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The Role of Palaeogene Clastics in the Tectonic Interpretation of Northern Dalmatia (Southern Croatia)

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Key words: Palaeogene, Thrust belt, Duplex structure, Platform carbonates, Northern Dalmatia, Croatia

Abstract

The Palaeogene coarse-grained clastics of Northern Dalmatia (Jelar breccia, Promina deposits and Flysch) are syntectonic deposits related to the structural evolution of the Dinaride Thrust Belt. The Jelar breccia is a proximal sedimentary unit deposited in response to early compression of the carbonate platform (Lutetian to Bartonian). Flysch deposits are considered as their distal equivalents. The Early Jelar breccia displays a blended clast composition related to the simultaneous erosion of various carbonate stratigraphic units along the Early Velebit Fault. The Late Jelar breccia, the next tectonically generated deposit, has an inverted clast composition related to the erosion of the faulted Velebit anticline. The next tectonic phase (Bartonian to possibly Oligocene) caused folding and thrusting of underlying platform carbonates and tectonic transport, cannibalisation and reworking of the existing Flysch, Early and Late Jelar breccias. Continuing compression created a new elongated foreland basin with NW-SE extension, filled with about 2000 m of prograding Promina deposits. The final structural setting of Northern Dalmatia was the result of thrusting of the northeast edge of the Promina deposits. This produced duplexing of internal thrusts, uplift of the Promina deposits on the highest topographic position and significant erosion. This polyphase and complex tectonism can be described by a thin skin tectonic model in which Upper Jurassic - Lower Cretaceous platform anhydrites acted as a perfect gliding surface.

1. INTRODUCTION

A polymict carbonate breccia known as the Jelar breccia (BAHUN, 1963, 1974; HERAK & BAHUN, 1980) on the slopes of the Velebit Mountain, as well as the Flysch and Promina deposits in the Ravni Kotari area represent syntectonic sediments during the structural evolution of the Dinaride Thrust Belt. The regional tectonic framework is a product of Continental - Continental (C - C) collision (ROEDER, 1983), where the Dinaric plate is overriding the Adriatic plate. In such model the Ravni Kotari area belongs to the imbricated zone and the Velebit Mountain belongs to the thrust belt of Dinaric plate (Fig. 1).

The age of the earliest Flysch deposits (Middle Eocene, Bartonian, NP 17 nannofossil zone; BENIĆ, 1991) or the latest carbonate platform deposits (Late Lutetian; DROBNE et al., 1991) dates the climax of tectonic compression of the area. Stratigraphic development of the imbricated zone remarkably differs from that of the thrust belt zone, especially during Late Jurassic and Early Cretaceous time. At that time considerably thick evaporite (anhydrite) complex was deposited in Ravni Kotari (SPAJIĆ, 1990). At the same time in the thrust belt area, tectonic instability and global sea level change resulted in geomorphological differentiation of the platform (TARI KOVAČIĆ, 1990[3]; LAWRENCE et al., 1991) so that the synsedimentary carbonate breccias (IVANOVIĆ et al., 1976b; HERAK & BAHUN, 1980), platy limestone of the Lemeš trough and the juxtaposed platform carbonates were deposited.

The polyphase structural evolution of the thrust belt resulted in the simultaneous thrust generated clastic deposition, of which the composition and appearance of sediments have been used to determine the structural style of the individual tectonic events. Blending of clasts[4], unroofing of clasts[5] and cannibalisation[6] of erosional deposits on the slopes of the mountain were the main criteria used to determine the structural setting of the Velebit Mountain. The Flysch deposits are considered to be the most distal sediment of the same origin. The composition of the Promina beds undoubtedly points to the erosion and resedimentation of the Jelar breccia (BABIĆ et al., 1991[7]; BAHUN, 1974; MRINJEK, 1993a, b).

Structural and stratigraphic interpretation of the representative seismic lines in Ravni Kotari aids in the interpretation of tectonic events and structural relationships related to the development of syntectonic deposits.

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4 Blending of clasts occurs during erosion of an escarpment caused by the thrust sheet moving along the ramp.

5 Unroofing of clasts appears when the large anticline structure were affected by erosion. As the result younger clasts are predominant in the lower part, and the oldest on the top of thus formed deposits.

6 Cannibalisation is a process which involves repeated erosion of erosional deposits.

7 Unpublished study for INA Naftaplin: BABIĆ, Lj., ZUPANIČ, J. & MRINJEK, E. (1991): Uloga prelaznih marinskih i rubnih taložnih sistema s krupnozrnatim klastitima u evoluciji sedimentnih bazena paleogena u Vanjskim Dinaridima.

