second-stage structures having almost completely different characteristics is quite possible. Therefore, it can be concluded that the coastal belt behaved as a single unit in the primary tectonic framework.

The arrangement of palaeogeographic units which are defined by the occurrence of particular syn-tectonic, predominately clastic-type deposits, is predetermined by the geodynamic processes of both stages of tectonism.

5. RECONSTRUCTION OF MT. VELEBIT KINEMATICS

Besides the kinematic problem related to the evolution of coastal belt of the External Dinarides, particular attention in modelling and geological interpretation has been paid to the wider Mt. Velebit area.

Within a wider contact zone between Mt. Velebit and Mt. Velika Kapela (Gorski kotar) where the geological relationships, and breaks in Palaeogene folded structures, prevent unambiguous interpretation, the model of "thrusting" of Mt. Velebit by northwestern-

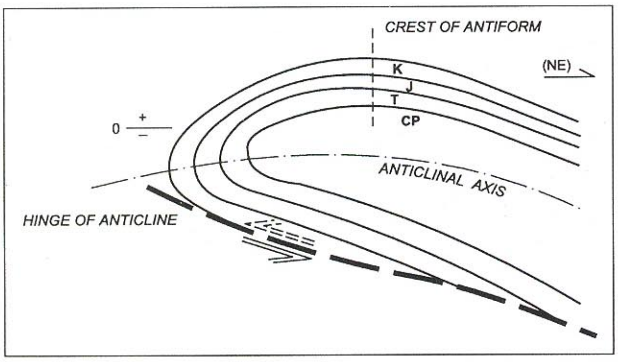


Fig. 9 Sketch drawing illustrating the probable shape and location of the primary Mt. Velebit anticline structure. Not to scale, relative orientation. Legend: CP) Carboniferous-Permian; T) Triassic; J) Jurassic; K) Cretaceous.

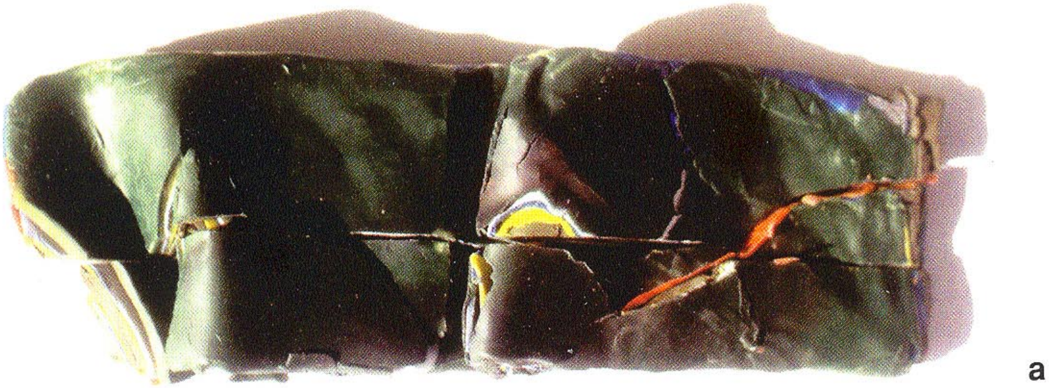
verging folding onto Mt. Velika Kapela was developed in more detail.

A similar modelling procedure was performed for the area of Mt. Velebit in order to explain the development of the Alan Stinički-Kosinjski Bakovac and Baške Oštarije structure. This could be also applied to the area of Velika Paklenica. These structures are characterised by outcropping older Triassic and/or Palaeozoic rocks, as for example within the Velebit anticlinal structure (SOKAČ, 1969, 1973; BAHUN, 1974).

Also, due to the non-competence behaviour of plasticine, it was not possible within such limited conditions to simulate the real structural characteristics of the study area. Instead of generally upright or inclined anticlines of the primary stage, it was easier to simulate in modelling an isoclinal anticline. This should be taken into consideration although it does not have any serious impact on the process itself.

