Adriatic Carbonate Platform-- Insights in External and Internal Dinaridic Units

5th to 9th of July 2016

FIELDTRIP GUIDEBOOK

Supported by:

AAPG
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Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia
National Park Northern Velebit, Croatia

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1. Geologic overview of Adriatic Carbonate Platform (AdCP)

The Adriatic Carbonate Platform (AdCP, **Fig. 1**) represents Mesozoic carbonate platform of the Perimediterranean region with the carbonate succession that in places reach c. 8000 m (**Fig. 2**) and ranges in age from the Middle Permian (or even Upper Carboniferous) to the Eocene (Vlahović et al., 2005). With an area of 80-200 km wide and nearly 700 km long, this carbonate succession nowadays is incorporated within the Dinaridic mountain belt uplifted during Paleogene and Neogene (similar as Southern Alps, Albanides, Hellenides and Taurides) as a part of External Dinaridic unit (Croatian Karst) along the Adriatic sea. In the same time sediments deposited along the AdCP passive and active continental margin, including ophiolites, are incorporated within the Internal Dinaridic units, a broad zone between the External Dinarides and Dinarides and the Pannonian Basin (Velić et al., 2003).

Sedimentary sucession of the AdCP begins with Carboniferous to Middle Triassic siliciclastic–carbonate deposits accumulated along the Gondwanian margin, on a spacious epeiric carbonate platform. With regional Middle Triassic volcanism connected with continental rifting and tectonic activity, isolated carbonate Southern Tethyan Megaplatform with the area of the future AdCP was formed (Vlahović et al., 2005). As a result, trough Middle/Late Triassic to Lower Jurassic AdCP was considerably extended, characterized by mostly continious shallow-marine carbonate deposition including Upper Triassic Hauptdolomit and Lower Jurassic limestones (e.g. Lithiotid limestone). Beside AdCP, during the middle to late Early Jurassic carbonate Southern Tethyan Megaplatform was dismebered into several other carbonate platforms (e.g., Apenninic and Apulian) isolated by deeper marine areas (e.g., Adriatic Basin, Ionian and Belluno basins, Lagonero Basin, and Slovenian and Bosnian troughs) (Vlahović et al., 2005). Common characteristic of these Mesozoic carbonate platforms was dominant shallow-marine carbonate deposition due to gradual subsidence, with periods of emergence due to either synsedimentary tectonics or eustatic changes (Vlahović et al., 2005). Environments ranged from peritidal through shallow subtidal–lagoons, restricted inner platform shallows, high-energy tidal bars, beach and shoreface to reefal–perireefal areas, with carbonate slope deposits in the areas of drowned platform and intraplatform troughs (Tišljar et al., 2002).

Besides active tectonic processes that formed shallow intraplatform trough (e.g. Gorski kotar and Knin area), dominant shallow-marine depositional rates were influenced by environment energy and global events, i.e., anoxic events (OAE- see Valhović et al., 2005 and references therein), which resulted in specific lithotype deposition and depositional cycles from high energy oolitic limestones to heavily bioturbated limestones. As a result, during the 125 My of the AdCP's existence trough Late Triassic, Jurasic and Cretaceous the thickness of deposited limestone and dolostone reached between 3500 and 5000 m.

The end of AdCP deposition was characterized by regional emergence trough Late Cretaceous and the Palaeogene with synsedimentary, compressional tectonic deformations which yielded deposition of in rudist rich carbonates Late Cretaceous in age and Eocene foraminiferal limestone with flysch depositon in newly formed flysch basins. (**Fig. 2**; Vlahović et al., 2005). The final tectonic uplift of the Dinarides commenced in Oligocene-Miocene (Dinaric phase of the Southern Alps; see Schmid et al. for details) with formation of thrust nappe systems, e.g., Dalmatian Zone and High Karst Unit (see **Fig. 5**) and deposition of clastic-carbonate sediments i.e., Promina marls, calcarenites, and conglomerates and Jelar i.e. Velebit carbonate breccias, and other strata features that could be found in areas of Italy, Slovenia, Bosnia and Herzegovina, Montenegro, and Albania (**Fig. 1**).

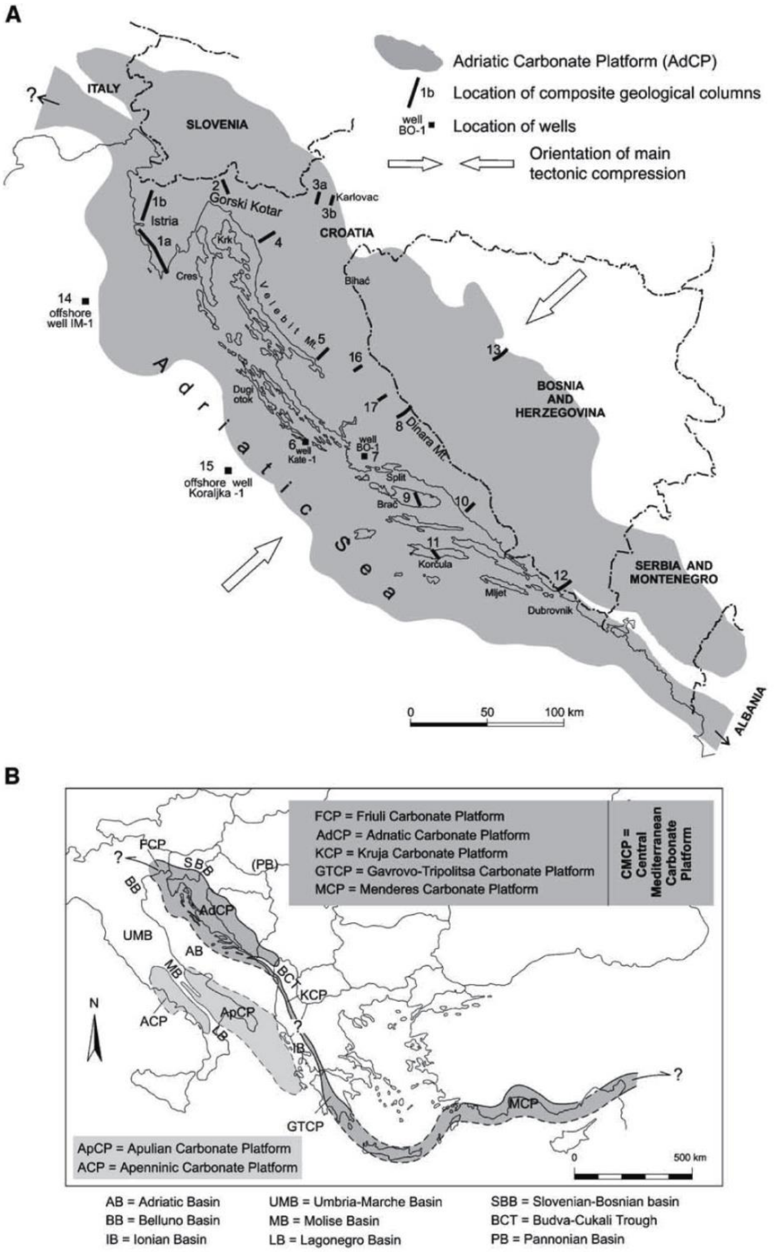
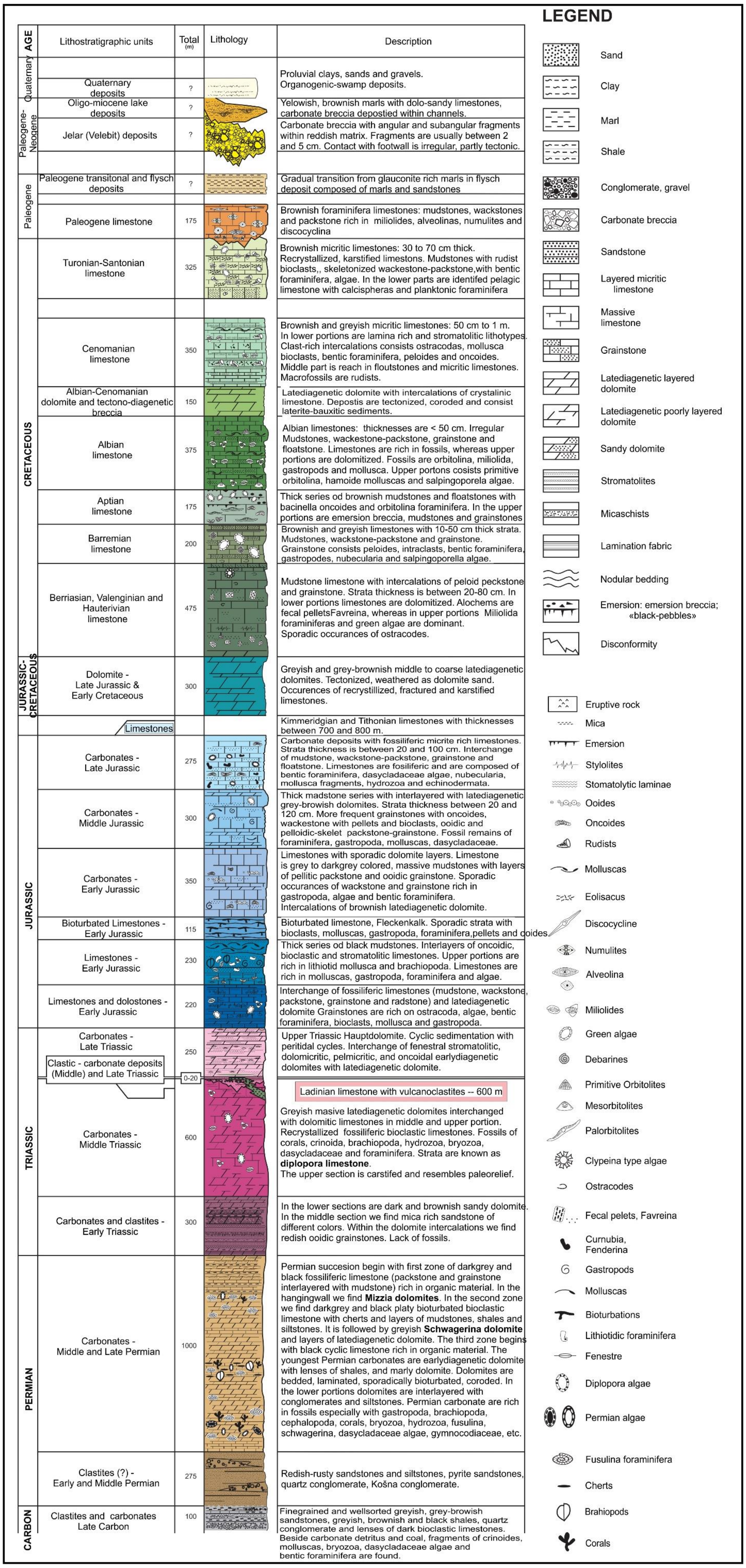


Fig. 1. A. Location map of recent Adriatic Carbonate Platform. B. Recent carbonate deposits in the central Mediterranean (after Vlahović et al., 2005)



AGE	Lithostratigraphic units	Total (m)	Lithology	Description
Quaternary	Quaternary deposits	?		Proluvial clays, sands and gravels. Organogenic-swamp deposits.
Paleogene-Neogene	Oligo-miocene lake deposits	?		Yelowish, brownish marls with dolo-sandy limestones, carbonate breccia depostied within channels.
	Jelar (Velebit) deposits	?		Carbonate breccia with angular and subangular fragments within reddish matrix. Fragments are usually between 2 and 5 cm. Contact with footwall is irregular, partly tectonic.
Paleogene	Paleogene transitonal and flysch deposits	?		Gradual transition from glauconite rich marls in flysch deposit composed of marls and sandstones
	Paleogene limestone	175		Brownish foraminifera limestones: mudstones, wackstones and packstone rich in miliolides, alveolinas, numulites and discocyclina
CRETACEOUS	Turonian-Santonian limestone	325		Brownish micritic limestones: 30 to 70 cm thick. Recrystallized, karstified limestons. Mudstones with rudist bioclasts,, skeletonized wackestone-packstone,with bentic foraminifera, algae. In the lower parts are identifed pelagic limestone with calcispheras and planktonic foraminifera
	Cenomanian limestone	350		Brownish and greyish micritic limestones: 50 cm to 1 m. In lower portions are lamina rich and stromatolitic lithotypes. Clast-rich intercalations consists ostracodas, mollusca bioclasts, bentic foraminifera, peloides and oncoides. Middle part is reach in floutstones and micritic limestones. Macrofossils are rudists.
	Albian-Cenomanian dolomite and tectono-diagenetic breccia	150		Latediagenetic dolomite with intercalations of crystalinic limestone. Depostis are tectonized, coroded and consist laterite-bauxitic sediments.
	Albian limestone	375		Albian limestones: thicknesses are < 50 cm. Irregular Mudstones, wackestone-packstone, grainstone and floatstone. Limestones are rich in fossils, whereas upper portions are dolomitized. Fossils are orbitolina, miliolida, gastropods and mollusca. Upper portons cosists primitive orbitolina, hamoide molluscas and salpingoporela algae.
	Aptian limestone	175		Thick series od brownish mudstones and floatstones with bacinella oncoides and orbitolina foraminifera. In the upper portions are emersion breccia, mudstones and grainstones
	Barremian limestone	200		Brownish and greyish limestones with 10-50 cm thick strata. Mudstones, wackstone-packstone and grainstone. Grainstone consists peloides, intraclasts, bentic foraminifera, gastropodes, nubecularia and salpingoporella algae.
	Berriasian, Valenginian and Hauterivian limestone	475		Mudstone limestone with intercalations of peloid peckstone and grainstone. Strata thickness is between 20-80 cm. In lower portions limestones are dolomitized. Alochems are fecal pelletsFavreina, whereas in upper portions Miliolida foraminiferas and green algae are dominant. Sporadic occurances of ostracodes.
JURASSIC-CRETACEOUS	Dolomite - Late Jurassic & Early Cretaceous	300		Greyish and grey-brownish middle to coarse latediagenetic dolomites. Tectonized, weathered as dolomite sand. Occurences of recrystillized, fractured and karstified limestones.
	Limestones			Kimmeridgian and Tithonian limestones with thicknesses between 700 and 800 m.
JURASSIC	Carbonates - Late Jurassic	275		Carbonate deposits with fossiliferic micrite rich limestones. Strata thickness is between 20 and 100 cm. Interchange of mudstone, wackstone-packstone, grainstone and floatstone. Limestones are fosiliferic and are composed of bentic foraminifera, dasycladaceae algae, nubecularia, mollusca fragments, hydrozoa and echinodermata.
	Carbonates - Middle Jurassic	300		Thick madstone series with interlayered with latediagenetic grey-browish dolomites. Strata thickness between 20 and 120 cm. More frequent grainstones with oncoides, wackestone with pellets and bioclasts, ooidic and pelloidic-skelet packstone-grainstone. Fossil remains of foraminifera, gastropoda, molluscas, dasycladaceae.
	Carbonates - Early Jurassic	350		Limestones with sporadic dolomite layers. Limestone is grey to darkgrey colored, massive mudstones with layers of pellitic packstone and ooidic grainstone. Sporadic occurances of wackstone and grainstone rich in gastropoda, algae and bentic foraminifera. Intercalations of brownish latediagenetic dolomite.
	Bioturbated Limestones - Early Jurassic	115		Bioturbated limestone, Fleckenkalk. Sporadic strata with bioclasts, molluscas, gastropoda, foraminifera,pellets and ooides
	Limestones - Early Jurassic	230		Thick series od black mudstones. Interlayers of oncoidic, bioclastic and stromatolitic limestones. Upper portions are rich in lithiotid mollusca and brachiopoda. Limestones are rich in molluscas, gastropoda, foraminifera and algae.
	Limestones and dolostones - Early Jurassic	220		Interchange of fossiliferic limestones (mudstone, wackstone, packstone, grainstone and radstone) and latediagenetic dolomite Grainstones are rich on ostracoda, algae, bentic foraminifera, bioclasts, mollusca and gastropoda.
TRIASSIC	Carbonates - Late Triassic	250		Upper Triassic Hauptdolomite. Cyclic sedimentation with peritidal cycles. Interchange of fenestral stromatolitic, dolomicritic, pelmicritic, and oncoidal earlydiagenetic dolomites with latediagenetic dolomite.
	Clastic - carbonate deposits (Middle) and Late Triassic	0-20		
	Carbonates - Middle Triassic	600		Ladinian limestone with vulcanoclastites -- 600 m Greyish masive latediagenetic dolomites interchanged with dolomitic limestones in middle and upper portion. Recrystallized fossiliferic bioclastic limestones. Fossils of corals, crinoida, brachiopoda, hydrozoa, bryozoa, dasycladaceae and foraminifera. Strata are known as **diplopora limestone**. The upper section is carstifed and resembles paleorelief.
	Carbonates and clastites - Early Triassic	300		In the lower sections are dark and brownish sandy dolomite. In the middle section we find mica rich sandstone of different colors. Within the dolomite intercalations we find redish ooidic grainstones. Lack of fossils.
PERMIAN	Carbonates - Middle and Late Permian	1000		Permian succesion begin with first zone of darkgrey and black fossiliferic limestone (packstone and grainstone interlayered with mudstone) rich in organic material. In the hangingwall we find **Mizzia dolomites**. In the second zone we find darkgrey and black platy bioturbated bioclastic limestone with cherts and layers of mudstones, shales and siltstones. It is followed by greyish **Schwagerina dolomite** and layers of latediagenetic dolomite. The third zone begins with black cyclic limestone rich in organic material. The youngest Permian carbonates are earlydiagenetic dolomite with lenses of shales, and marly dolomite. Dolomites are bedded, laminated, sporadically bioturbated, coroded. In the lower portions dolomites are interlayered with conglomerates and siltstones. Permian carbonate are rich in fossils especially with gastropoda, brachiopoda, cephalopoda, corals, bryozoa, hydrozoa, fusulina, schwagerina, dasycladaceae algae, gymnocodiaceae, etc.
	Clastites (?) - Early and Middle Permian	275		Redish-rusty sandstones and siltstones, pyrite sandstones, quartz conglomerate, Košna conglomerate.
CARBON	Clastites and carbonates Late Carbon	100		Finegrained and wellsorted greyish, grey-browish sandstones, greyish, brownish and black shales, quartz conglomerate and lenses of dark bioclastic limestones. Beside carbonate detritus and coal, fragments of crinoides, molluscas, bryozoa, dasycladaceae algae and bentic foraminifera are found.