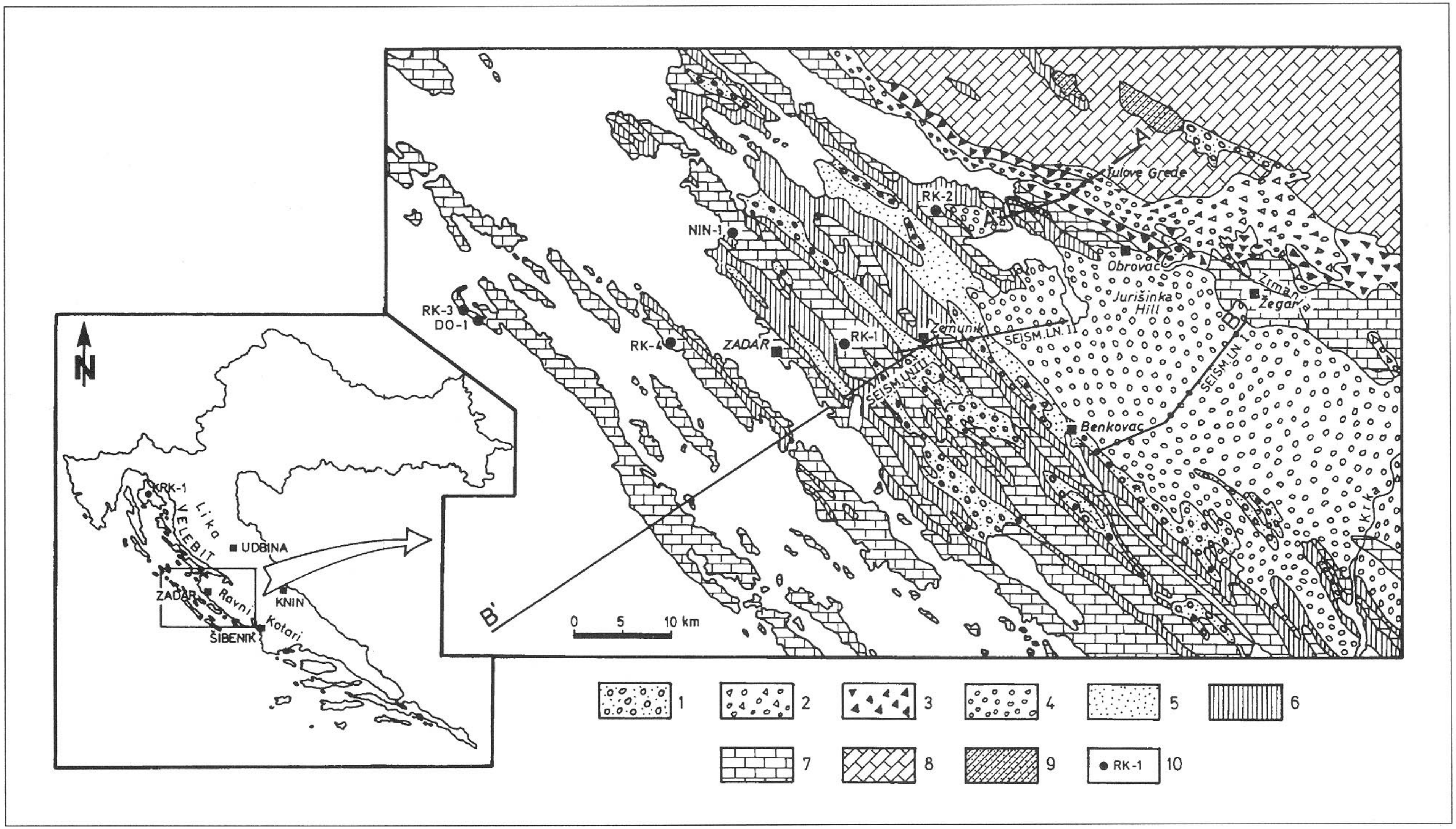

Fig. 1. Location and geology of the study area in Northern Dalmatia (adapted from Basic geologic map of SFRY, 1:500 000) showing the location of deep wells, seismic and geologic cross-sections.
1 - Quaternary; 2 - Late Jelar breccia; 3 - Early Jelar breccia; 4 - Promina deposits; 5 - Flysch; 6 - Eocene carbonates; 7 - Cretaceous carbonates; 8 - Triassic, Jurassic and Permian carbonates; 9 - Carboniferous clastics; 10 - Deep wells.

The interpretation was based on the surface geology of the surrounding area (GRIMANI et al., 1975a, b; IVANOVIĆ et al., 1976a, b; MAJCEN et al., 1970, 1973) and deep exploration wells from Ravni Kotari, the Islands and off-shore Adriatic (Fig. 1).

2. GEOLOGICAL SETTING

The tectonic model presented here is largely dependent on the stratigraphic development of the strata involved (Fig. 2). It means that the stratigraphic difference between the thrust belt (Velebit Mt.) and the imbricated zones (Ravni Kotari and islands) is mostly responsible for the striking differences between the two generated tectonic styles.

During the Permian and Lower Triassic deposition took place on the very shallow clastic shelf, where carbonate platform sedimentation occurred locally (Middle to Late Permian - TIŠLJAR et al., 1991; Early Triassic - GRIMANI et al., 1975b).

During the Middle and lowest part of the Late Triassic the "block" and "basin" differentiation was a response to regional extension. Narrow basins (TARI KOVAČIĆ, 1990[3]) stretching in line with the Dinaric structural trend were formed, in which a varying amount of pyroclastic sediments were deposited in response to local volcanic activity together with other, partly pelagic deposits. The platform carbonates were deposited on the uplifted blocks. Toward the end of the Late Triassic, the basins were filled up and an extensive carbonate platform was formed. The platform carbonates have shown a tendency to grow outward from the preexisting highs and covered at least the preexisting basin areas (TARI KOVAČIĆ, 1991[3]). The same tectonostratigraphic relationships observed in the outcrops in Dinarides are also evident in seismic cross sections (Fig. 3).

The extensive carbonate platform conditions established in the Late Triassic were retained through the Early and Middle Jurassic. A depositional balance was achieved as subsidence kept pace with sea level changes. Untill the Late Jurassic there were no significant stratigraphic differences between the thrust belt and the imbricated zone.

During the Late Jurassic the tectonic compression that started earlier (Middle Jurassic) at the eastern margin of Dinaric plate (LAWRENCE, 1990[8]) began to progress westward and was reflected in the strong differentiation of the carbonate platform. Tectonic plunge was accompanied by synchronous global sea level rise so that the uplifted parts of the platforms were locally exposed to erosion and down-faulted parts were drowned. The adjacent "Lemeš" intraplatform trough in the Lika area was generated by tectonic plunge and synchronous sea level rise (JENKINS, 1990[9]).

In Ravni Kotari and the island area a thick "evaporite" complex was discovered in deep wells RK-1, 2, 3, 4, Do-1, Nin-1, Brač-1, Vis-1 (Fig. 1), at depths greater than 1800 meters. It is composed of alternating anhydrite, rarely gypsum, stromatolitic limestone and dolomite and a great number of fault (collapse?) breccias. The evaporite has been dated as probably Late Jurassic to Early Cretaceous age (from Malmian to Albian) based on sparse fossil remains and isotope analysis (TIŠLJAR et al., 1981; ŠIFTAR, 1982; TASKER et al., 1990[10]). The sediments were deposited in subaeqous basins and rarely as sabkhas (JENKINS, 1990[9]). The large extension and considerable thickness of the evaporites are the result of synchronous tectonic readjustment of the carbonate platform. The thickness of the complex is in the range of 100 - >1200 m. In two deep wells it appears to have been tectonically repeated twice or even three times.