The idea of an isoclinal anticlinal structure of Mt. Velebit should not be rejected. Similar ideas on Mt. Velebit can be found in the literature. It is variously interpreted as the High Karst nappe front (SIKOŠEK & MAKSIMOVIĆ, 1971); the tip of a blind fault located below sea-level (HERAK, 1971); part of a huge fold with a core formed of Palaeozoic rocks outcropping in the area of Lika (HERAK, 1973), or a "reactivated" antiform (SOKAČ et al., 1976). Following these ideas, the structure of Mt. Velebit could be envisaged as the limb of a primary recumbent isoclinal anticline (Fig. 9). The locally increased or even double thickness of a Mesozoic-Palaeogene sedimentary complex, the position of the deep seismic marker horizon and the Moho discontinuity, accordingly, might support the same idea.

Two cross-striking northwest-verging folds characterised by marked anticlinal parts are assumed by the model (Figs. 10a & 10b). One could correspond to the northernmost Mt. Velebit (area of Senj-Vratnik-Žuta Lokva) and the other to the Alan Stinički-Kosinjski



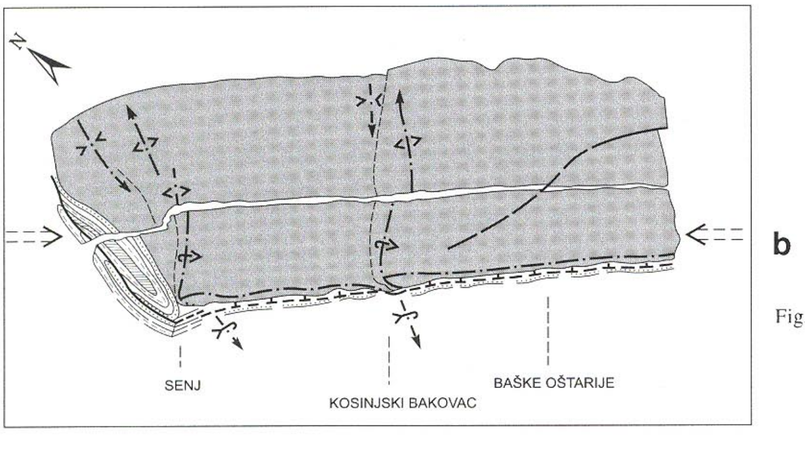
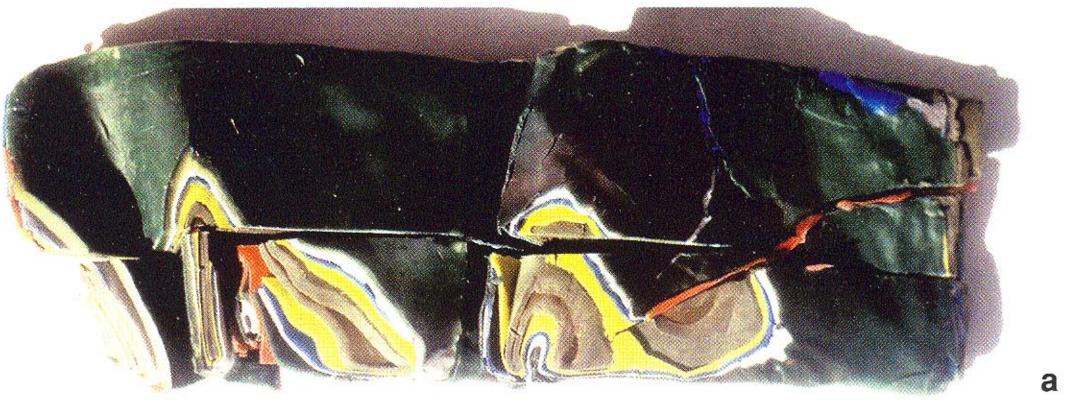


Fig. 10 a) Model for the area of Mt. Velebit. Primary stage I, i.e. Dinaride-striking, overturned isoclinal anticline deformed during the orthogonal stage II of re-structuring. b) Geological interpretation of the model.