Fig. 2. Shematic geological column with Paleozoic, Mesozoic and Cenozoic sedimentary sequences of AdCP.

2. Geodynamic evolution of Adria micorplate

The Alpine-Carpathian-Dinaridic orogenic system that encircles the Pannonian Basin System, is a part of a much larger Circum-Mediterranean orogenic system (**Fig. 3**). This orogenic system comprises tectonic units derived from paleogeographic domains of the Adriatic microplate, European continental plate and Neotethys Ocean that are incorporated into thrust systems of different polarity (Schmid et al., 2008; Ustaszewski et al., 2008). The Western and Eastern Alps, and Carpathians thrust systems face the European foreland, while the Southern Alps, and Dinaridic thrust systems face the Adriatic foreland (Ustaszewski et al., 2008).

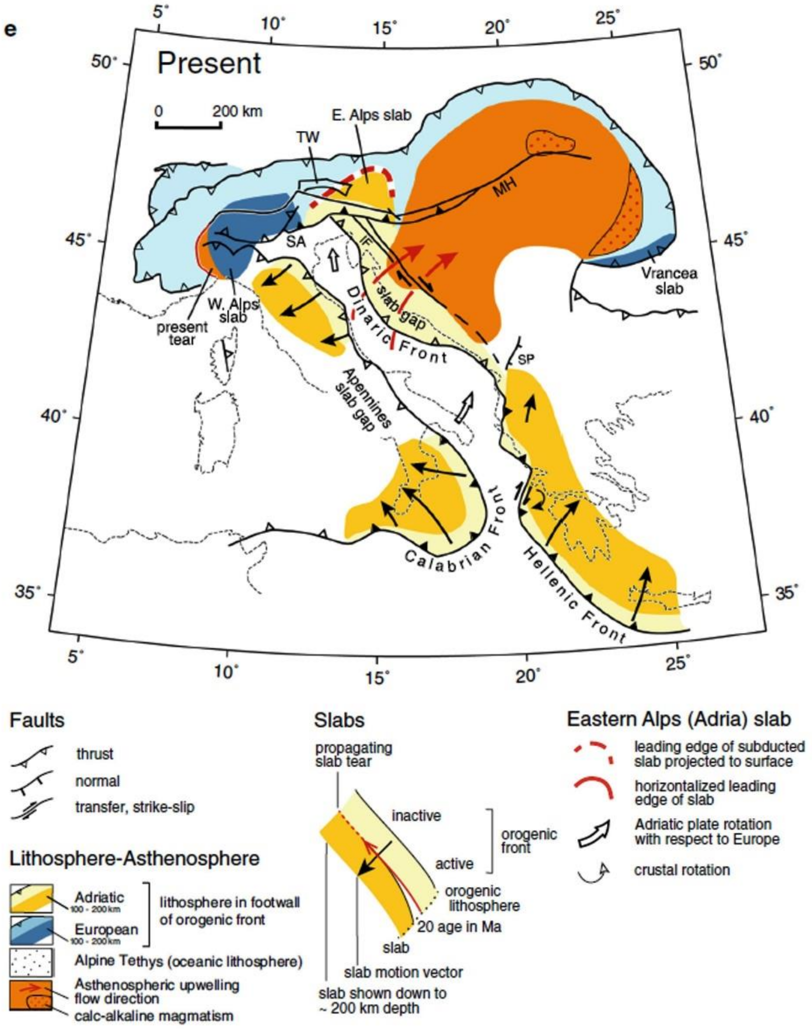


Fig 3. Northward subduction of Adriatic lithosphere beneath Eastern Alps and shortening of the Pannonian Basin. Arrows indicate mantle flow. (after Handy et al., 2014)

This opposing structural facing is caused by change in subduction polarity between the European plate and Adriatic Microplate that is composed of Adriatic and the Apulian carbonate platforms (Schmid et al., 2008; Ustaszewski et al. 2008, and references therein). The tectonic evolution of these large orogenic systems started with the Triassic (c. 220 Ma) opening of the Neotethys oceanic embayment between the African and Eurasian Plates (**Fig.**

4a, Schmid et al., 2004, 2008). The NW part of the Neotethys, also known in literature as the Meliata-Maliac Ocean (Channell and Kozur, 1997; Stampfli et al., 1998; Stampfli and Borel, 2004, and references therein) continued to spread during the Late Triassic and Early to Mid-Jurassic. The opening of the central Atlantic Ocean initiated at the end of the Early Jurassic (Favre and Stampfli, 1992; Schmid et al., 2008) and its easternmost branches of the Alpine-Carpathian Tethys, i.e. the Piemont-Liguria and Ceahlau-Severin oceanic domains (**Fig. 4b**) led to the onset of the closure of the Neotethys in the Western Vardar oceanic domain as indicated by ophiolite obduction onto the eastern margin of the Adriatic Microplate (Schmid et al., 2008). Ophiolitic units that were obducted during the Middle Jurassic are well exposed in the Central Dinaridic Ophiolite Zone of Bosnia and Herzegovina and on ”inselbergs” in NW Croatia (Mt. Medvednica, Mt. Ivanščica, and Mt. Kalnik, **see Fig. 5** e.g. in Pamić et al., 2002; Babić et al., 2002; Slovenec and Pamić, 2002; Lugović et al., 2007; Slovenec and Lugović, 2008, 2012; Tomljenović et al., 2008). According to Schmid et al. (2008), some parts of the Neotethys Ocean, the Eastern Vardar oceanic domain remained open and evolved into a back-arc basin during the Cretaceous period (**Fig. 4c**; e.g. Ustaszewski et al., 2009).

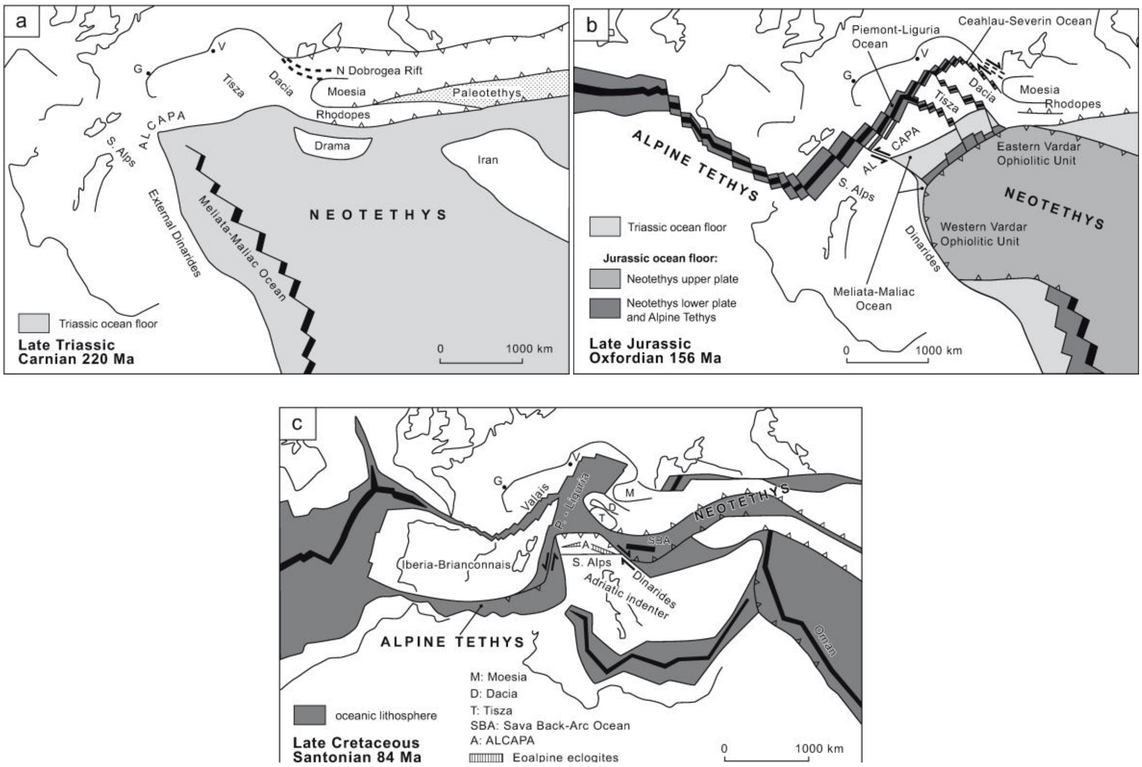


Fig. 4. Shematic palinspastic reconstruction of geodynamic evolution of European and African continents (after reconstruction presented by Schmid et al. , 2008 and references therein) visualizing distribution of oceanic and continental areas in a) Late Triassic (Carnian, 220 Ma), b) Late Jurassic (Oxfordian, 156 Ma) , and c) Late Cretaceous time (Santonian, 84 Ma).

The final closure of this paleooceanic realm commenced in the Late Cretaceous–Early Paleogene (Schmid et al., 2008; Ustaszewski et al., 2008, 2009). During the Middle Eocene and Oligocene the Eastern Vardar oceanic closure resulted in a regional E-W oriented compression leading to the Westerly directed thrusting of the Tisza MegaUnit over the Internal Dinarides (**Fig. 5**, Schmid et al., 2008; Ustaszewski et al., 2008). This tectonic event established structural relations between the tectonic units of Tisza Mega-Unit and the

Internal Dinarides that are characterized by Westerly directed reverse faults, and the Tisza Mega-Unit being in a higher structural position in relation to the Internal Dinarides (**Fig. 5**).

Continuous covergence between the Adriatic Microplate and the European plate in the Late Oligocene-Early Miocene (recent convergence rate between Adria indenter and Europe is ≤ 4.17 mm/yr according to Bennett et al. 2008) further resulted in the formation of thrust systems in the Alps and Dinarides (**Fig. 6;** Vlahović et al., 2005), and c. 400 km easterly directed extrusion of the ALCAPA block (including the Eastern Alps, West Carpathians and Transdanubian ranges north of Lake Balaton, see for details in Tari et al., 1999; Csontos and Vörös, 2004). The easterly extrusion of these units was mostly accommodated by the orogen-parallel transcurrent Periadriatic Fault that extended into the Mid-Hungarian Fault Zone further to the east (**Figs. 3 and 5;** e.g. Fodor et al., 1998; Tomljenović and Csontos, 2001) as a result of slab retreat of the subducted European plate beneath the Inner Carpathians and active extension of the back-arc-type in the Pannonian Basin (Royden and Horváth, 1988; Ratschbacher, 1991, Ratschbacher et al., 1991; Frisch et al., 1998; Fodor et al., 1998; Horváth et al. 2006; Cloetingh et al. 2006; Schmid et al., 2008). Furthermore, this lateral escape and extrusion affected the northern passive continental margin of Adriatic carbonate platform, i.e. Internal Dinarides (see Vlahović et al. 2005 for details) bounded by the Mid-Hungarian and the Periadriatic–Balaton lines where up to 100° of clockwise rotation recorded by paleomagnetic data (Tomljenović, 2002; Tomljenović et al., 2008) was interpreted. Consequently, these structural fragments of the Internal Dinarides rotated from their original NW "Dinaridic strike" into the present day NE to E-W strike aligned with the Periadriatic and Mid-Hungarian shear zone (**Figs. 5)**.