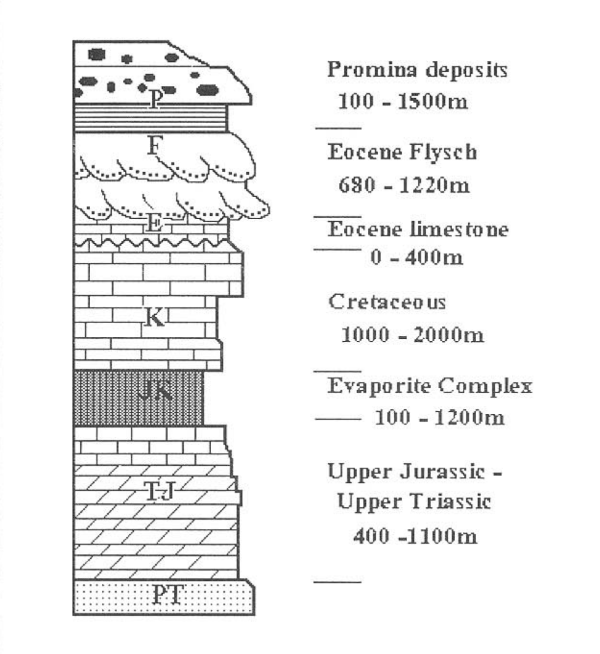

Fig. 2. A schematic stratigraphic column of Ravni Kotari, generalized and keyed to the alphanumeric simbols carried on the seismic cross sections (Fig. 3).

The evaporites are extremely significant for the entire tectonic style of the studied area. They present a decollement, a perfect gliding surface which allowed the thrust sheets composed of Cretaceous and Eocene deposits to override one another, thus creating the imbricated zone (Fig. 3) of folded and faulted structures.

In the thrust belt area where Jurassic and Cretaceous evaporites are lacking, other layers of low shear strength, for example Permian evaporites, Triassic clastics, bauxite deposits or even late diagenetic dolomites

[8] Unpublished study for INA Naftaplin: A study of the petroleum potential of the Dinarides, Croatia.

[9] Unpublished study for INA Naftaplin: A study of the petroleum potential of the Dinarides, Croatia.

[10] Unpublished study for INA Naftaplin: TASKER, R. D. et al. (1990): Final Report on the Technical Evaluation of the Dinaride Area of Croatia. AMOCO Yugoslavia Petroleum Company.

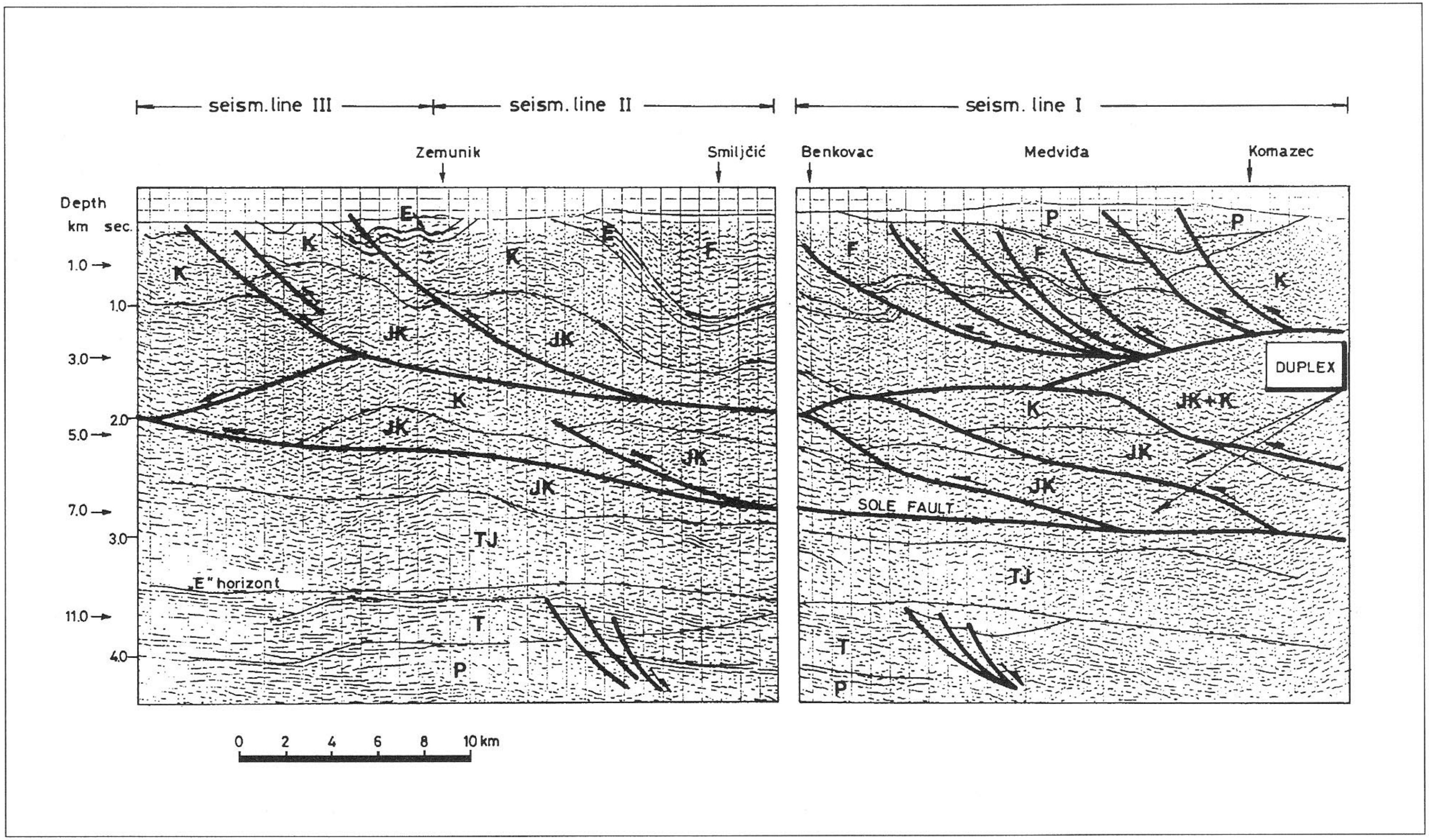

Fig. 3. A composite seismic cross section of the study area. For alphanumeric simbols see Fig. 2 (Published with permission by INA - Naftaplin, Zagreb).