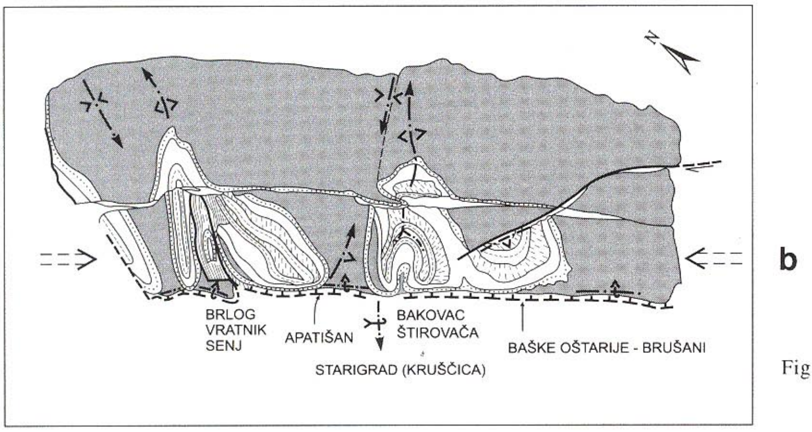


Fig. 11 a) Model. Horizontal section of the model shown on Fig. 8. b) Geological interpretation of the model.

Bakovac structure. Further to the southwest, a dextral strike-slip diagonal fault is presumed that terminates to the northwest. Strike-slip followed by oblique-slip movement for the southwestern block was simulated, and resulted in fault-propagating anticlinal formation and uplift.

A planar section or one which would approximately mimic recent topography, shows that structural and geological elements similar to those found in the field are characteristic for the second generation structures (Figs. 11a & 11b).

Two examples in the contact zone between Mts. Velebit and Velika Kapela that confirm good correlation between the model (Figs. 10b & 11b), geological relations in the field (Fig. 12) and kinematic process proposed by modelling can be taken as representative. Firstly, the arrangement of older and younger chronostratigraphic units (T_3 - J_{1-2}, K_2^{1-2}) indicating the anticline and syncline cores of which the Hvar-striking Cretaceous syncline of Stražbenica, south of Jezerane, is a typical example. Secondly, data on strike and dip direction of bedding as shown in the area of Vratnik - Brinje - Jezerane - Švica - Crni Kal, where the strike of bedding rapidly changes from the NW - SE Dinaride-strike into the WNW - ESE or WSW - ENE strike, dipping to the NNW or SSE.

A more simple and unambiguous correlation between the presented model (Figs. 10b & 11b) and geological relationships can be found in the wider area along the Starigrad - Alan Stinički - Kosinjski Bakovac line (Fig. 13). Here, two anticlines are clearly defined by geological mapping, both separated by a wider zone of Jelar-formation breccia. The Jasenova Kosa - Štirovača anticline which is more complicated, was formed in Triassic and Jurassic sedimentary rocks, and further north, the Apatišan anticline was formed in Jurassic sediments. Both of these are well defined by a typical arrangement of chronostratigraphic units and corresponding orientation of bedding, though differ clearly in strike orientation. The Jasenova Kosa anticline shows a typical Dinaride-strike orientation while the Apatišan anticline strikes generally east - west, plunging to the east. Adjacent to the latter an anticlinal tip is located west of Kosinjski Bakovac.

In interpretation of the structures based on analogies with the model (Figs. 10b & 11b) the following units are defined: the Štirovača - Jasenova Kosa anticline is a primary Dinaridic-striking structure which is translated towards the northwest. The northwestern rapid termination of this structure, close to the anticlinal tip which lies west of Kosinjski Bakovac, represents a Hvar-striking, north-verging anticline formed by orthogonal (stage II) superimposed folding. During subsequent tectonics, a fault formed trending parallel to this structure along the Kosinjski Bakovac - Alan line. Similarly, the Apatišan anticline, striking WNW - ESE, is defined as a flexure that belongs to the orthogonal system of superimposed, south to southwestern-verging folds. It is sup-