2.1. Present day stress field

By comprising a large database of earthquake focal mechanisms and slip vectors produced by a high-sensitivity seismic monitoring network, borehole breakout analysis, *in situ* stress measurement and GPS measurement data in the area of the PBS and the surrounding orogens, there is possibility to address and understand the relationship between neotectonics, surface processes and recent litospheric dynamics (**Fig. 7**, Cloetingh et al., 2006; Bada et al., 2007).

The Europe-Africa subduction and collisional zones with their associated back-arc basins of the Mediterranean system represent a region of complicated and prominent short-scale stress perturbation (**Fig. 7**, Bada et al., 2007). These prominent horizontal stress field perturbations are caused by an active N-ward to NNE-ward directed convergence between the stable Europe and the independently moving Adriatic Microplate with convergence rates of between 3 and 4.5 mm/year (**Fig. 8**; Grenerczy et al., 2005). During the Miocene and recent times the Adriatic Microplate behaved as a rigid block and was considered to be the driving force for horizontal shortening and significant seismic activity in deformation zones along the boundaries (Anderson and Jackson, 1987; Grenerczy et al., 2005; D'Agostino, 2008; Jamšek Rupnik, 2013).

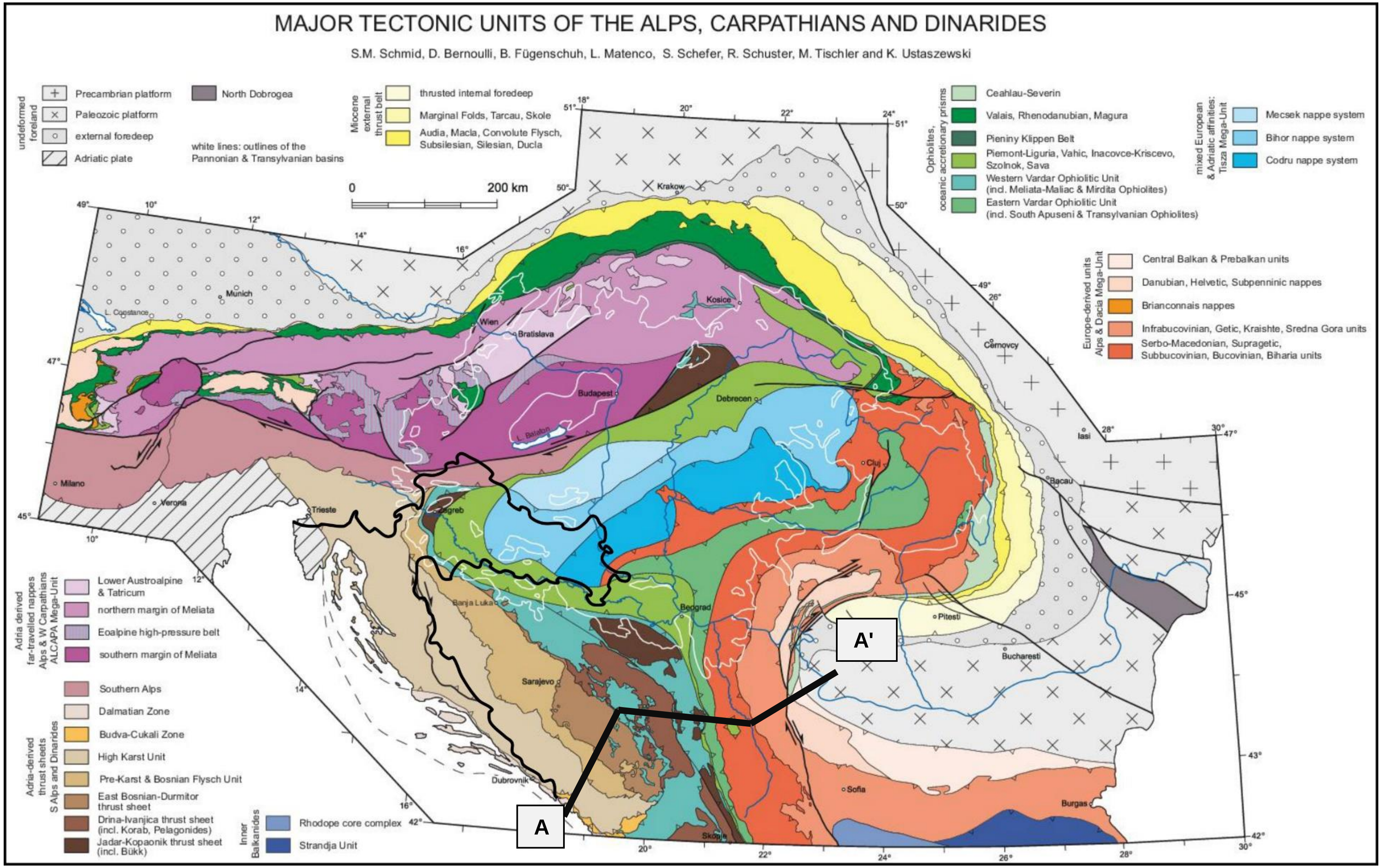


Fig. 5. Geotectonic units of Alps, Carpathians, Dinarides and Pannonian Basin System. See **Fig. 6** for profile (after Schmid et al., 2008)

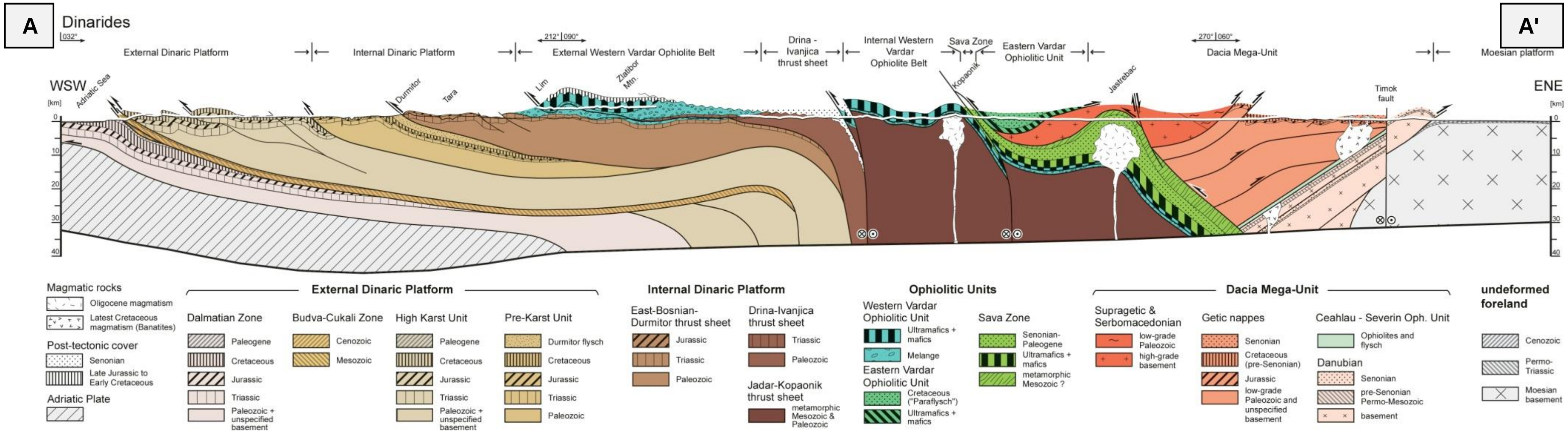


Fig. 6. Schematic cross sections across the Dinarides, External and Internal Vardar Ophiolite Belt, Drina Ivanjica trust sheet, Sava Zone, and Dacia Mega-Unit (after Schmid et al., 2008)

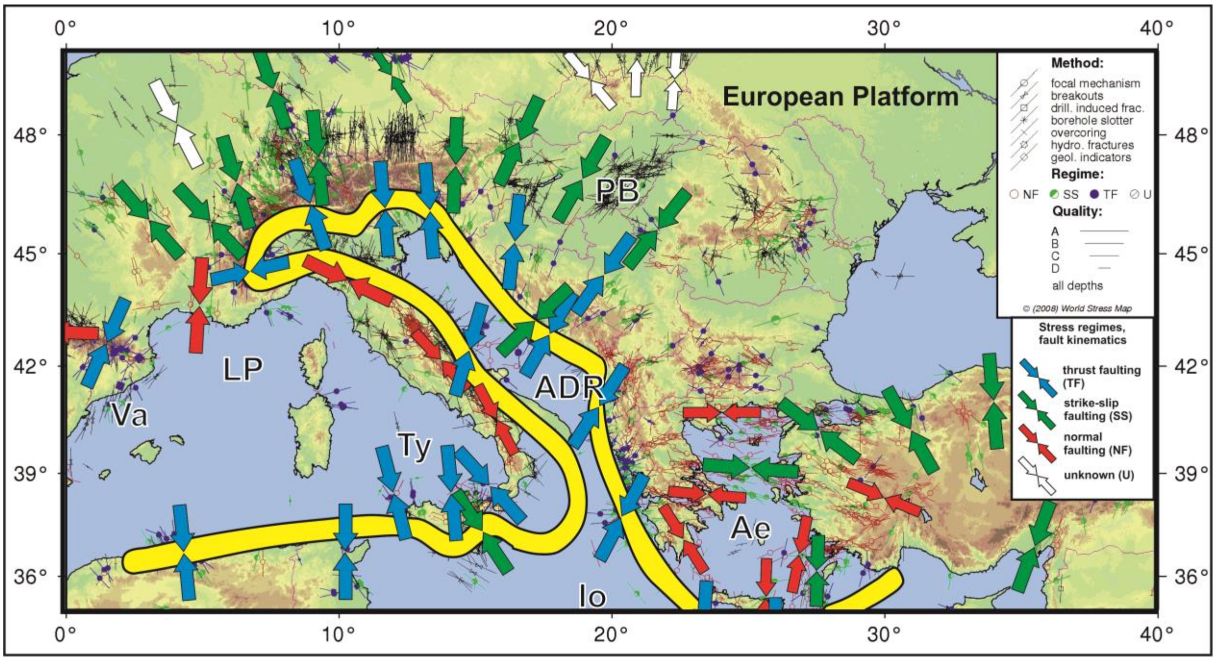


Fig. 7. Present-day maximum horizontal stress directions (Sh_{max}) and tectonic regimes in the Europe-Africa subduction and collisional zone (after Reinecker et al., 2005; Bada et al., 2007; Heidbach et al., 2008). The yellow zone indicates the Adria Microplate (ADR) boundary. Abbreviations: Ae-Aegean sea, Io-Ionian Sea, Ty-Tyrrhenian basin, LP-Liguro-Provençal basin, Va-Valencia trough, PBS-Pannonian Basin.

The total convergence between Adria indenter and stable Europe is partitioned in collisional zones of (**Fig. 8**): i) Adriatic Microplate-Eastern Alps and complementary Alpine-North Pannonian unit by 2-3 mm/yr, ii) Adriatic Microplate and Central Dinarides by 1-1.5 mm/year near shore and 2 mm/year spreading across the Dinarides, and iii) 1-2 mm/year is transferred as far-field intra-plate stresses within the weak Pannonian lithosphere (Grenerczy et al., 2000; Grenerczy et al., 2002; Grenerczy et al., 2005). Distribution of seismicity, inverted GPS site velocities, change in Euler vector, and earthquake slip vectors were used by D'Agostino et al. (2008) who also suggest that the Adriatic Microplate is fragmented into a northern (Adria) and a southern (Apulia) section separated by the Gargano-Dubrovnik seismic zone (**Fig. 8).**

The Pliocene - Quaternary tectonic evolution of the AdCP and surrounding Pannonian Basin System is characterized by compression and transpression (Horváth and Tari, 1999; Dolton, 2006), whereas build-up of intra-plate stresses within the Pannonian lithosphere is associated to the present NE-ward translation and counterclockwise rotation of the Adria Microplate that converged with the Alpine orogenic belt (**Figs. 6** and **8**; Gerner et al., 1999; Márton et al., 2003; Márton et al., 2005; Grenerczy et al., 2005; Pinter et al., 2005; Jarosinski et al., 2006; Ustaszewski et al., 2008; Jarosinski et al., 2011). According to Bada et al. (2007) and Jarosinski et al. (2011) this is caused by complete consumption of the subducted lithosphere of the European foreland and the detachment of the subducting slab in the Carpathians (**Fig. 6**) that ultimately caused the PBS to become locked and subjected to a compressional stress field with varying stress orientations.

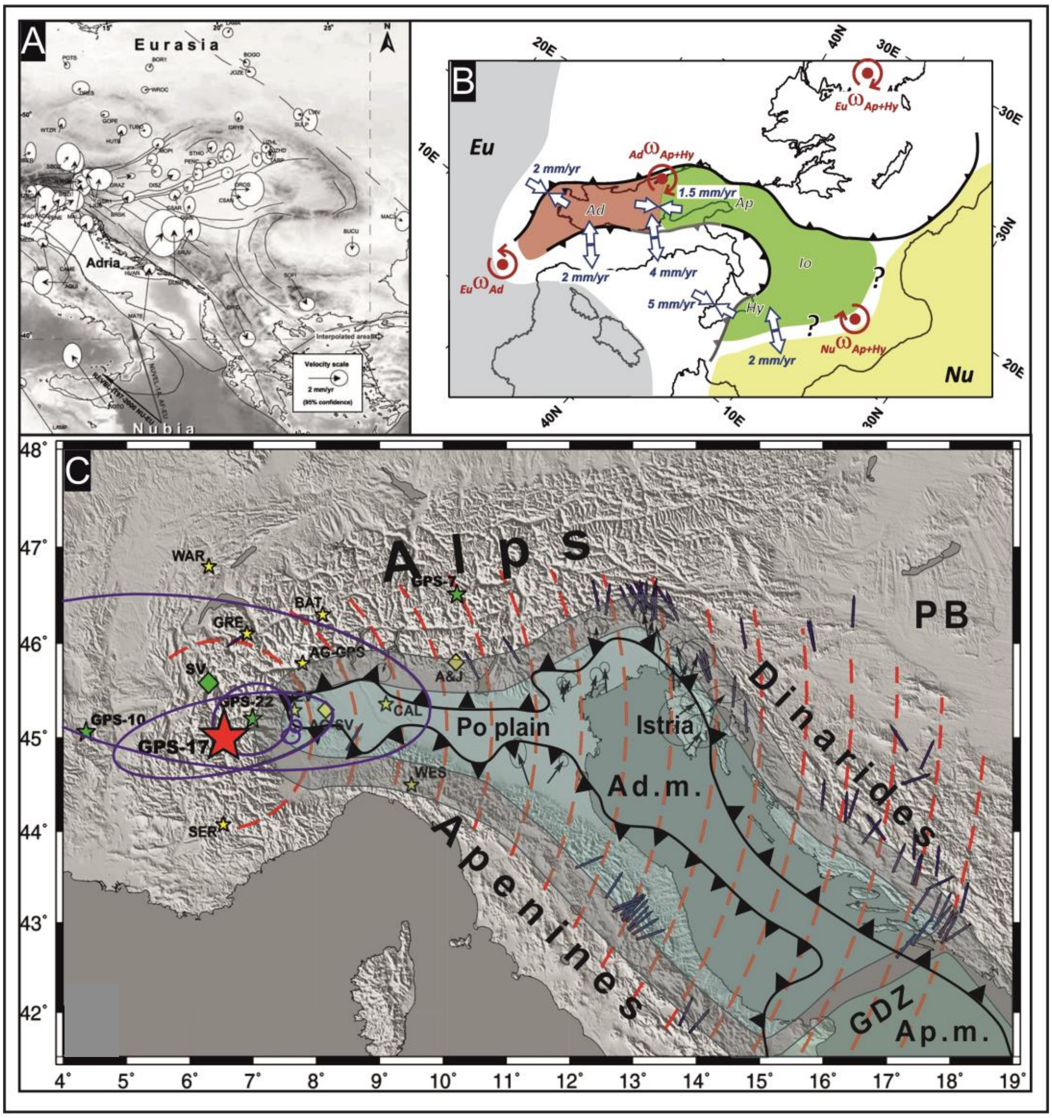


Fig. 8. A) GPS velocities with respect to Eurasia (after Grenerczy, 2002; Grenerczy et al., 2005). B) Seismotectonic sketch of the Adria Microplate subdivision (Ad-Adria, Ap-Apulia) with regional directions and deformation rates of shortening and extension (after D'Agostino et al., 2008). C) Summary figure with observed GPS site velocities and Adria Microplate Euler pole (GPS-17) used in the study of Weber et al. (2010). The dark grey zone indicates the Adria Microplate boundary. Abbreviations: Ad.m.-Adria Microplate, Ap.m.-Apulia Microplate, GDZ-Gargano-Dubrovnik deformation zone, PBS-Pannonian Basin System.