(TASKER et al., 1990[10]) of more or less local extension act as gliding surfaces.

Late Cretaceous and Eocene carbonates are widely exposed in the outcrops in Ravni Kotari, and are also well known from the wells. The Late Cretaceous is characterised by oyster and rudist deposits of Cenomanian, Turonian and Senonian age (IVANOVIĆ et al., 1976; MAJCEN et al., 1973). "Oligostegina" deposits are also marked. Locally developed facies of organic rich platy limestone mark a Cenomanian and Turonian global sea level high stand.

At the end of the Late Cretaceous a major proportion of the Dinaric platform was emergent. In the studied area the period of non deposition, erosion and karstification lasted untill the Eocene. This very strong unconformity is also marked by truncated (eroded) reflectors on seismic cross sections.

Carbonate platform sedimentation was reestablished during the Early Eocene. The Cuisian mudstone - wackestone "miliolid" limestone and Lutetian "foraminifera" limestone (alveolinas, discocyclinas and nummulites) were deposited in restricted to open shelf conditions.

Toward the end of the Lutetian sedimentation on the carbonate platform was terminated by regional drowning caused by advanced tectonic compression. Deepening of the sedimentary basin resulted in the deposition of another marker bed: a nodular marly wackestone with dispersed discocyclinas, glauconite grains and increased numbers of planktonic foraminifera and terrigenous material some tens of metres thick - the so called "transitional beds" that represent the transition from platform carbonates to the Flysch deposits.

The Palaeogene Flysch was deposited in a large foreland basin (BABIĆ & ZUPANIČ, 1983; MARINČIĆ, 1981) stretching from the Gulf of Trieste to Albania. Flysch sedimentation generally prograded toward the Adriatic and was dependent on the timing of a particular phase of compression during thrust belt genesis. It varies from the Maastrichtian within the inner parts of the thrust belt (BLANCHET, 1975; CHOROWICZ, 1975; CADET, 1978) to Late Eocene (MARINČIĆ, 1981; DROBNE, 1977; DROBNE et al., 1991; BENIĆ, 1992[11]) in the Adriatic offshore. The earliest phase of compressional uplift in the Velebit area gave the rise to Flysch sedimentation in Northern Dalmatia. Proximal Flysch sequences are composed of lobe, channel and interlobe sandstone bodies with hemipelagic deposits of transverse palaeocurrent direction to the southwest (BABIĆ & ZUPANIČ, 1983). The palaeocurrent direction of the distal, fine grained Flysch sequence is parallel to the Dinaric structural trend, either to the northwest or southeast (MARINČIĆ, 1981).

Similarly along the front of the hanging wall of the Dinaric thrust belt from the Istrian peninsula to Kotor bay, especially on the slopes of Velebit and Mosor Mts., in Lika and Herzegovina a significant amount of variously dated breccia deposits occur (Fig. 4). In this paper we considered breccia deposits on the southwestern slope of Velebit Mt. which were dated as Cretaceous (IVANOVIĆ et al., 1976a, b) and Palaeogene age according to their clast composition. The breccia which contain Palaeocene (precisely Lower and Middle Eocene) clasts is called the Jelar breccia (BAHUN, 1963). So far no detailed sedimentological research has been carried out, but several published papers (BAHUN, 1963, 1974; FRITZ et al., 1978; HERAK & BAHUN, 1980; SAKAČ et al., 1993) and the regional tectonic setting allow us to interpret the Jelar breccia as the lateral and synchronous facies of the earliest Flysch deposits.

Clast composition is the most important source of information on the origin and genesis of the breccia and it's sedimentological and structural interpretation (STEIDTMAN & PAOLA, 1988). Blending of clasts suggests erosion of a prominent escarpment composed of different stratigraphic units, while the unroofing of clasts is usually the result of erosion of the extensive faulted anticline. In this article we differentiate two types of breccia, according to clast composition.

The older breccia (Fig. 1) composed of blended, heterogeneous, completely unsorted angular fragments of carbonate rocks of Triassic, Jurassic, Cretaceous and Eocene age, is called Early Jelar breccia. The most comprehensive description of these deposits is given by HERAK & BAHUN (1980). In addition to clast description they also describe the large slumps of huge blocks that locally preserve the original bedding. The contacts with older rocks and other sedimentary structures are completely hidden. The breccia is very well cemented and very hard but the cement does not yield fossils. Comprehensive sedimentological studies are required in the future, and they will hopefully answer many questions about the site of deposition and sedimentary processes. The age of the fragments is not valid in respect of chronostratigraphy so that the age of the deposits can only be relative, and heavily reliant on the structural intrerpretation.

The large escarpment in a compressive tectonic style is usually related to the movement along the ramp which is the earliest phase of tectonic compression (Fig. 7B), and what explains composite blending of clasts in a stratigraphic range from the Triassic to Eocene.

The second type of breccia is composed of the unroofed clasts eroded from the extensive Velebit anticline during the next, somewhat younger tectonic phase (Fig. 7C). We call it the Late Jelar breccia (Fig. 6). It is widely exposed in the outcrops on the western and southern flanks of Velebit Mt. The breccia is composed of Jurassic and Early Cretaceous fragments, and was therefore dated as Early to Late Cretaceous (IVANOVIĆ et al., 1976b; CHOROWICZ, 1977).

[11] Unpublished study for INA Naftaplin: Biostratigrafska sinteza klastita paleogena u Vanjskim Dinaridima na osnovu nanofosila.