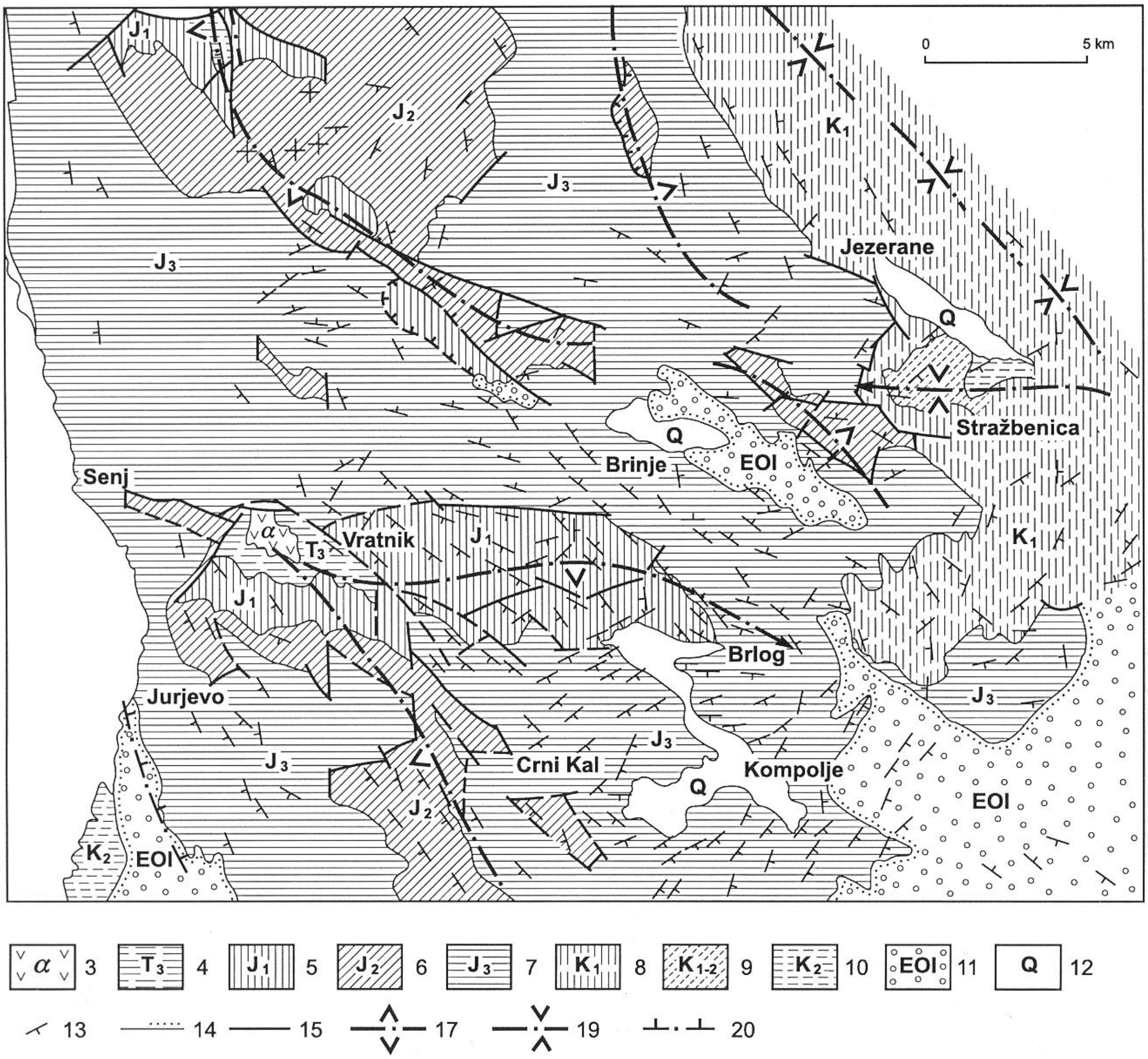


Fig. 12 Simplified geological map of the contact zone between Mts. Velebit and Velika Kapela (after MAMUŽIĆ et al., 1969; ŠUŠNJAR et al., 1970; VELIĆ et al., 1974; VELIĆ & SOKAČ, 1981). Legend for Figs. 12, 13, and 14: 1-12) Main chronostratigraphic units: 1) Carboniferous-Permian clastic and carbonate rocks; 2) Lower to Middle Triassic and Middle Triassic predominantly clastic rocks; 3) amphibole porphyry; 4) Upper Triassic dolomite; Carbonates: 5) Liassic; 6) Dogger; 7) Malmian; 8) Lower Cretaceous; 9) Lower to Upper Cretaceous limestones and dolomites; 10) Upper Cretaceous carbonates; 11) Jelar - calcareous breccia; 12) Quaternary deposits. 13-16) Symbols on geological map: 13) strike and dip of bedding; 14) normal contact and unconformity; 15) fault; 16) anticline axis; 17) anticline i.e. antiform axis; 18) "axis" of anticline (antiform) limb; 19) syncline, i.e. synform axis; 20) fault, reverse fault; 21) relative amount and sense of fault block movement.

posed that between these two antiform units there is a synclinal structure which originated during the second phase of tectonic activity, showing the Late Cretaceous rocks within a core along the Starigrad - Kruščica line. Shortly after formation, it was filled with molasse type limestone breccia of the Jelar formation.