The Euler pole of the counterclockwise rotating Adriatic Microplate located in the Western Alps by e.g. Anderson and Jackson (1987), Calais et al. (2002), Oldow et al., (2002) has been recently confirmed by Weber et al. (2010) as 45.03°N and 6.52°E (**Fig. 8**, pole GPS-17) that is furthermore characterized by angular velocity vectors of 0.297 ± 0.116°/Ma. Besides those stresses that directly propagate from Adria through the Dinarides far into the PBS, the significant stress transfer occurred due to "Adria push" that was achieved by dextral strike-slip motions and pure thrusting south of the Periadriatic Line and Mid-Hungarian fault zone. This process resulted in the Pliocene and Quaternary structural inversion of the inherited structural trends in the PBS (Grenerczy et al., 2005; Reinecker et al., 2005; Bada et al., 2007; D'Agostino et al., 2008; Jarosinski et al., 2011; Jamšek Rupnik, 2013).

The present-day horizontal stress pattern (S_{Hmax}) in the PBS is shown by heterogeneous stress indicators, mainly through borehole breakout and fault plane solutions data, which suggest that the alignment of compression and the trend of the principal maximum stress axis changes gradually from NNW-SSE to N-S in the Southern, central - Eastern Alps, respectively, and finally into NNE - SSW to NE - SW in the Dinarides and SW part of the PBS (**Fig. 9**; Bada et al., 1999; Bada et al 2007; Herak et al., 2009).

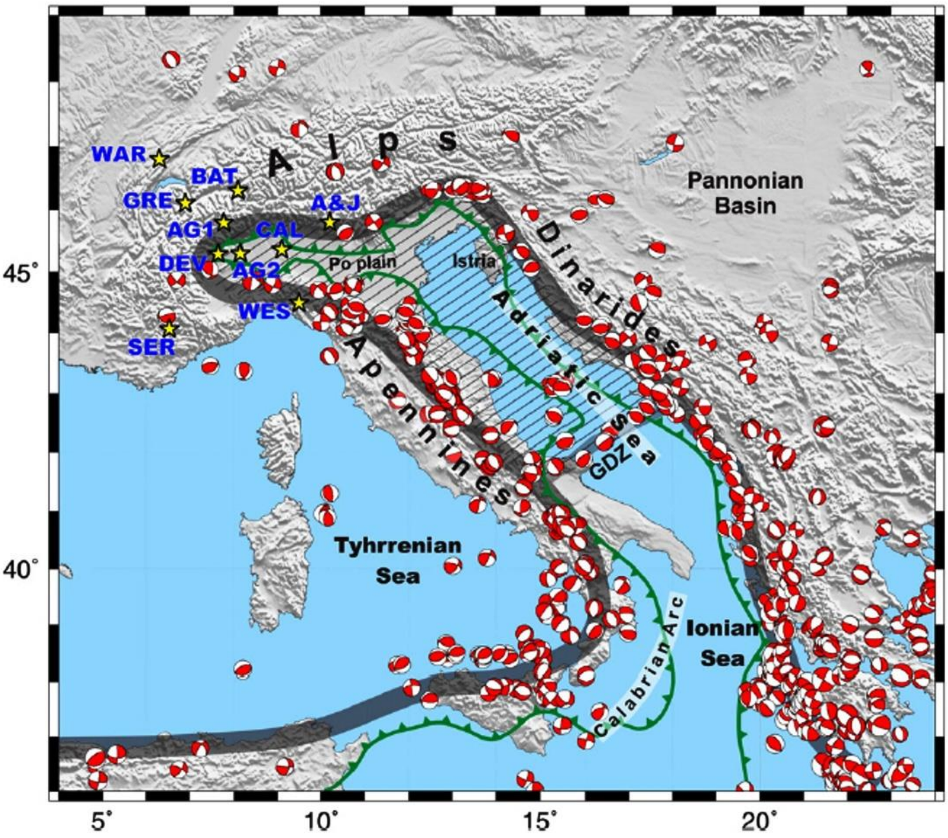


Fig. 9. Circum-Adriatic topography with seismicity and earthquake focal mechanisms taken from the Italian CMT dataset (1976–2008) and the European-Mediterranean RCMT database (1997–2008). The heavy grey lines separate the Adriatic microplate from possible additional microplates (not shown) and Nubian (African) lithosphere to the south, and Eurasian lithosphere to the north, east, and west. The Gargano–Dubrovnik zone (GDZ) is southern boundary of the Adriatic microplate. Green line shows deformed (thrust) margin front around Adriatic region. Yellow stars depict published locations of Adria–Eurasia Euler poles (after Weber et al., 2010, and references therein).

3. Hydrocarbon domains of Croatia

From the petroleum geology point of view, the territory of Croatia can be divided into three hydrocarbon domains: the **Pannonian Basin**, **Dinaridic fold and thrust belt** onshore, and the **Adriatic Basin** offshore (**Fig. 10**).

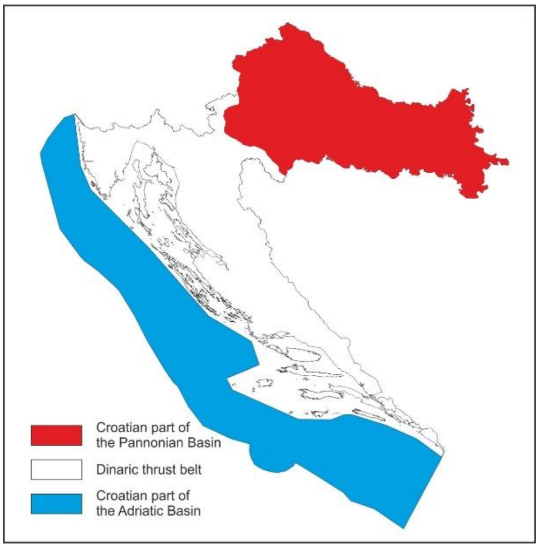


Fig. 10. Hydrocarbon provinces within the Croatian territory

The majority of the country's hydrocarbon production, both oil and gas, is derived from the Pannonian Basin, with the producing fields found across four depressions (**Fig. 11**). In the Adriatic Basin, only natural gas has been discovered and the production areas are concentrated in the northern part of the Adriatic Sea (**Fig.12**).

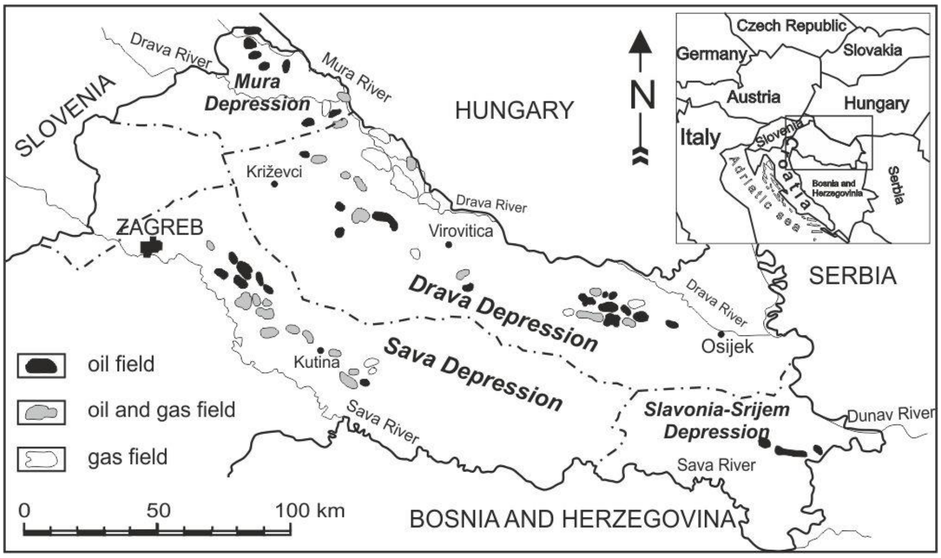


Fig. 11. Location of oil and gas fields within the Croatian part of the Pannonian Basin (after Velić, 2007)

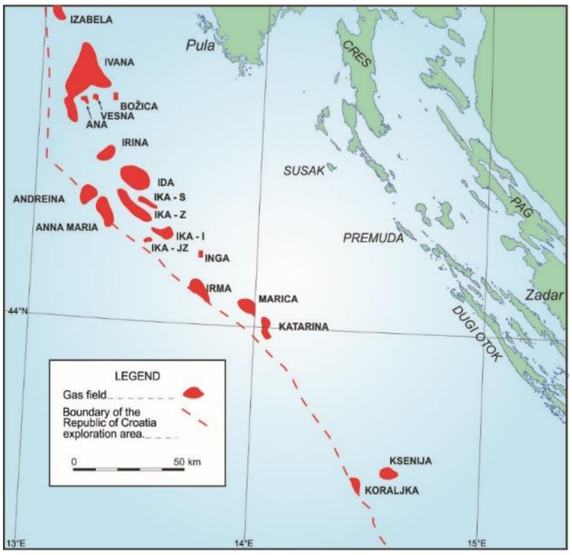


Fig. 12. Location of gas fields within the Croatian part of the Adriatic Basin (after Velić et al., 2015)

Confirmed hydrocarbon plays in the Pannonian basin area are restricted to the Neogene-Quaternary infill although hydrocarbon accumulations can be found in the pre-Neogene basement rocks but the hydrocarbons themselves come from the Miocene source rocks. The whole Neogene-Quaternary infill can be up to 7000 m thick in the Drava Depression and over 5000 m in Sava Depression (Saftić et al., 2003). These two depressions have the most significant hydrocarbon volumes discovered and exploited up to date in the Croatian part of the Pannonian Basin. Schematic lithology, position of the hydrocarbon reservoirs, source rocks, depositional environments and tectonic events that resulted in the geological settings can be observed in Figure 13.

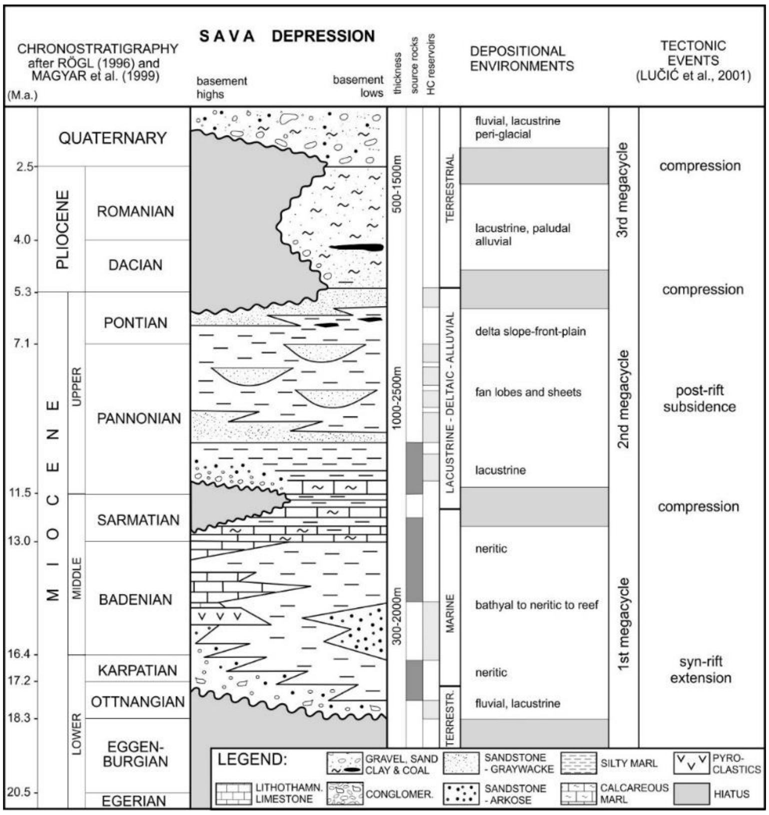


Fig. 13. Schematic stratigraphic column of the Sava Depression (Saftić et al., 2003)

In the Dinaridic thrust fold and trust belt there are no confirmed hydrocarbon accumulations, whereas in the Croatian Part of the Adriatic Basin, only the biogenic methane accumulations of Pliocene-Pleistocene age were successfully exploited. Nevertheless, there are several intervals with proven source rocks onshore and offshore. Stratigraphy, lithology, petroleum system elements and hydrocarbon shows and accumulations in the Northern Adriatic offshore and in the Southern Adriatic offshore are shown in Figures 14 and 15.