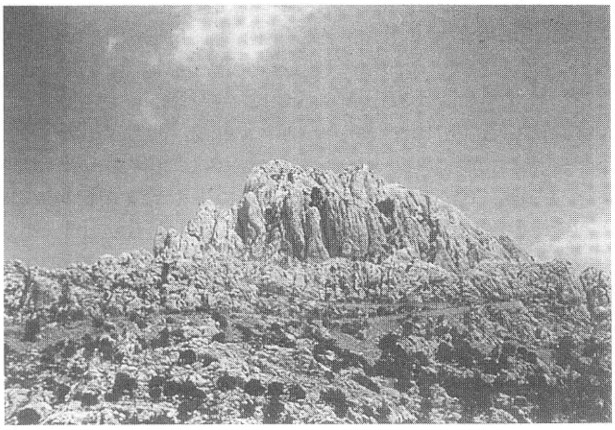

Fig. 4. Typical morphology of the Jelar breccia, Tulove Grede, Southern Velebit.

Fig. 5. Alluvial Promina deposits: Jurišinka Hill, Northern Dalmatia.

IVANOVIĆ et al. (1976b) considered breccias as the sedimentary response to local and regional tectonic disturbances of different Jurassic and Cretaceous time intervals. CHOROWICZ (1977) considered them as the result of tectonic disturbances at the "transverse" tectonic zone extending from Split to Karlovac during the Cretaceous. Clast size ranges between several millimeters and large blocks several metres in diameter. The contact between the breccias and other stratigraphic units, especially the Jelar breccia (Early Jelar breccia in this article) and Promina deposits is uncertain or completely unknown. BAHUN (1963) and HERAK & BAHUN (1980) described and interpreted the Jelar and other carbonate breccia of Velebit mountain. They considered them as the result of polyphase tangential tectonic disturbances and related them to the more distal Flysch deposits. They were the first who discussed previous opinion about the Cretaceous age and origin of the breccias. In spite of the lack of substantial field evidence they considered them as "...components of only one major lithostratigraphic complex that was formed during a single orogenic event ...occurring in several phases...". We considered those breccias to be younger than the Jelar breccia, because of clasts compositon which suggest that they were created in the next tectonic phase as the result of erosional unroofing of the extensive Velebit anticline (Figs. 7B and C).

The Promina deposits cover a vast area of Northern Dalmatia (Fig. 1). Some deposits of different age but similar site of deposition and origin in Herzegovina (DRAGIČEVIĆ et al., 1986, 1992) are also called the Promina (?formation).

The Promina deposits represent an approximately 2000 meter thick carbonate clastic succession with a clear shallowing trend from deep marine turbidites to shallow marine and alluvial deposits (IVANOVIĆ et al., 1976b; BABIĆ & ZUPANIČ, 1983) (Fig. 5). The Promina deposits either comformably overlie the Late Lutetian Flysch Formation or unconformably cover Cretaceous and Palaeogene carbonates in the internal part of Northern Dalmatia (Fig. 6). The Promina sediments are the youngest tectonically generated deposits in the area (BAHUN, 1974; BABIĆ & ZUPANIČ, 1983).

It is necessary to comment on the relationship between the Early part of the Promina deposits and the underlying Middle Eocene Flysch unit. At examined outcrops along the roads or ravines the contact between the Middle Eocene Flysch and Promina turbidites either is hidden or virtually concordant (Figs. 1 and 6). The lowest part of the Promina deposits consist mainly of classic carbonate turbidites (BABIĆ & ZUPANIČ, 1983) and olistostromes, so that local continuity of sedimentation from Flysch to Promina deposits was proposed by many authors (IVANOVIĆ et al., 1976b; BABIĆ & ZUPANIČ, 1983; BENIĆ, 1991; MAGDALENIĆ & VRSALOVIĆ-CAREVIĆ, 1968; QUITZOV, 1941). On the other hand the Flysch and lowest turbiditic unit of the Promina deposits are usually distinguished one from another although there are no clear and unique criteria. Even the earliest studies (KERNER, 1896, 1901; SCHUBERT, 1905) distinguished them from each other. KÜHN (1934, 1946) concluded that this was because of an intra-Eocene tectonic deformation (Illyrian Orogenic Phase). Today seismic results indicate that the northeastern margin of the Flysch basin underwent strong compression which caused regional uplift and strong erosion (truncation) of the Flysch deposits (Figs. 3 and 7D). Younger compressional stress created a new foredeep basin that was restricted in the West by an uplifted "island belt" and opened to the sea to the northwest and/or southeast. The topography of the basin was changed. Therefore the palaeocurrent pattern of the Promina turbidites differs from that of the Flysch deposits (BABIĆ & ZUPANIČ, 1983).

In addition to the above mentioned basal turbidite unit, the Promina deposits consist of shallow marine (BABIĆ & ZUPANIČ, 1990) and alluvial deposits (BABIĆ & ZUPANIČ, 1988; MRINJEK, 1993a, b). The major part of the Jelar breccia was eroded and resedimented in alluvial fans and braided rivers (MRINJEK, 1993b). The vertical transition from considerably deep to shallow marine, as described by

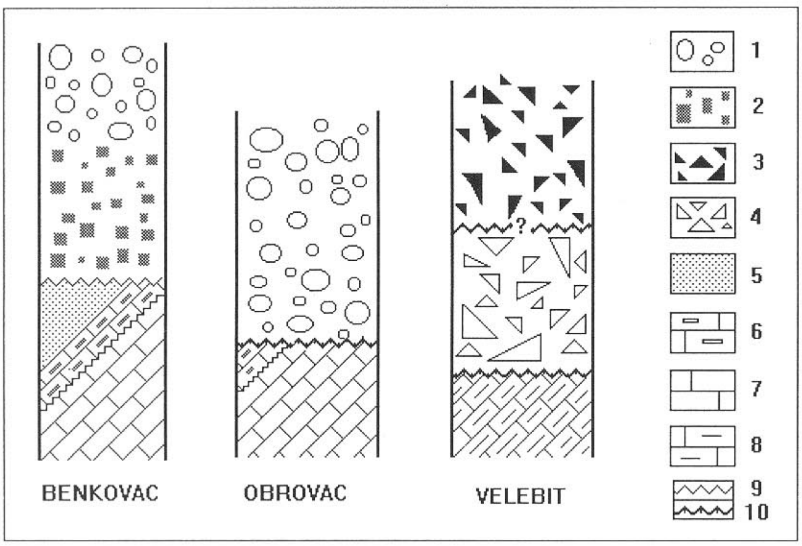

Fig. 6. Stratigraphic relationships of the Promina deposits and older deposits. 1 - Alluvial Promina deposits; 2 - Marine Promina deposits; 3 - Late Jelar breccia; 4 - Early Jelar breccia; 5 - Flysch; 6 - Foraminiferal limestone; 7 - Cretaceous carbonates; 8 - Jurassic carbonates; 9 - Submarine unconformity; 10 - Subaeral unconformity.