Also in this case, the possibility of dextral transcurrent faulting related to the orthogonal compressive stress field of the stage II tectonic activity was considered. It is exemplified by positive correlation between the model (Figs. 10b & 11b) and the geological setting of the area of Baške Oštarije (Fig. 14). The arrangement of the chronostratigraphic units and corresponding orientation of bedding, unambiguously suggest that a primary anticlinal structure, as well as parts of this Dinaridic-striking structure, are separated by the Brušane - Baške Oštarije fault. In correlation with the model, during stage II tectonic activity, the movement of a southwestern block towards the northwest along this fault is supposed. The block movement along the fault is specific: it is partly compensated by folding and uplift that are related to a negative dilation along a direction parallel to the collisional force orientation, i.e. parallel to the b-axes of primary, Dinaridic-striking structures. Except for changes in length, the shape of Dinaridic anticlinal structures do not change considerably regionally, due to

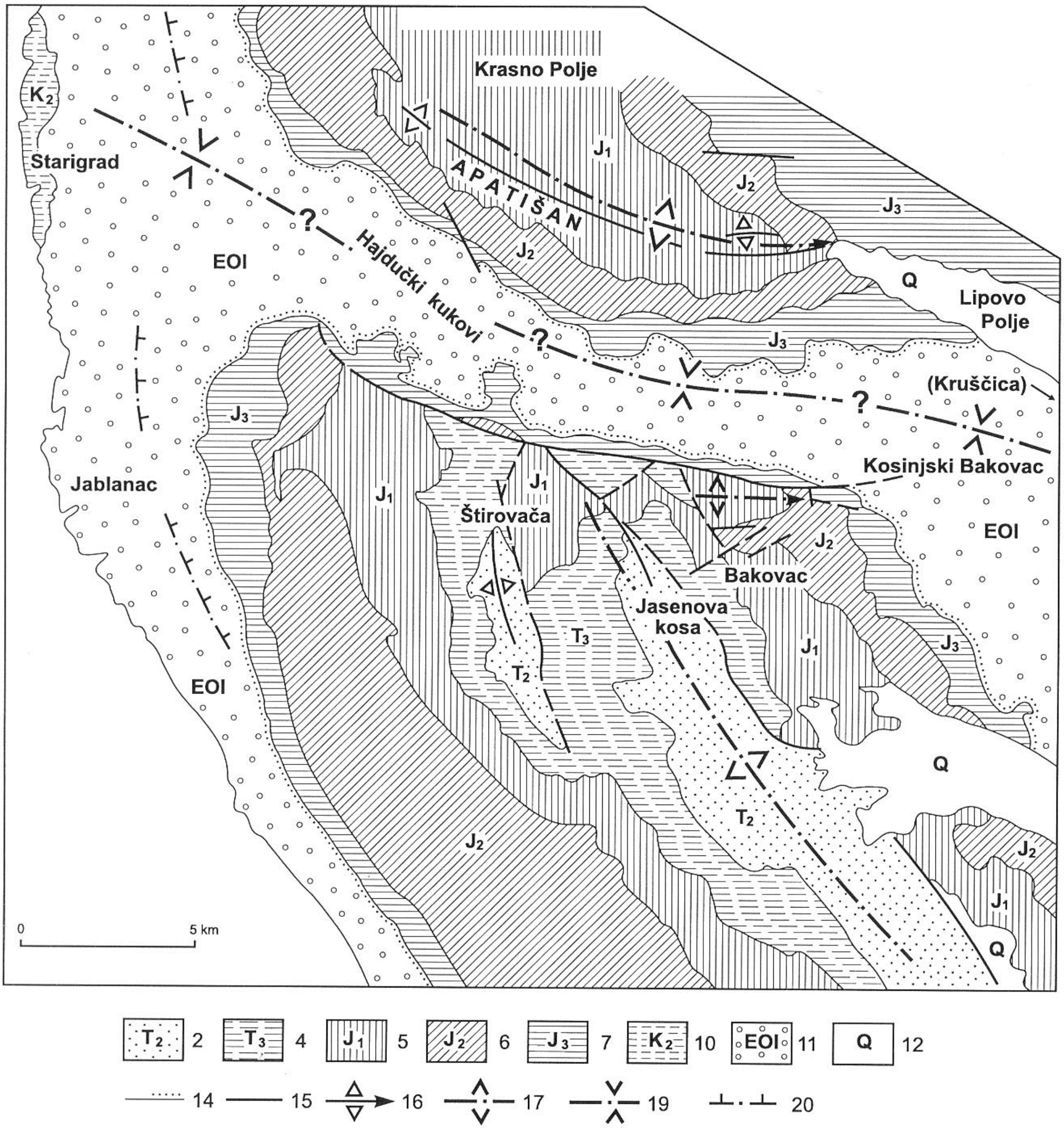


Fig. 13 Simplified geological map of the Starigrad - Kosinjski Bakovac area (after MAMUŽIĆ et al., 1969; VELIĆ et al., 1974; SOKAČ et al., 1974). For legend see Fig. 12.

the simultaneous action of the primary collisional movement.

Considerably good correlation between the geological setting and supposed kinematic model could be found at several localities to the southeast, i.e. in the area of Rizvanuša - Počitelj - Medak - Sv. Rok - Gračac (Fig. 15). All together, they could be interpreted as an en-echelon, transpressive fault system. The strike slip movements of fault blocks are partly compensated by a fault-bend anticline folding parallel to the b-axis of a primary formed anticline and their uplift. The northwestern parts of these orthogonal, complicated monoclines, where the faulting is completely or partially compensated by folding, are defined either as flexures and/or overturned folds or as reverse faults, respectively, verging in the direction of fault block movement.

6. CONCLUSION

To understand the kinematics of geodynamic processes as a basis for the reconstruction of the formation of structures, the use of models became inevitable. The same concept was applied here, although not performed in appropriate conditions and probably not with appropriate material. Nevertheless, concordance between the