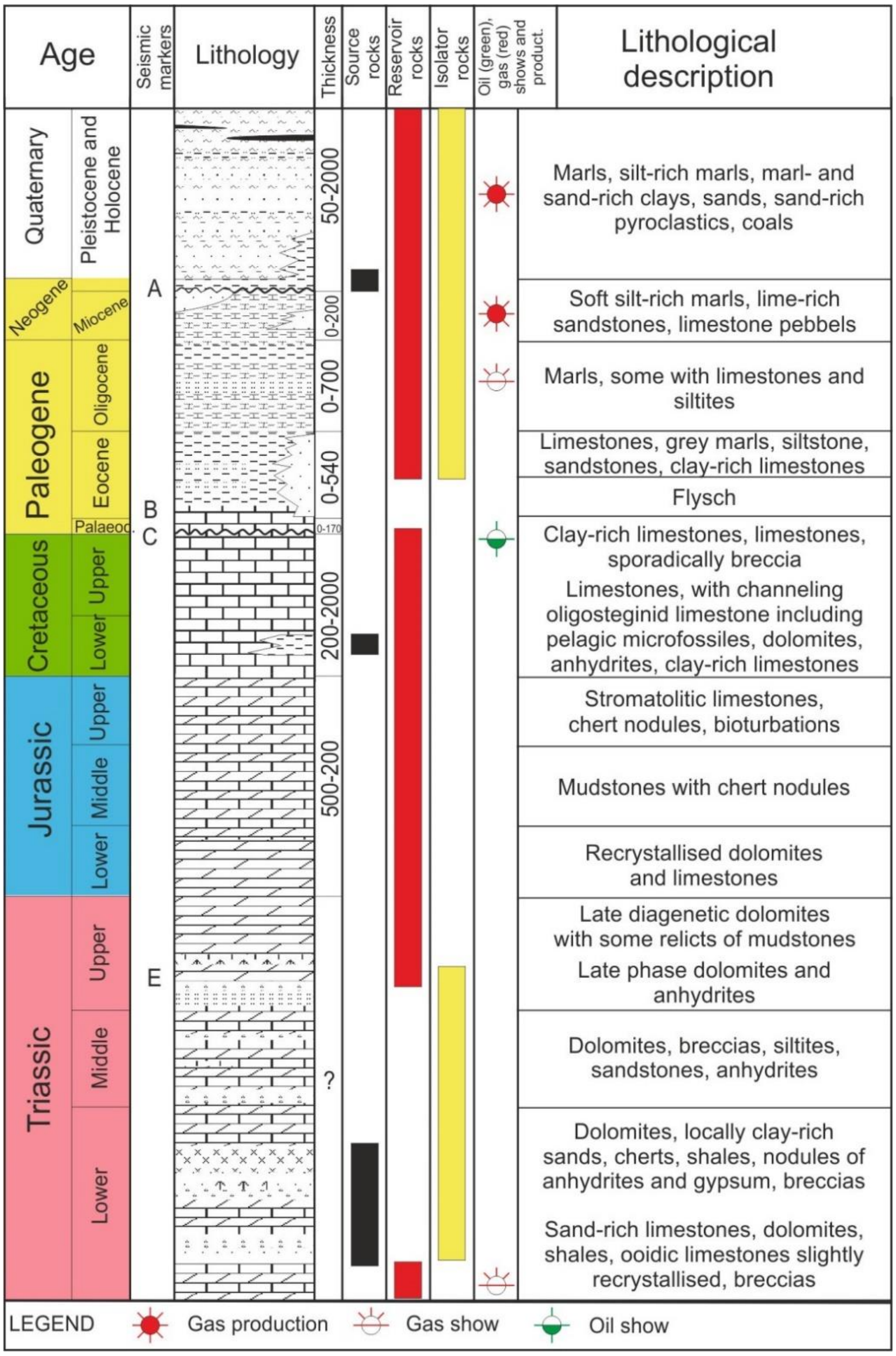


Fig. 14. Stratigraphic column of northern part of the Adriatic Basin based on offshore well data. Petroleum system elements are shown respecitvely (after Velić et al., 2015).

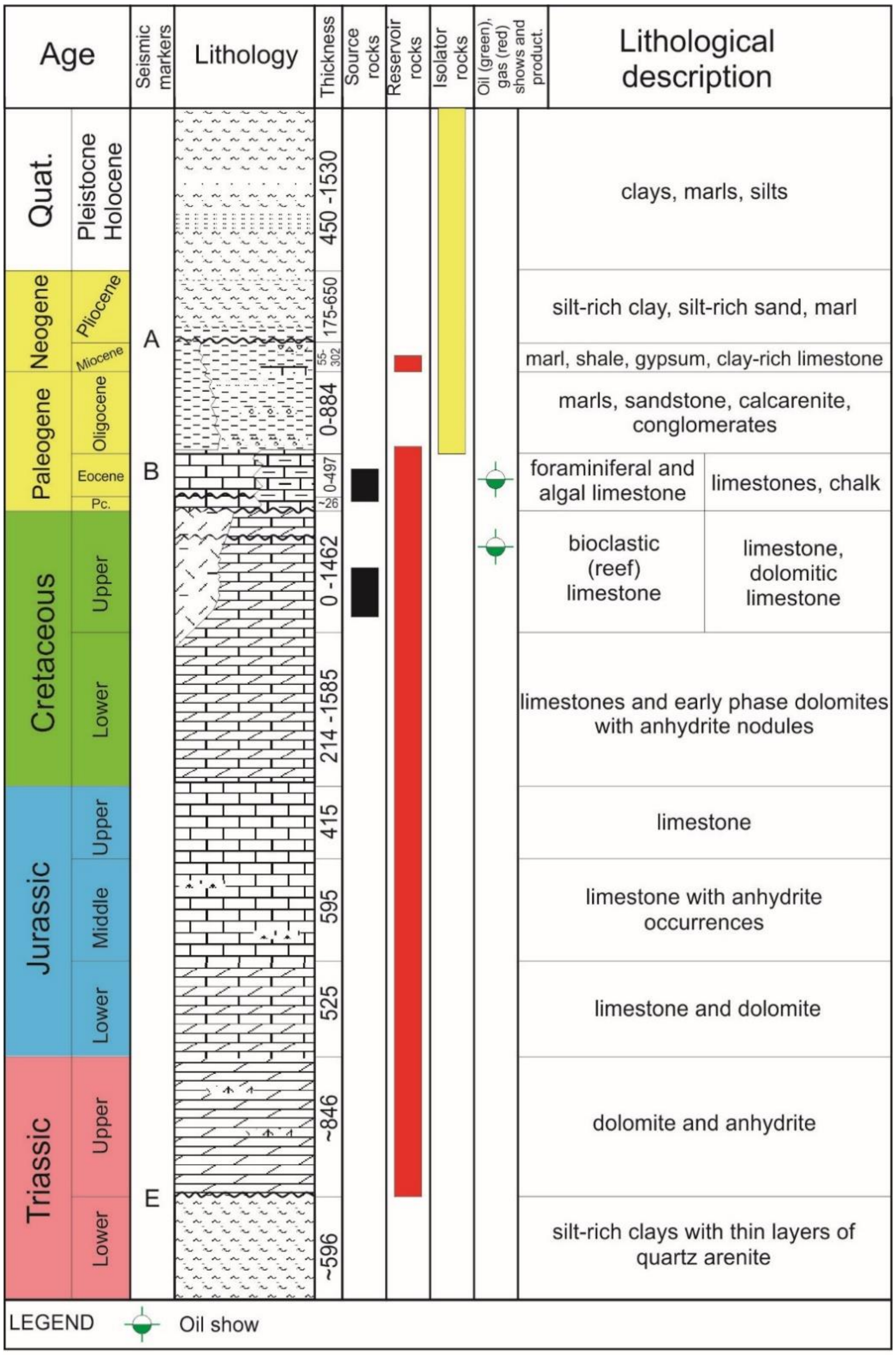
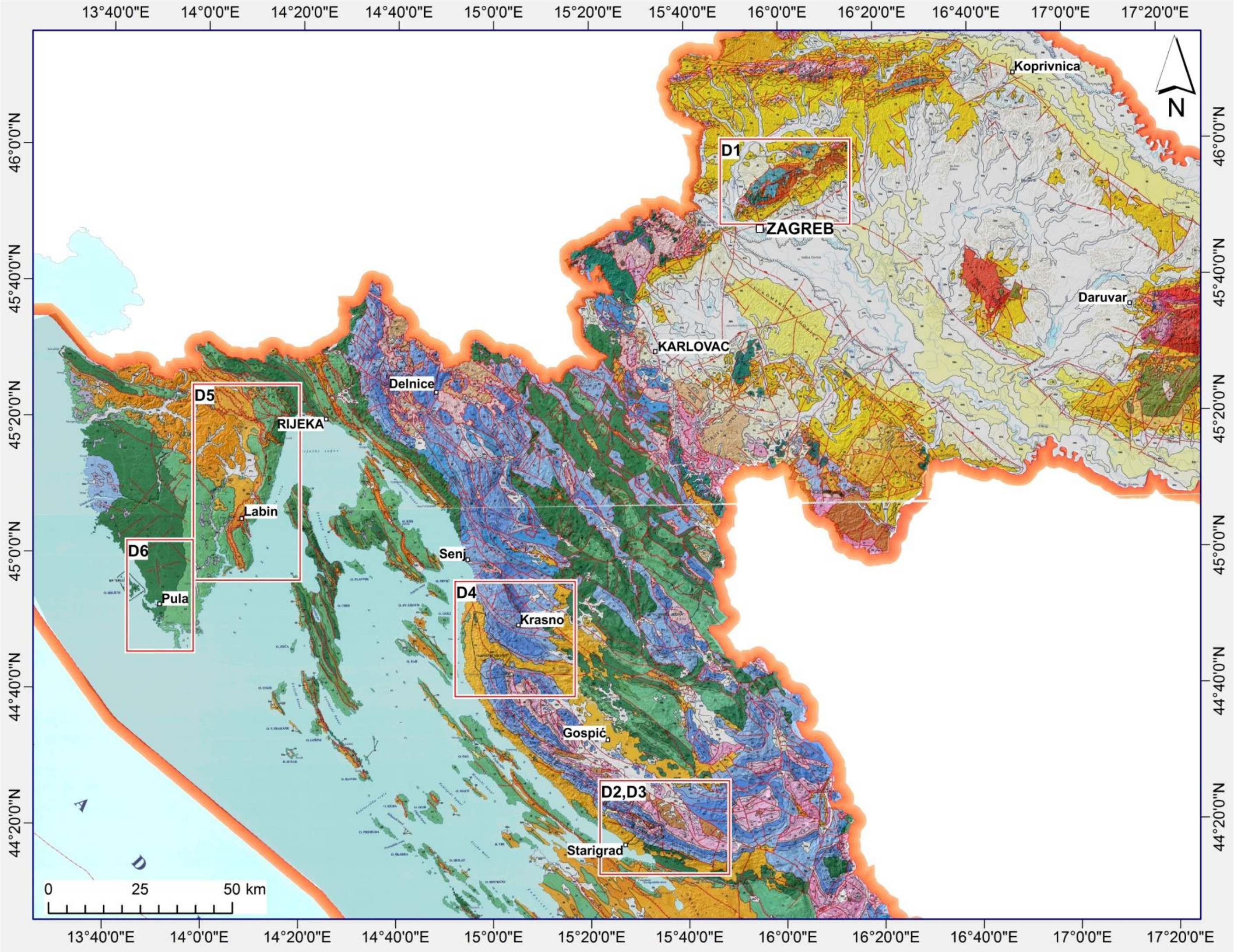


Fig. 15. Stratigraphic column of southern part of the Adriatic Basin based on offshore well data. Petroleum system elements are shown respecitvely (after Velić et al., 2015).



Geological map of Croatia with identifed areas of fieldtrip excursion on daily basis.

***1. DAY** (04. 07. 2016.)* – Internal Dinaridic units --

Mt. Medvednica- Geologic and tectonic settings

The Mt. Medvednica, with neighbouring “inselbergs” of Mts. Žumberak, Kalnik and Ivanščica, lies in the Dinarides–Alpine–Pannonian basin transition zone, at the location where **the Sava suture zone**, a major suture between the European- and Adria-derived tectonic units (Pamić 2002; Schmid et al., 2008; Ustaszewski et al. 2010), sharply turns from the NW into the NE direction, and further extends along the Zagorje–Mid-Transdanubian Shear Zone up to the central Carpathians (**Fig. 1-1**).

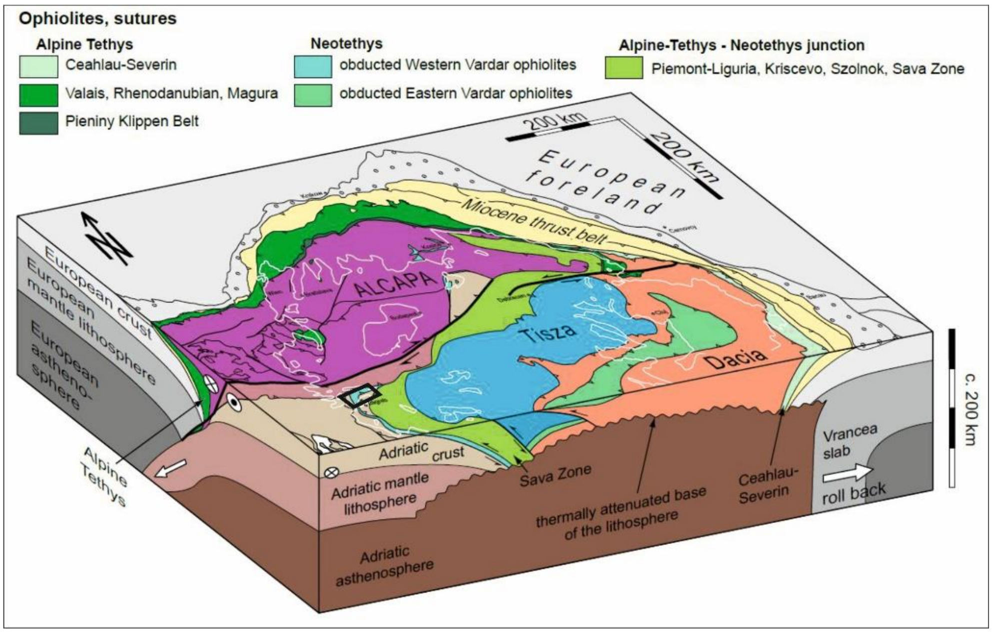


Fig. 1-1. Location of Mt. Medvednica (black rectangle) in a regional framework of major tectonic units and the present-day lithospheric structures in the Eastern Alps, Carpathians and northern Dinarides (after Ustaszewski et al., 2008).

The Sava suture zone resulted from convergence between the European and Adriatic plates during Mesozoic and Cenozoic times. It gradually evolved from the Late Jurassic-Cretaceous subduction zone of the Neotethys (the Meliata-Vardar ocean) into the Late Cretaceous-Paleogene collision zone between the European-derived Tisza-Dacia Mega-Unit and the Adria-derived tectonic units of the internal Dinarides (Fig. 1; Schmid et al., 2008; Ustaszewski et al., 2008, 2010).