BABIĆ & ZUPANIČ (1990), and from braided river to alluvial fan sediments together with facies characteristics and palaeocurrent pattern suggest that these are the components of an extensive and southwestward prograding braid-delta system (MRINJEK, 1993b). According to MRINJEK (1993a, b) the alluvial Promina deposits (Fig. 5) are the result of deposition in an extensive and complex alluvial setting characterised by alluvial fans and braided rivers with a clearly developed southwestward proximal to distal trend. Since the Promina deposits display an overall upward prograding trend and have the thrusted and faulted hinterland, the evolution of the Promina deposits can be explained by repeated and progressive thrusting to the southwest during the Late Eocene and Oligocene that also gave rise to periodic rejuvenation and southwestward tectonic transport of the source area.

The older palaeontological data (IVANOVIĆ et al., 1976b) dated the age of the Flysch deposits as late Middle Eocene, based on planktonic and large foraminifera (*Nummulites*, *Discocyclina*). A recent study (BENIĆ, 1991) also dated the oldest Flysch deposits as belonging to the NP-16/17 nannofosil zone (Bartonian). Since the carbonate turbidites and shallow marine limestone represent the lateral (distal) equivalent of the continental deposits the age of the Promina deposits could be considered to be the same as the age of the turbidites. According to the nannofossil analysis (BENIĆ, 1991) it is of nannofossil zone NP 18 - 20 or slightly younger, i. e. Late Eocene and Lowest Oligocene.

After this time, erosion and non deposition took place over the entire area, with the exception of extraneous lacustrine and fluvioglacial deposits (MARJANAC, 1992[12]) of Miocene and Pleistocene age.

[12] Unpublished study for INA Naftaplin: Sedimentološko-stratigrafska istraživanja naslaga neogena i kvartara Vanjskih Dinarida.

3. INTERPRETATION OF SEISMIC LINES IN RAVNI KOTARI AREA

In Ravni Kotari and some other areas in the Dinarides several seismic lines were shot in 1988 (Fig. 1). Seismic line I extends toward the northeast from Benkovac to Žegar. The other two lines, II and III, were shot along the road from Zemunik to Karin (Fig. 1). The latter are tied together, but there are no ties to the first line so that the grid does not allow complete control over the entire area. All the lines are perpendicular to the Dinarides and give reliable information about tectonic events and structural relationships involved in the Dinaric thrust belt beneath the Promina deposits.

Interpretation of seismic lines relies heavily on the surface geology of the surrounding area (i.e. the closest outcrops, particularly of Triassic and Jurassic rocks). RK-1, RK-2, RK-3, RK-4, Nin-1, Dugi Otok-1 and ten more wells from islands and the off-shore Adriatic provide useful additional data for in-depth determination of the geological setting (Fig. 1). The sedimentary thickness of expected stratigraphic units as estimated from well data and published stratigraphic columns (GRIMANI et al., 1975a; IVANOVIĆ et al., 1976a; MAJCEN et al., 1970) is shown in Fig. 2.

The same tectonostratigraphic relationships of Triassic deposits recognized at outcrop are also obvious in the seismic cross sections. Beneath seismic horizon E (Fig. 3) which is also known as "the Base of the carbonates", depositional patterns reflect the stretching and rifting of Pangea as a half graben/tilted block geometry during the Middle Triassic. Seismic facies (frequency/amplitudes/continuity of the seismic signals) of all deposits above E horizon (Mesosoic and Tertiary carbonates) except the Tertiary clastics involved carbonate deposits that are of Late Triassic, Jurassic, Cretaceous and Eocene age.

In almost all the Adriatic offshore and onshore seismic lines, as well as in the studied area the "E" horizon is present as one or more strong, very deep seismic reflectors at the depth of 3.0 to 4.0 Ms (Fig. 3). With regarding to their seismic character, and adhering to stratigraphic thicknesses they are recognized as the ?Middle Permian unconformity, Middle Triassic (probably Anisian clastics) and/or Ladinian-Carnian clastics and evaporites. According to the structural analysis and geological interpretation (LAWRENCE et al., 1991; TASKER et al., 1990[10]) an erosional unconformity can be recognized between the Permian and Triassic deposits, as well as a rifting event (listric faulting and graben infill) of Early to Middle Triassic age (Fig. 3). It is obvious that the Triassic clastics are not involved in thrust sheets above the basal detachment (Jurassic and Cretaceous anhydrite). On the other hand, according to the well data (Nin-1, Brač-1, RK wells and others), Cretaceous carbonates and anhydrite, and in places Eocene carbonates were tectonically repeated.

The Tertiary clastic Flysch deposits that are carried within imbricated structures are good indicator of the structural style of the topmost thrust sheet. Beside them the unconformity between Cretaceous and early Eocene limestones and between Flysch and Promina deposits are also good reflectors, found only in the topmost thrust sheet (Fig. 3).

The results of seismic interpretation indicate a substantial amount of shortening in particular by thrusting. Cretaceous and younger units are overthrusted one another to the southwest. The decolement for the thrusts is interpreted as the Early Cretaceous and/or Late Jurassic evaporites (TASKER et al., 1990[10]). The compressive tectonic style apears to be restricted exclusively to the portion of the sediments above basal detachment, with the underlying units remaining relatively undisturbed. These relationships have lead us to use a "thin skin"[13] tectonic model in our interpretation of the structural evolution of the area.