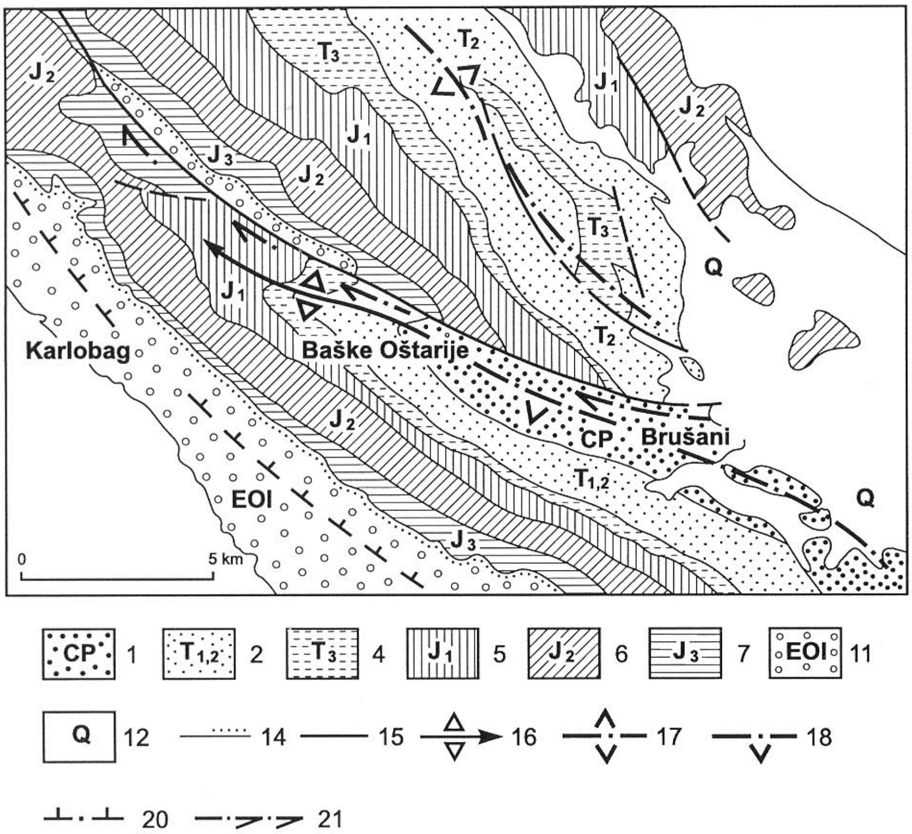


Fig. 14 Simplified geological map of the Karlobag-Baške Oštarije-Brušane area (after SOKAČ et al., 1974). For legend see Fig. 12.