During the Miocene (at about 20-18 Ma), following the syn-collisional tectonics in the Palaeogene, the Sava suture zone was inverted from a low-angle thrust into the low-angle NE-dipping extensional detachment, which led to the formation of the Sava basin at the SW margin of the Pannonian basin system. During the Miocene subsidence in the Sava basin, which locally resulted in deposition of over 5.000 m of Neogene-Qauternary sediments, tectonic units of the internal Dinarides and the Sava suture zone became largely covered by Miocene sediments.

The present day structural architecture of Mt. Medvednica and its surrounding area mostly resulted from the latest Miocene–Quaternary shortening (inversion in the SW part of the Pannonian basin), which led to the formation of km-scale E- to ENE-striking anticlines (isolated hills or *inselbergs*) separated by NW- and SE-dipping reverse faults from intervening synclines. As a rule, cores of anticlines expose pre-Neogene rocks of tectonic units of the internal Dinarides, eastern Alps and the Sava suture zone, while synclines comprise Miocene–Quaternary sediments of the Pannonian basin system. Anticlines and synclines are are frequently cross-cut by NW-striking dextral and NE-striking sinistral faults (**Fig. 1-2**).

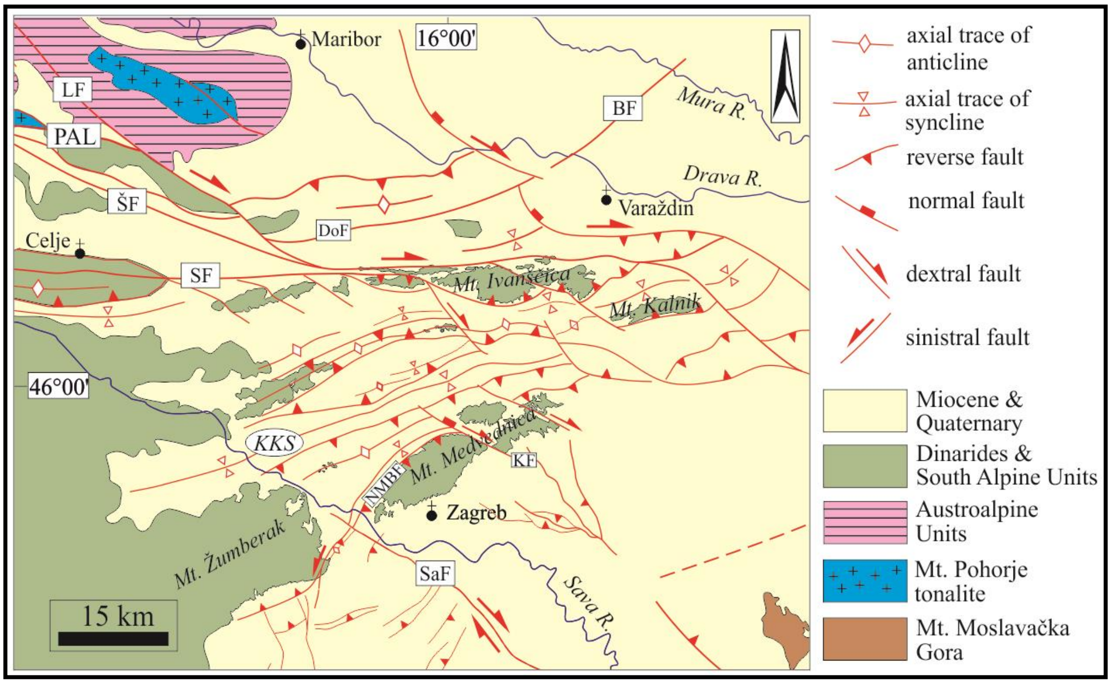


Fig. 1-2. Map of the Latest Miocene–Quaternary structures in the Dinarides-Alpine-Pannonian basin transition zone (from Tomljenović & Csontos, 2001 with references, partly modified). Abbreviations: ŠF-Šoštanj fault., DoF-Donat f., SF-Sava f. in Slovenia, KKS-Konjščina – Krško syncline, NMBF-North Medvednica Boundary f., KF-Kašina f. and SaF-Sava f. in Croatia.

The structural architecture of the Mt. Medvednica

In its central part north of Zagreb, Mt. Medvednica is an asymmetric antiform composed of a metamorphic core overlain by non-metamorphic Mesozoic and Cenozoic rocks, which are according to Tomljenović et al. (2008) and van Gelder et al. (2015) attributed to the following pre-Neogene structural units described here below from the bottom to the top (**Figs.1-3** and **1-4**):

1) **Greenschist facies metamorphic core** composed of two distinct lithologies, a metavolcanic series and a metasedimentary series (Lugović et al., 2006; Tomljenović et al., 2008, and references therein). The metavolcanic series is dominantly made up of chloritic schists that have still preserved in few places their original basaltic or intermediate volcanic protolith. The metasedimentary series contains in its lower part dark phyllites with rare intercalations of quartzites, overlain by massive marbles, carbonatic schists, metagreywackes, metaconglomerates, and fine-grained quartzites derived from the metamorphism of radiolarites (Basch, 1995; Tomljenović, 2002). Locally, the metavolcanics are interlayered with marbles, which is an effect of

isoclinal folding combined with an original multilayered stratigraphy of the protolith. The metavolcanics from the greenschist facies metamorphic core indicate peak metamorphism between 135 and 122 Ma based on Ar/Ar dating of white micas (Borojević Šostarić et al., 2012). The associated PT conditions were in the order of 350–410°C and 3–4 kbar (Judik et al., 2006, 2008; Lugović et al., 2006). K-Ar dating of muscovite from metasediments in the metamorphic core suggested that the period of peak metamorphism took place until 110 Ma (Belak et al., 1995; Judik et al., 2006, 2008). Furthermore, Ar/Ar dating of the metavolcanics inferred a younger age of 80 Ma that overprinted the peak metamorphism. This younger age was interpreted to be related to the period of Late Cretaceous contraction associated with subsidence in the Gosau-type basins (Borojević Šostarić et al., 2012).

2) **Subgreenschist facies Paleo-Mesozoic metasediments** exposed near the margins of the metamorphic core, which are mostly represented by pelagic shales, turbidites, and carbonates. Biostratigraphic dating analyzing both the protolith of the greenschist facies metamorphic core and the flanking Paleozoic metasediments indicate Silurian to Late Triassic ages (Đurđanović, 1973; Sremac and Mihajlović-Pavlović, 1983) and Middle to Upper Triassic protoliths (Belak et al., 1995). K-Ar illite dating in the subgreenschist facies metamorphosed sequence yielded ages between 124 and 95 Ma (Belak et al., 1995; Judik et al., 2006). In these rocks, peak temperatures are in the range of 100–240°C (Judik et al., 2008).

3) **Ophiolitic mélange** cropping out in the NW part of the mountain, which represents a chaotic assemblage of blocks of mafic and ultramafic rocks (ophiolites), greywackes, radiolarites, limestones, sandstones and turbidites embedded together in a shaly silty matrix (Pamić and Tomljenović, 1998), that is interpreted as a part of the Western Vardar Ophiolites obducted during the Mid-Late Jurassic-Earliest Cretaceous times (Schmid et al., 2008 and references therein). Biostratigraphic dating of blocks of radiolarites has yielded Upper Ladinian-Carnian and Upper Bajocian-Lower Callovian ages (Halamić and Goričan, 1995; Halamić et al., 1999), while scarce fauna in the matrix has been dated as Lower Jurassic to Bajocian (Babić et al., 2002).

4) **Upper Cretaceous-Paleocene alluvial to deep-marine sediments** that unconformably cover over the metamorphosed Paleozoic-Triassic rocks and the ophiolitic mélange. This show a gradual transgressive pattern from massive conglomerates and alluvial fan deposits at the base to sandstones and Scaglia Rossa hemipelagic carbonates higher up in the sequence (Crnjaković, 1980; Lužar-Oberiter et al., 2012). These deposits are stratigraphically continuous with the uppermost Cretaceous turbidites (carbonatic and clastic) that are commonly observed elsewhere along the Sava suture zone (e.g., Ustaszewski et al., 2010). Based on similar biostratigraphic ages and lithofacies characteristics, these Upper Cretaceous-Paleocene sediments are often referred to as *the Gosau deposits* (Borojević Šostarić et al., 2012; Judik et al., 2006; Tomljenović et al., 2008) analogous to coeval and similar deposits widely observed in the Eastern Alps.

5) **Žumberak nappe**, which is the highest pre-Neogene structural unit of the Mt. Medvednica that thrusts over the ophiolitic mélange and the Cretaceous-Paleocene sediments in the SW part of the mountain (Tomljenović et al., 2008 with references),

composed of a thick succession of Triassic shallow-marine clastic and carbonate sediments.

The pre-Neogene units of the Mt. Medvednica are unconformably overlain by the **Miocene sediments** of the Pannonian Basin. However, due to generally N-S directed shortening active since the latest Miocene time (Tomljenović and Csontos, 2001), the structural position of Miocene sediments around the Medvednica antiform is not uniform. In the north-eastern part, i.e. to the NE of the Kašina Fault (KF in **Fig. 1-2**), these sediments unconformably cover over both limbs of the antiform. By contrast, in the central and south-western part, to the SW of the Kašina Fault, Miocene sediments are exposed only along the SE limb of the antiform at elevation between 200 and 400 m, while on the NW limb these sediments are hidden in the footwall of the North Medvednica Boundary Fault (NMBF in the profile of **Fig. 1-3**) and buried below 400 m thick pile of Pliocene-Quaternary sediments deposited in the footwall of this fault, found at present in the core of the neighbouring Stubica-Zaprešić syncline (**Fig. 1-3).**

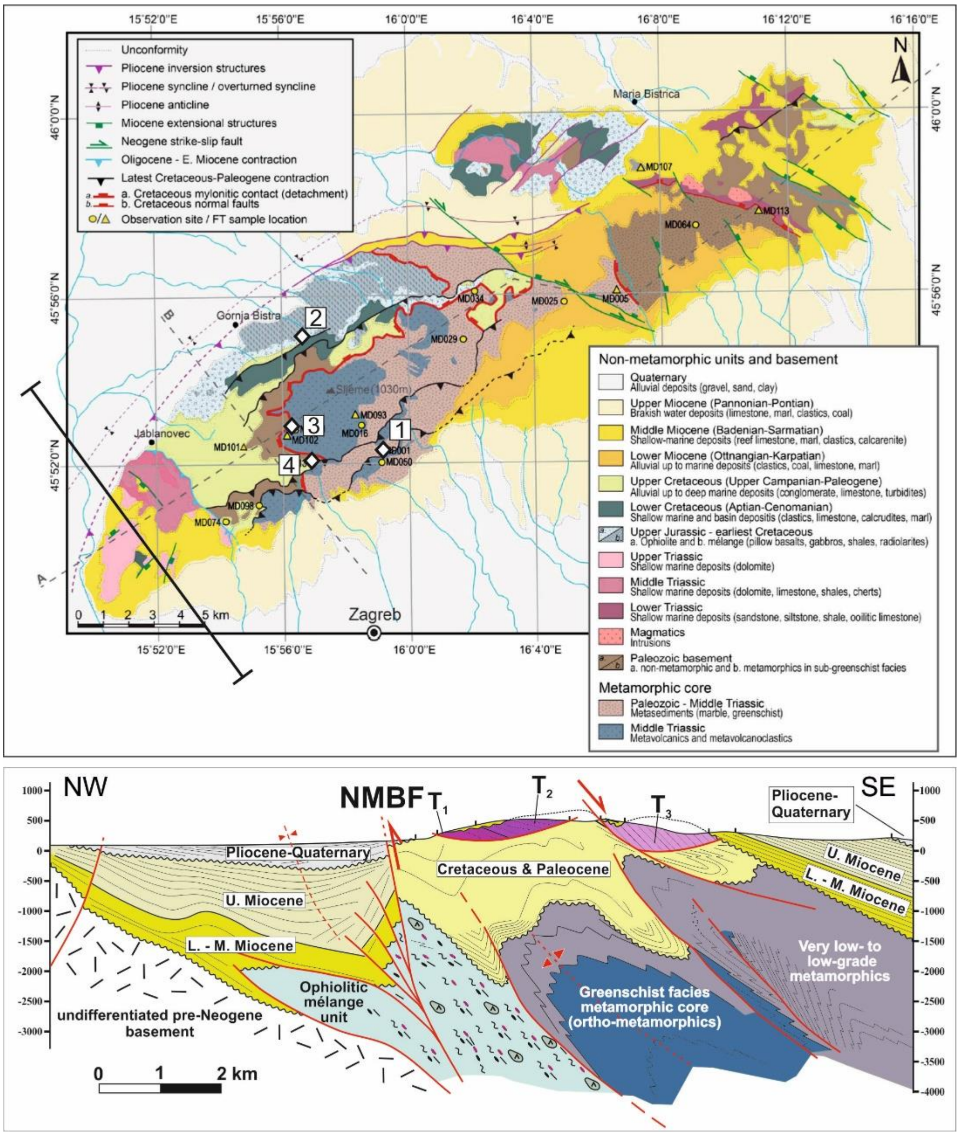


Fig. 1-3. Upper part: Geological map of the Mt. Medvednica (from van Gelder et al. 2015, compiled from Basch, 1995; Tomljenović et al., 2008; Matoš et al., 2014 with references therein). Excursion

stops are indicated with numbers **1-4**. Lower part: Geological profile across the SW end of Mt. Medvednica (after Tomljenović, 2002; slightly modified).

Stop 1:

Low-grade metasedimentary rocks of the Medvednica metamorphic core

The stop 1 is a short walk along Gračani - peak Sljeme (1033 m) road following the Bliznec creek for some 500 m. Along this walk, although exposed sporadically, practically all major members of the Early Cretaceous Metamorphic complex can be found, grouped by Belak et al. (1995b) into four distinctive units (**Fig. 1-4**). All units comprise metamorphic rocks metamorphosed under P-T conditions of the greenschist facies. K-Ar measurements carried out on six whole rock samples of orthogreenschists and metasediments and their monomineral concentrates obtained ages ranging from 122 to 110 Ma (Belak et al., 1995). In metacarbonate rocks from the surrounding outcrops, conodonts of Devonian, Carboniferous and Middle Triassic ages were determined (Đurđanović, 1973). In most of metasedimentary rocks found here the syn-metamorphic foliation (S1) is generally parallel to earlier bedding, accompanied by a stretching lineation (L1), both penetrative on micro and mesoscopic scale of observation. This deformation was followed by (or was synchronous with ?) tight to isoclinal W- to NW-vergent folding (D2) with fold axes oriented mostly parallel or slightly oblique to the stretching lineation. This folding was penetrative as well, documented in micro to macroscopic scale of observation (**Fig. 1-5**). As a result, large-scale folds commonly include smaller-scale, parasitic folds in their limbs and hinge zones, all showing similar geometry (hinge thickening and limb thinning) and parallel orientation of fold axes. Isoclinal folding was accompanied by the axial plane crenulation cleavage (**Fig. 1-5**), and by well-developed pencil structures in slates and fine-grained metasediments formed by foliation/cleavage intersection (L2=S1/S2). Neogene deformation phases generally resulted with faulting and kink-type folding observed in these rocks throughout the Mt. Medvednica.