4. DISCUSSION

The sedimentary response to tectonic events is very obvious, especially in the upper thrust sheets. Following the rule of "stacked trays" (LOWEL, 1987) the upper sheet is the oldest one, so it should be covered with sediments that were created mainly as a sedimentary response to the tectonic stress. The earliest compression phase (Fig. 7B) along the Early Velebit fault created "Cretaceous" and Jelar breccias as proximal facies and Flysch deposits as their distal equivalent.

The Jelar breccias outcropping on the southwestern slope of Velebit Mt. (Fig. 1) are the product of blending of carbonate clasts of Jurassic, Cretaceous and Eocene age. The rocks of the source area were simultaneously eroded as they passed up and over the ramp along the Early Velebit Fault (Fig. 7B). The Early Jelar deposits are therefore the oldest tectonically generated unit which is a sedimentary response to the initial phase of the Velebit thrusting.

The next tectonically generated deposits are related to the folding and early faulting of the Velebit anticline (Fig. 7C). The outcrops are marked on Fig. 1 as Late Jelar breccia. It is composed of Jurassic and predominantly Cretaceous limestone clasts. We consider them to be younger than the Early Jelar breccia, related to the steep-dipping, predominantly vertical uplift of Velebit's hanging wall, when Mesozoic carbonate rocks on the basinward limb of the leading edge of anticline were sequentially eroded. This conclusion finds support in the very similar surface appearance of a Cretaceous breccia on the island of Krk, where unroofing or inverted clast stratigraphy is documented in the deep exploratory well Krk-1 (Fig. 1). It should be mentioned that unroofed sequences are characteristic strictly of the colluvial and alluvial fan deposits, because in more distal, braided river and marine environments, clast composition is blended by fluvial or wave/current processes. The breccias are from the same source as the majority of Middle Eocene Flysch deposits in the Adriatic on-shore and off-shore areas. The age of this phase is determined by the age of the Flysch deposits - Late Lutetian and Bartonian, nannofossil zone NP 16 - 17 (BENIĆ, 1991).

Folding and thrusting of Cretaceous and Eocene limestones and Late Eocene Flysch, as well as the Early and Late Jelar breccias were the result of the next phase of compression (Fig. 7D). Advanced compression produced a new sedimentary basin in front of the uplifted blocks in the northeast, and ended with uplift and significant erosion toward the end of the Eocene. The palaeotopographic low, probably a single elongated depression trending NW-SE, was partly restricted from the open sea to the southwest, but open to the northwest and southeast. It was filled with alluvial and marine sediments known as the Promina deposits. In the North of Dalmatia the age of the Promina turbidites is Late Eocene (Priabonian) and these do not belong to the same sedimentary basin as the Middle Eocene Flysch deposits. Alluvial beds of the youngest Promina sequences are the youngest sediments exposed on the surface. The final structural setting and present day geomorphologic outlook of the Northern Dalmatia terrain was caused by duplexing of internal thrusts (Figs. 3 and 7E).

Significant erosion and the recent position of the Promina deposits in the most elevated parts of the area reflect advanced tectonic compression in younger, i.e. lower thrust sheets. This compressional stress seems to be quite young. Although the quality of reflection data is rather poor, duplex structures can be recognized beneath the topographic high on the surface (Fig. 3). The large anticlinorium of the Cretaceous and Eocene limestones on seismic line III (Figs. 1 and 3) was

[13] Thin skin is described in BATES & JACKSON (1987) as the term used by RODGERS (1963) for an interpretation that folds and faults of miogeosincline and foreland rocks in an orogenic belt (thrust belt and foreland) involve only certain amount of Late strata and lie on the decollement, beneath which the structure differs. It is also called No Basement Interpretation.