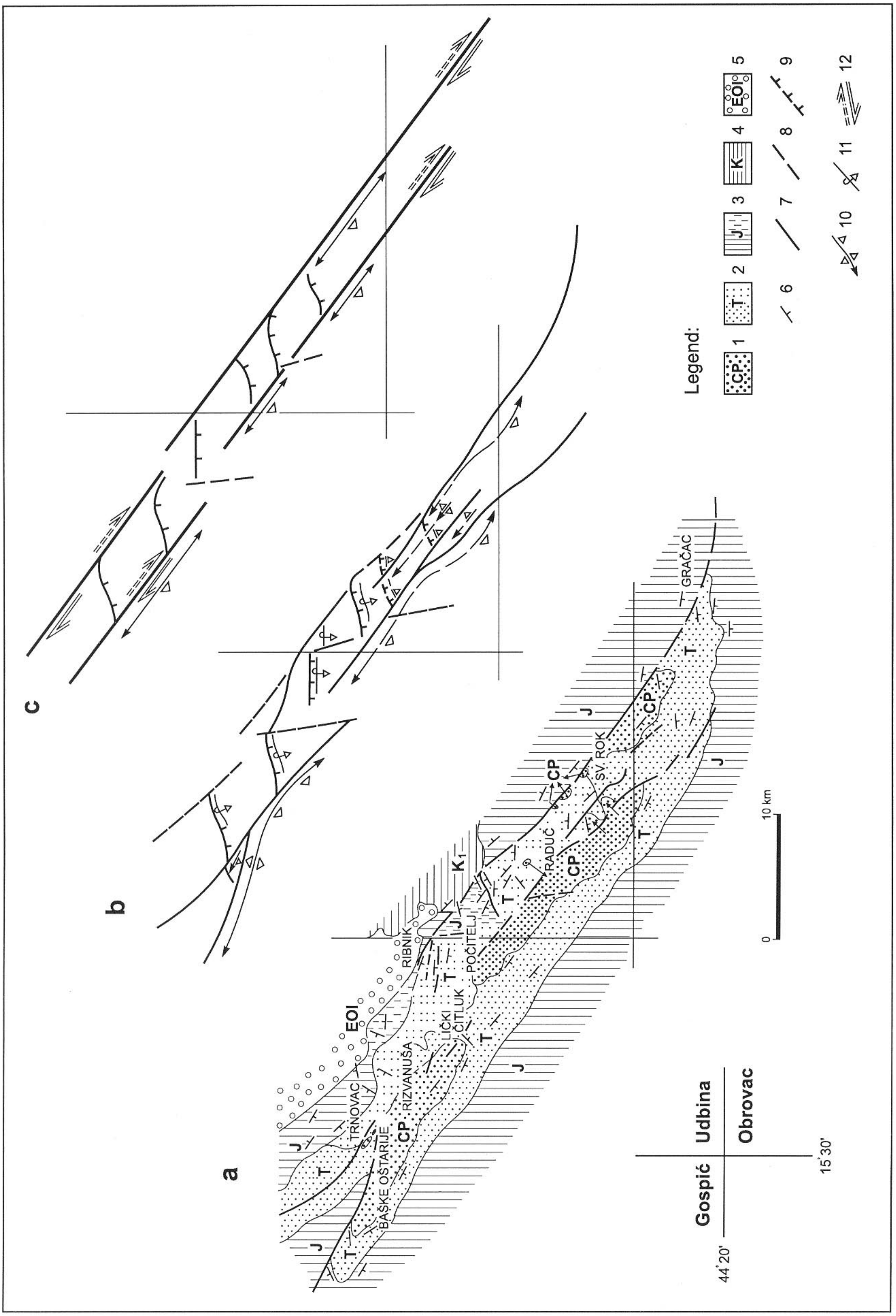
model and the recent geological setting justifies this applied procedure which produced relevant insights.