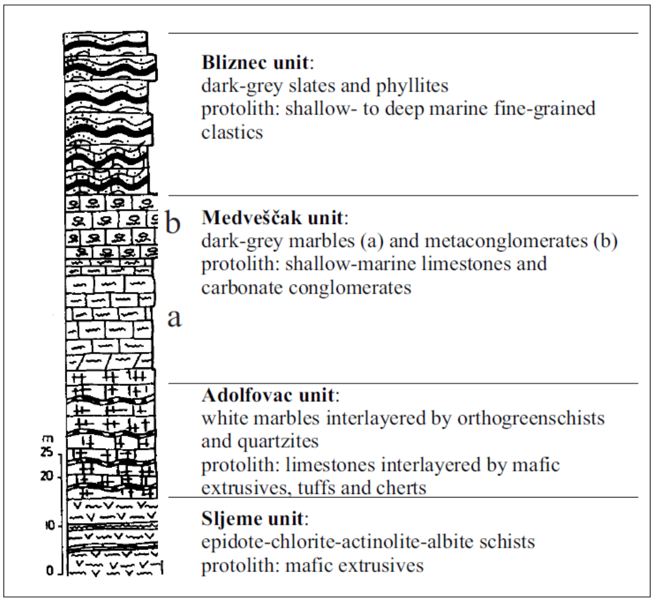


Fig. 1-4. Schematic column showing major lithological units of the Early Cretaceous low-grade metamorphic core of the Mt. Medvednica (after Belak et al., 1995b).

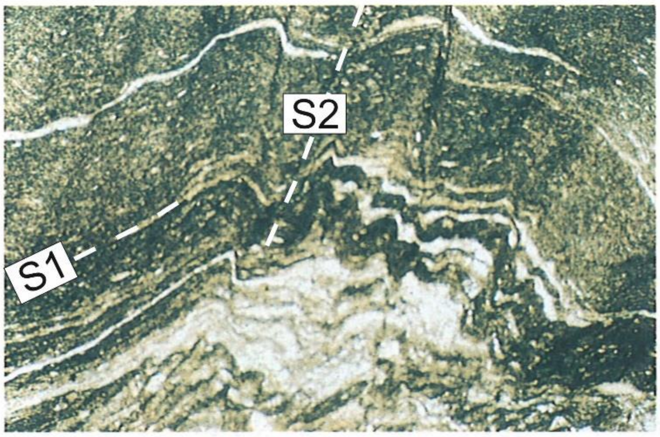


Fig. 1-5. Micro-scale folding of S1 and axial plane crenulation cleavage (S2) in a black slate-phylite from Bliznec creek in the Mt. Medvednica (from Belak et al., 1995b).

Stop 2:

Middle Jurassic- Early Cretaceous Ophiolitic mélange

The stop 2 is about 500-1000 m long exposure along the forest road from Markov Travnik due east. Along this road different types of rocks and structural fabrics comprising the Middle Jurassic-Early Cretaceous ophiolitic mélange could be seen, described in detail by Babić et al. (2002) and assigned to the Repno Complex. In general, this complex is described as a chaotic assemblage of shales, sandstones, cherts, pillow lavas, gabbros and ultramafics, interpreted as accretionary wedge genetically related to the obduction of Western Vardar Ophiolites (Schmid et al., 2008 and references therein), which is composed of **matrix** and different types of rock **inclusions**.

According to Babić et al. (2002) the matrix is mostly dark grey to black, locally reddish, mostly siliceous, free of carbonate and pervasively sheared (**Fig. 1-6**). Inclusions embodied in the shale matrix are mostly represented by sandstones, less common by cherts, siltstones and shales. Besides, inclusions of diabase, gabbro, serpentinites and limestones have been reported at different locations along the NW slope of Medvednica within the similar “block-in-matrix” fabric. The shape of inclusions varies from rounded to angular, while many are lensoid and elongated parallel with cleavage in the matrix. Based on palynological dating that indicates Early Jurassic to Bajocian age of the melange matrix (Babić et al., 2002), together with biostratigraphic dating of radiolarites and limestones embodied within the matrix (e.g. Halamić et al., 1999), the formation of the ophiolitic melange was presumed between the Middle Jurassic and Early Cretaceous (Hauterivian) (Babić et al., 2002).

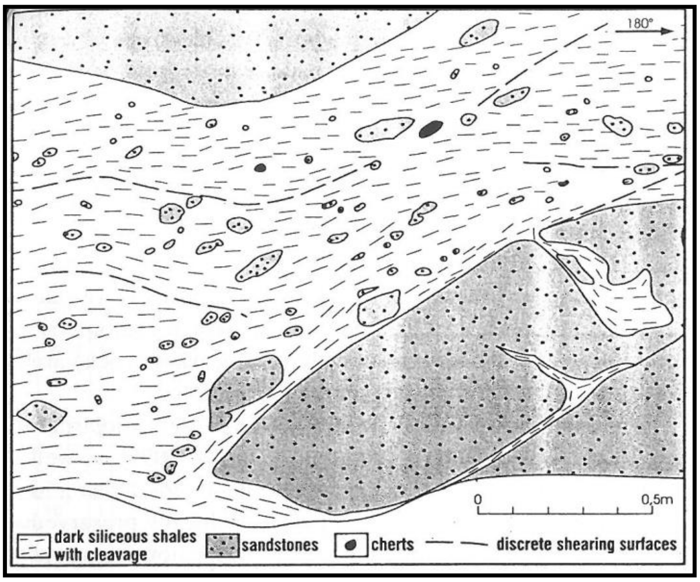


Fig. 1-6. Sketch of the relationship between shaly matrix and different types of rock inclusions typical for the ophiolitic melange (the Repno Complex) described by Crnjaković (1987) at outcrop on the NW slope of Mt. Medvednica (from Babić et al., 2002).

Stop 3:

Devonian-Carboniferous (?) metacarbonates and ortho-greenschists of the Medvednica metamorphic core

Two members of the metamorphic complex crop out along the road near the "Grafičar" mounting lodge: dark-grey metacarbonates and orthogreenschists. Vegetation cover mimics the character of their contact, which is, however, presumed by van Gelder et al. (2015) as the Late Cretaceous low-angle extensional detachment characterised by mylonitic fabric documented in metacarbonates and orthogreenschists.

Outcropping metacarbonates are distinctly foliated rocks with generally SSW-dipping foliation parallel to the original bedding (S1//S0). This foliation is marked by recrystallized irregular stretched lenses of quartz aggregates and organic material concentrated along stylolite surfaces (Prtoljan et al., 1995). As a rule, the foliation is accompanied by a well-preserved SW-dipping lineation (L1). Microtectonic study on samples from this locality revealed that these rocks show evidence of ductile shearing and displacement-controlled growth in non-coaxial progressive deformation, containing characteristic fabric elements typical for mylonites (Tomljenović et al., 2008; van Gelder et al., 2015). Nicely preserved fibrous overgrowths of calcite in a pressure shadow around the pyrite documented in a thin section made out in sample from this outcrop indicate a top-NE sense of shear (**Fig. 1-7**).

Some 100 - 200 metres along the road from outcropping metacarbonates, orthogreenschists crop out. These are foliated and lineated rocks showing similar mylonitic fabric as the one documented in metacarbonates, characterized by dynamic recrystallization of porphyroclasts (predominantly feldspars) in foliated matrix containing sin-kinematic minerals of chlorite, epidote, amphibole and mica. The most common kinematic indicators found in these rocks are mantled porphyroclasts (mostly of sigma- type), strain shadows, oblique foliation and mica fish. Due to a strongly variable degree of recrystallization some greenschists show well preserved original ophitic and granular texture as found in thin sections normal to the foliation and the lineation. Chemical compositions of orthogreenschists indicate their origin from primitive intra-oceanic arc basalts and andesites, while chlorite geothermometry points to greenschist facies metamorphic conditions of 300-350 °C (Lugović et al., 2006).

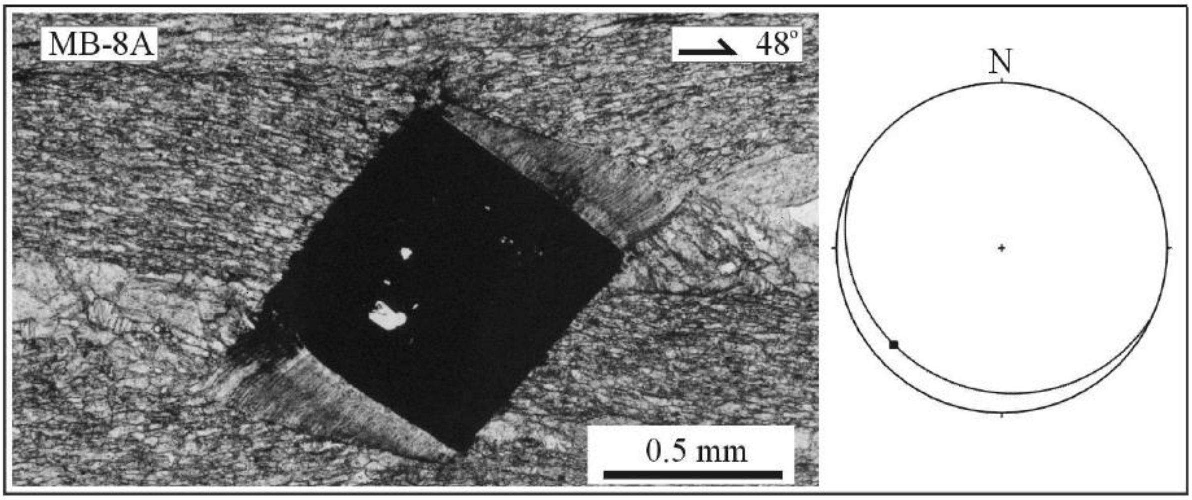


Fig. 1-7. Thin section of metacarbonate mylonites outcropping near Grafičar mountain lodge showing cubic pyrite with fibrous overgrowths that indicate top-NE sense of shear (from Tomljenović, 2002).

Stop 4:

Upper Cretaceous alluvial to deep-marine sediments (*Gosau deposits*) at the Glog

This stop exposes about 70 m thick section of Upper Cretaceous (Santonian-Maastrichtian) sediments (**Fig. 1-8**) that unconformably cover over the Medvednica metamorphic core and the ophiolitic mélange (see in **Fig. 1-3**). Here, the section starts with coarse-grained and poorly- to well-sorted breccia-conglomerates composed of fragments derived from different metamorphic rocks mostly slates, metacarbonates and orthogreenschists, which can be found in outcrops close to the Late Cretaceous unconformity, thus representing the main and local source area for these clastic rocks. Matrix is a coarse- to fine-grained sandstone of the same composition. According to Crnjaković (1979) the Upper Cretaceous clastic sediments are deposited in a coastal shelf and possibly alluvial-fan environment.

In contrast to other localities on Mt. Medvednica where conglomerates gradually grade into sandstones and shales, at this particular locality they are in tectonic contact with grey, green and red-coloured *Globotruncana*-bearing marly limestones known as the Scaglia-limestones, which are considered as Upper Campanian (Nedela-Devide, 1957). These limestones grade upward into a sequence of clayey biomicrites, calcarenitic sandstones and sandy to silty marls, characterised by sedimentary structures typical for

Bouma-sequences. Accordingly, they are considered as flysch deposits of Late Cretaceous (Maastrichtian) age (Crnjaković, 1981).

The Upper Cretaceous sediments at the Glog locality are characterised by SW-plunging and NW-vergening open to tight folds, associated with weak to penetrative axial plane cleavage (**Fig. 1-7**). The cleavage is best developed in marly or shaly lithologies and in places of more intense deformation such as in the footwall of the major thrusts, like the one that can be seen along the main road down to Zagreb, and which emplaced orthometamorphics over the Upper Creteceous sediments. In turbidite sequences composed of alternating silty marls and sandstones, different structural features related to the formation of cleavage can be seen like cleavage refraction, pencil cleavage and pencil structures formed by cleavage/bedding intersection. In the Scaglia-limestones, the same cleavage is expressed as stylolitic or pressure solution cleavage. Ductile deformation in Upper Cretaceous rocks is associated with reverse faults developed in sets and characterized by imbrication and sigmoidal drag folding of bedding and cleavage, locally with formation of boudinage, Riedel shears and en echelon tension veins. All these structures indicate a progressive non-coaxial shear with top-to-the-NW tectonic transport direction in the present day coordinates.

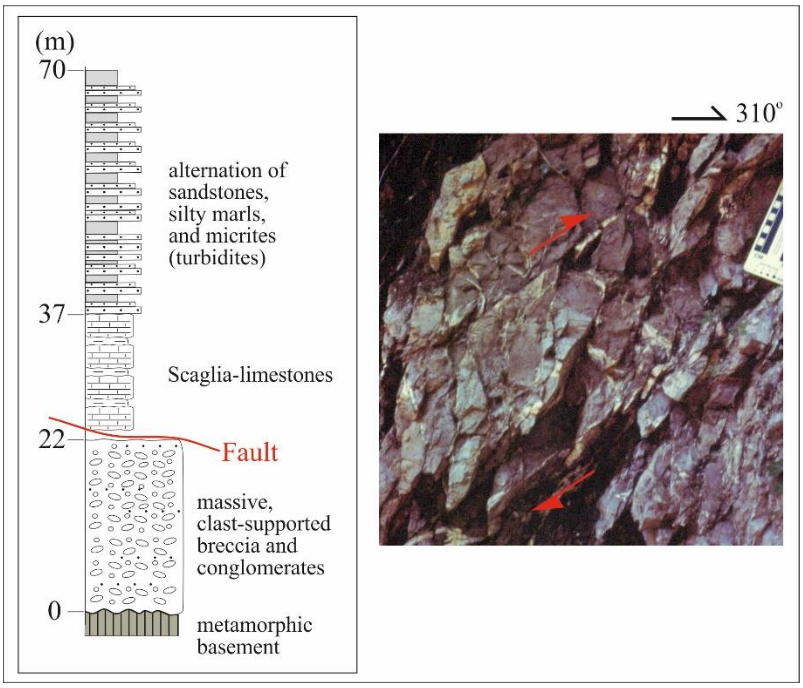


Fig. 1-8. Left: Lithological column of Upper Cretaceous sediments at the Glog locality (after Marinčić et al., 1995). Right: Reverse faults, cleavage and tension veins formed by non-coaxial shear with top-NW tectonic transport direction (from Tomljenović, 2002).