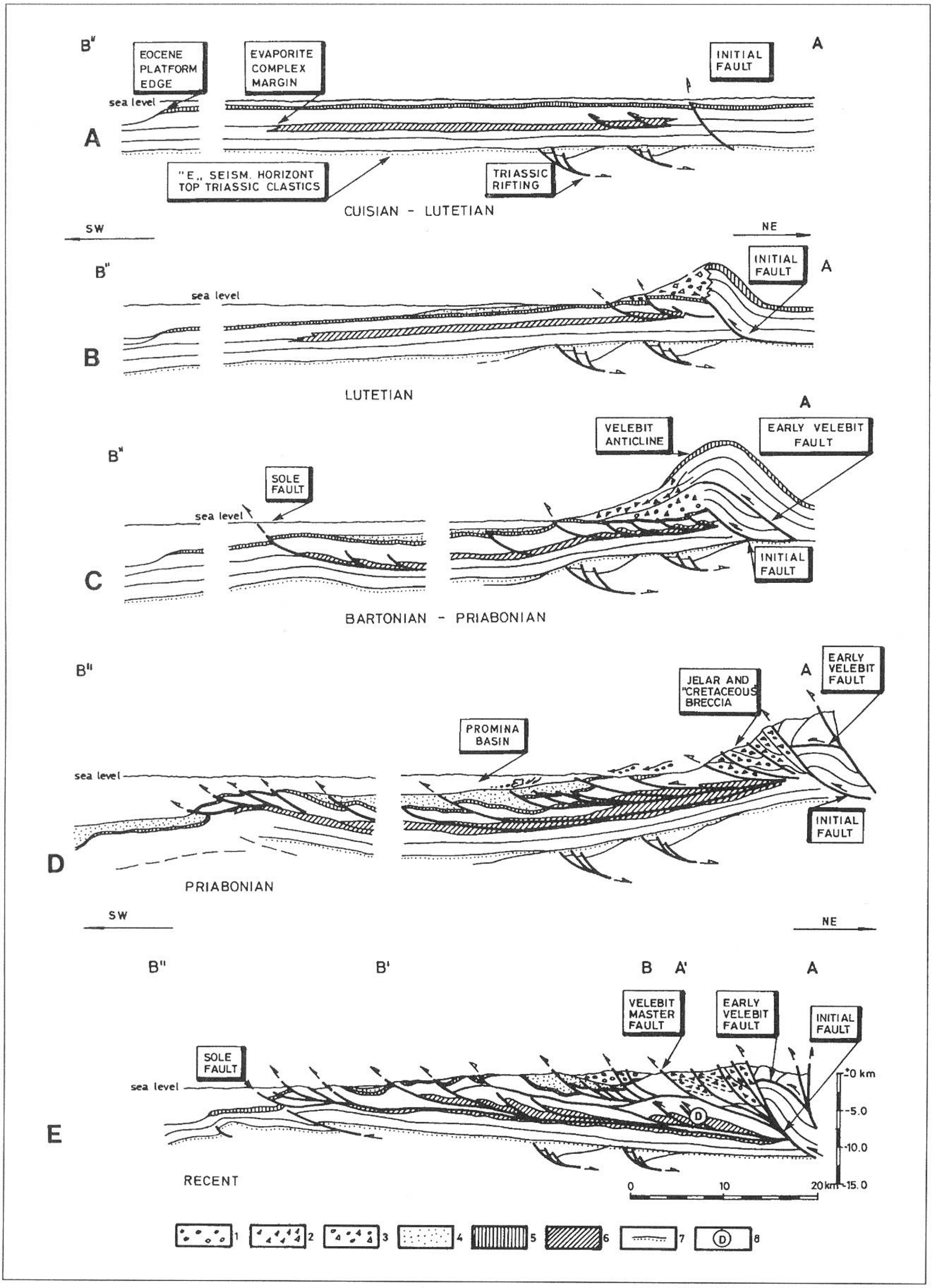

Fig. 7. Tectonic evaluation of Velebit Mt. and Ravni Kotari. 1 - Promina deposits; 2 - Early Jelar breccia; 3 - Late Jelar breccia; 4 - Middle Eocene Flysch; 5 - Eocene limestone; 6 - Evaporite complex - Late Jurassic-Early Cretaceous; 7 - Top Triassic clastics or base of Mesozoic carbonate platform, seismic horizon "E"; 8 - Duplex structure. A - Early and Middle Eocene (Cuisian-Lutetian, older than nannofossil zone NP-16); B - Middle Eocene (Lutetian, NP-16); C - Middle-Late Eocene (Bartonian-Priabonian, NP 16-17); D - Late Eocene (Priabonian, NP 18-20) or some younger.

formed by the same events, but probably responded to the next, slightly younger tectonic phase.

Following the rules of clast dispersion (STEIDTMANN & SCHMITT, 1988) the Jelar and Promina deposits may be seen as synthetic tectogenic sediments, where the direction of sedimentary transport was the same as the tectonic transport.

For major thrust the time of thrusting youngs in the direction of tectonic transport (LOWEL, 1987). Therefore the clastic wedge sediments associated with older thrust are commonly uplifted on the hanging wall of the younger thrust. During the next tectonic event the advancing tectonic compression resulted in folding and faulting of the previously formed blended and unroofed clasts dispersal sequences - in our case Early and Late Jelar breccia deposits (Fig. 7C).

Based on the field observations from infrequent outcrops (IVANOVIĆ et al., 1976; BABIĆ & ZUPANIČ, 1983) carbonate turbidites of the Promina deposits seem to be comformable on the Middle Eocene Flysch. Flysch deposits formed in the foredeep during the initial compressional stress (Fig. 7), and were folded and faulted together with the Cretaceous and Eocene limestones at the time of major tectonic compressive stress (Lutetian to Priabonian) when the Early Velebit Fault was active. At the same time in the Ravni Kotari area thrusting occurred in the Late Jurassic and Early Cretaceous carbonate over the anhydrite decollement.

The Promina basin was formed as the result of the same phase of tectonic compression. The west and south east edges of the basin were drowned and the north-east edge was uplifted as shown by the presence of bauxite. Seismic lines definitely show that the Promina basin is a completely different sedimentary realm, undisturbed by folding or reverse faulting. Turbidites of both units are virtually concordant on the surface, because their environment did not change in spite of the strong tectonic phase that separated them. They both represent rather distal and deep marine deposits. Palaeogeographic reconstruction (MRINJEK, 1993a, b) suggests that the Promina basin was an isolated basin filled with partly marine, partly alluvial deposits. Advanced tectonic stresses provided a supply of sediments so that the alluvial deposits prograded and filled the basin.

The final structural setting and the present day geomorphological outlook of the Ravni Kotari terrain are the result of duplexing of internal thrusts beneath the Promina basin. That compressional stress seems to be quite young. As the result the Promina deposits were uplifted to the highest topographic position which also resulted in significant erosion.

5. CONCLUSIONS

Tectonic consideration of a large area and the timing of tectonic activities involves a certain amount of speculation. We would like to point out such evidence as would support the structural interpretation of chosen seismic lines.

1. Early Cretaceous - Late Jurassic evaporites (mainly anhydrite) are identified only in deep wells (RK-1, RK-2, RK-4, DO-1, Nin-1, Brač-1, Vis-1) at depths from 1800 to 3700 m, ranging in thickness between 100 and 1200 meters, and repeated twice or three times in very deep Brač-1 and Nin-1 wells. Such structural appearance of evaporites is evident in seismic lines and leads to the conclusion that major topographic highs of the Cretaceous-Eocene anticlines over the entire area are caused by duplexing of early thrusts.

2. The Jelar breccia and the Flysch deposits are the syntectonic deposits and the timing of their depossition is related to the structural evolution. Their compossition aid in the interpretation of the structures

3. Blending of clasts is common in the Jelar breccias and Promina conglomerates. For the Jelar breccia this indicates erosion of a large escarpment caused by ramping. For the Promina deposits cannibalisation of early breccias took place.

4. Unroofing of the Late Jelar breccia should be the object of detailed sedimentological studies. At the moment this speculation was inferred from the scarce field description and evidence about unroofing of similar "Cretaceous" breccia outcrops on the island of Krk. Also in the lowest portion of the 1500 m thick breccia complex in Krk-1 well there are predominant limestone particles of the Eocene age. The Late portion of the complex consists almost exclusively of the Cretaceous clasts.

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