The study area, simulated by the model, is limited to the coastal zone and its hinterland, including the area from Hrvatsko primorje and Gorski kotar to Dubrovnik-Konavle and eastern Herzegovina. Geologically, the area is characterised by tangential folded and faulted structures grouped into the NW-SE striking, SW-verging structures, i.e. Dinaride-striking structures, that predominate, and the E-W striking, north- or south-verging structures, i.e. Hvar-striking structures, which are less prominent.

Two stages of kinematic processes that controlled the formation of these structures are confirmed by modelling. The first stage, related to the commencement of collision tectonics in the studied region, resulted in Dinaride-striking, southwest-verging folds, reverse faults and imbricate structures. A uniform tectonic fabric for the whole coastal belt region is reconstructed. It is composed of structural units, i.e. antiforms of Velika Kapela, Velebit, Svilaja, Mosor, Biokovo, Dubrovnik and Konavle, that are in reverse contact with a neighbouring synforms to the southwest. In many published papers this antiform-synform contact zone is interpreted as a thrust fault, marked by clastic sediments of the Jelar and Promina Formations or by contemporaneous flysch sediments of considerable thickness. It is concordant with a correspondingly dipping seismic marker boundary. Further to the southwest, i.e. in the region of Northern Dalmatia, Kvarner Islands and, especially Ravni Kotari and Istria, any indications for the occurrence of orthogonal Hvar-striking structures are missing, contrary to the neighbouring regions located to the southeast. Due to this fact, it is supposed that the main subduction contact between the Adriatic and Dinaridic geodynamic units lies within the same belt. During subsequent geodynamic processes this belt partly disintegrated and the structural relationships become more difficult to understand.

Subsequent processes that represent the next stage of structural formation, simultaneous to active collisional movement related to the primary stage, are characterised by the predominant compressive force of orthogonal refolding, i.e. re-structuring, acting along a

Fig. 15 a) Simplified structural sketch of Mt. Velebit in the area of Baške Oštarije - Gračac (after IVANOVIĆ et al., 1973; ŠUŠNJAR et al., 1973; SOKAČ et al., 1974). b) Sketch interpretation of structures according to model of orthogonal re-structuring. c) Development of transpression zones due to en-echelon system of dextral strike-slip faulting. Legend: 1) Carboniferous to Permian sedimentary rocks; 2) observed and supposed rocks of Triassic age; 3) observed and supposed location of Jurassic rocks; 4) Cretaceous carbonate rocks; 5) calcareous breccia of Jelar formation; 6) strike and dip of bedding; 7) geological boundary; 8) fault; 9) reverse fault; 10) anticline axis, and axis of anticline limb; 11) overturned anticline; 12) direction of actual and relative fault block movement.


a
b
c
Gospić
Udbina
Obrovac
44°20'
15°30'
J
T
CP
BAŠKE OŠTARIJE
TRNOVAC
RIZVANUŠA
EOl
LIČKI ČITLUK
POČITELJ
RIBNIK
K_1
RADUČ
SV. ROK
GRAČAC
0
10 km
Legend:
CP 1
T 2
J 3
K 4
EOl 5
6
7
8
9
10
11
12

direction parallel to the b-axis of primary, Dinaride-striking structures.

The primary Dinaride-striking structures experienced considerable negative dilation compensated by orthogonal refolding, reverse and strike-slip faulting. Locally, the latter resulted in transpression. All these processes led to development of orthogonal, secondary, Hvar-striking, mostly south- and north-verging structures. Distribution and arrangement of these structures within the study region are explained by the model and defined by geological, gravity and seismic explorations.

According to the presented data it can be concluded that the whole coastal region, during a complicated geodynamic process, acted as a uniform geodynamic unit. Moreover, this prevailed even after subsequently induced tectonic activity which, however, did not change the basic characteristics of previously formed structures.

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Manuscript received November 18, 1997.
Revised manuscript accepted May 18, 1998.