***2. DAY** (05. 07. 2016.)* – External Dinaridic Units--

Mt. Velebit -- (Mali Alan Pass section)

The fold-thrust belt of Mt. Velebit, i.e., external Dinarides was formed by a thin-skinned Cenozoic thrusting eastern Adriatic plate margin (e.g. Blašković, 1998; Tari, 2002; Tari Kovačić and Mrinjek, 1994; Schmid et al., 2008; Korbar, 2009; with references), as a result of continuous convergence between the African promontory and European plate in this part of the Mediterranean (e.g. Channell et al., 1979; Dercourt et al., 1993; Stampfli and Borel, 2001). The convergence onset in Middle Jurassic with formation of Adria–Europe collision zone that yiedled closure of the Neotethys Ocean and ophiolite obduction over the eastern Adriatic plate margin (Middle–Late Jurassic; e.g. Pamić et al., 2002; Tomljenović et al., 2008; Schmid et al., 2008). Closure of the Neotethys and NE-directed subduction of the Adria microplate underneath the Tisza Unit was terminated along the Sava Zone during the Latest Cretaceous–Earliest Paleogene (see **Fig. 5**; e.g. Pamić, 2002; Schmid et al., 2008; Ustaszewski et al., 2010). This in general yielded formation of thrust sheets that propagated from Internal Dinarides to the southwest, to external part of the orogen with formation of external Dinarides fold-thrust belt during Eocene and Oligocene (e.g. Tari, 2002; Schmid et al., 2008; Korbar, 2009; Ustaszewski et al., 2008, 2010).

Mt. Velebit represent a fault-related anticline that streches from Senjska Draga (NW) to Zrmanja River (SE) with length of 150 km, 14 km average width, covering an area of 2280 km^2 (Velić, 2007a). With typical karst morphology, composed of continous Late Paleozoic (Carboniferous and Permian), Mesozoic to Oligocene clastic and carbonate succesions (**Fig. 2-1**) that are classic shallow-water sediments in the wider Mediterranean area (Velić, 2007a; Tari Kovačić and Mrinjek, 1994). The stratigraphic range of Mt. Velebit rocks according to Velić (2007a) could be subdivided in six sedimentary megasequences: i) Middle Carboniferous-Early Permian clastics and shallow marine limestones, ii) Middle Permian-Middle Triassic carbonate depostion with vulcanoclastics, iii) Late Norian -Santonian dololomite and fossiliferus limestones, iv) Eocene foraminiferal limestone, v) Oligocene-Pliocene Promina conglomerate and Velebit breccia, and vi) Quaternary glacio-fluvial, fluvial and gravitational deposits.

Due to its complexity, the tectonic structure of multiple faulted Mt. Velebit anticline is explained by two scenarios. According to Bahun, (1974) and Prelogović et al. (1995, 2004) Mt. Velebit is uplifted in a hangingwall of NE-dipping reverse Velebit fault that strikes along the Mt. Velebit's coastline and is recent covered by the carbonate breccia (i.e., Jelar or Velebit breccia; Bahun, 1963; Vlahović et al., 2012), whereas in second scenario Korbar (2009) indicated Mt. Velebit anticline as a positive flower structure formed along the Cenozoic transpressive, dextral-reverse fault (**Fig. 2-2**). This two scenarios are highly debatable as large areas are covered by the youngest deposits e.g., Velebit breccia and Quaternary deposits and as such imortant tectonic contacts and fault zones are covered.

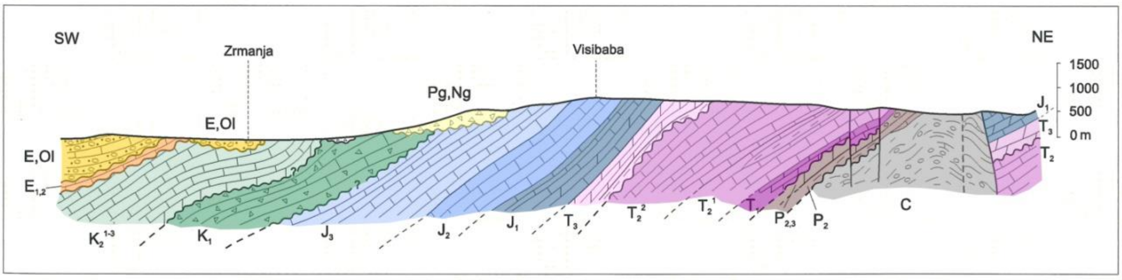


Fig. 2-1. Geological profile of Velebit Mt. – approximately 4 km E of the Mali Alan Pass (after SOKAČ in JELASKA & VELIĆ, 1971). Legend: C – Carboniferous shale, conglomerate and sandstone; P_2 – Middle Permian sandstone; $P_{2,3}$ – Middle–Upper Permian dolomite; T_1 – Uppermost Lower Triassic dolomite with terrigenous admixtures; T_2^1 – Anisian limestone with intercalation of clastics (pelite and siltite); T_2^2 – Ladinian limestone; T_3 – Upper Triassic dolomite with red clastics in its base; J_1 – Lower Jurassic limestone, subordinate dolomite; J_2 – Middle Jurassic limestone; J_3 – Upper Jurassic limestone; K_1 – Lower Cretaceous limestone breccia and limestone; K_2^{1-3} – Upper Cretaceous limestone; $E_{1,2}$ – Eocene foraminiferal limestone; E, Ol – Eocene, Oligocene "Promina" clastics; Pg, Ng – Paleogene, Neogene – Jelar breccia.

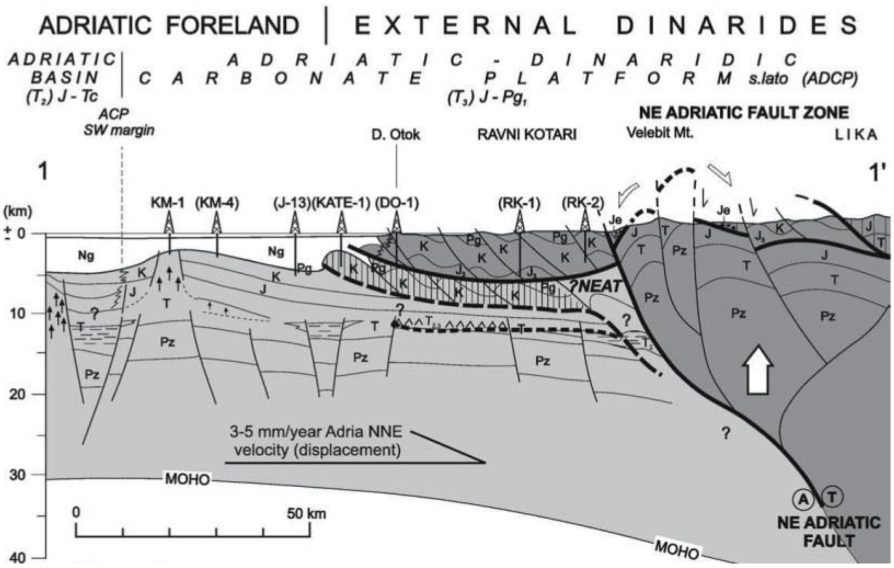


Fig. 2-2. Recent structural arrangement of the External Dinarides in the central portions of Dinarides. (after Korbar, 2009).

Considering the fact that Mesozoic sedimentary succession is the best exposed along the Mali Alan pass, in the southern part of Mt. Velebit, our profile along this tour will cover mainly Middle to Upper Triassic and Lower to Middle Jurassic carbonate succession, Triassic clastics and Oligocene to Miocene Jelar, i.e, Velebit carbonate breccia. With eight geological stops (**Fig. 2-3**) along the tour, the total length is 7 km, with elevation difference of 312 m. The maximum height will be achieved at the Mali Alan pass at 1044 m.

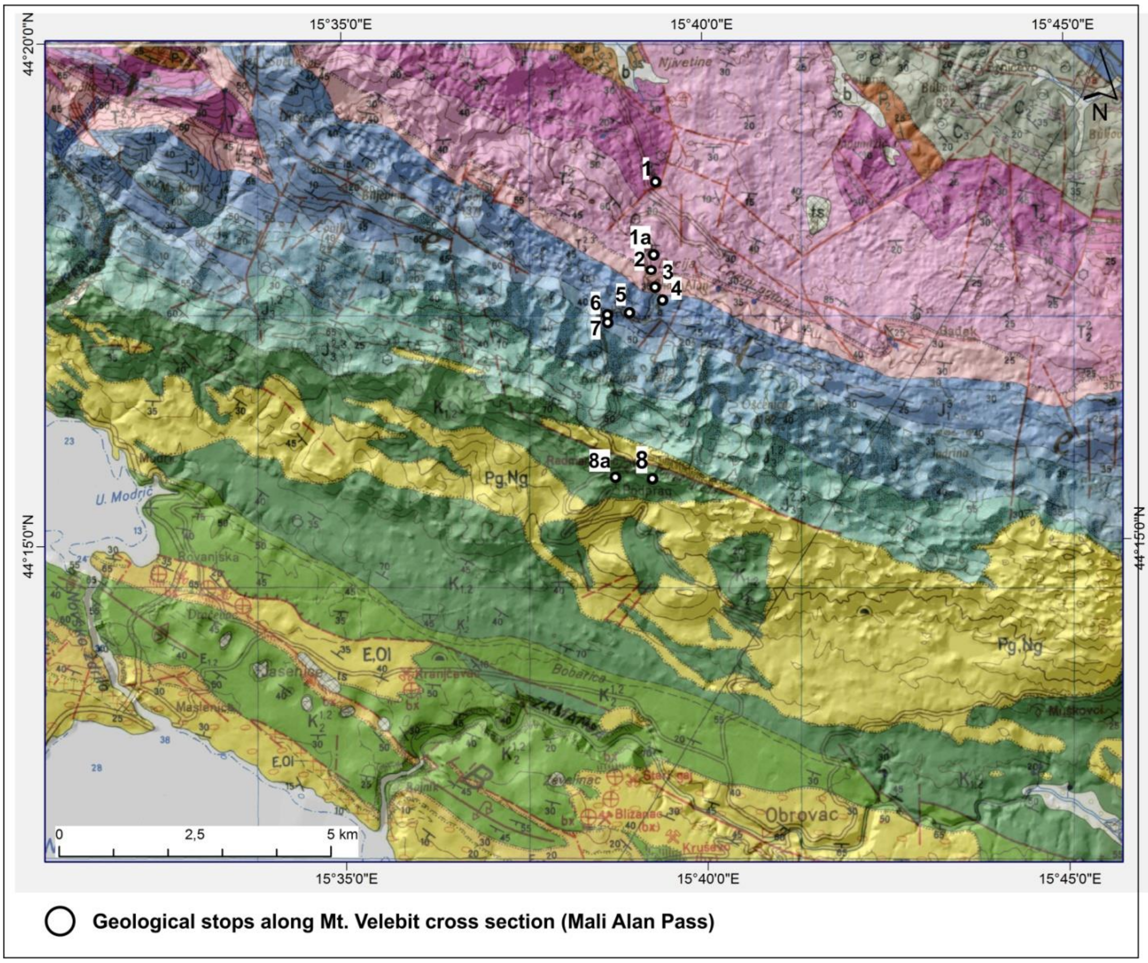


Fig. 2-3. Geological map with numbered stops along the Mali Alan pass section.

Stop 1 and 1a:

Diplopora limestone—Anisian±Ladinian (c.247.2-237.0 Ma)

Limestones outcrops along the road-cut of the Sv. Rok-Mali Alan-Obrovac mountain road. Limestones are mostly massive, layering is poorly recognized, in some places thicker than 2m (**Figs. 2-4** and **2-5**). Colorification is light grey, resembling recrystalized sparitic limestone of various textural types (mudstone, wackstone, fenestral mudstone, peloid-intraclastic packstone-grainstone and oncoidal floatstone (Grgasović, 2007). Contact between Upper Triassic dolomites is erosional and is followed by red clastics. Limestones are rich in dasycladacean algae *Diplopora annulata* and *Kantia dolomitica* (**Fig. 2-6**). Thalluses are visible as small rings, elipses, or elongated algae exteriors (Grgasović, 2007). The total thickness of Diplopora limestone succession in area of Mt. Velebit reach c.500 m

Fig. 2-4. Outcrop of Diplopora limestone along the road Sv. Rok-Mali Alan-Obrovac.

Fig. 2-5. Detail of the outcrop of Diplopora limestone with makroscopic visible remnants of *Diplopora annulata* along the road Sv. Rok-Mali Alan-Obrovac.

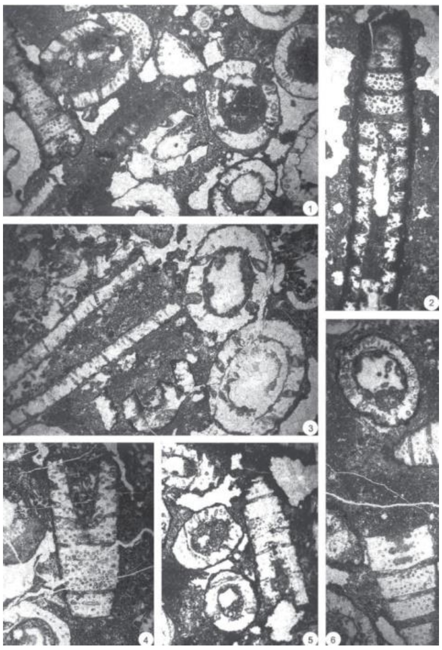


Fig. 2-6. Microscopic section of microfacies of *Diplopora annulata* SCHAFHÄUTL and Kantia dolomitica PIA. Sv. Rok–Mali Alan Road, Ladinian. Each ring (annulum) bears two whorls of trichophorous branches (after Sokač, 2007)

Stop 2:

Clastic series—Carnian-Norian (c.237.0 - 208.5 Ma)

In the Mt. Velebit area the contact between Diplopora limestone and Upper Triassic dolomites is often identifed as erosional that is sporadically marked with terrigenous clastic sediments, i.e. red clastics, claystones, conglomerate and even hematite bauxite (c. ≤ 100 m. thick succession; see Tišljar et al., 2007 for details). Formation of these clastic sediments are related to longlasting continental emersion phase and formation of significant paleorelief in Middle Triassic which in some places resulted in either direct contact between Diplopora limestone and Upper Triassic dolomites or enabled deposition of clastic material, i.e., red clastics in paleodepressions (**Figs. 2-7** and **2-8**).

Along the road Sv. Rok-Mali Alan-Obrovac we don't have direct red clastic succession, however irregular karstified Diplopora limestone that is often dolomitized, fractured and impregnated with reddish matrix indicate paleorelief and vicinity of terrigeneous sediments, i.e. red clastics.

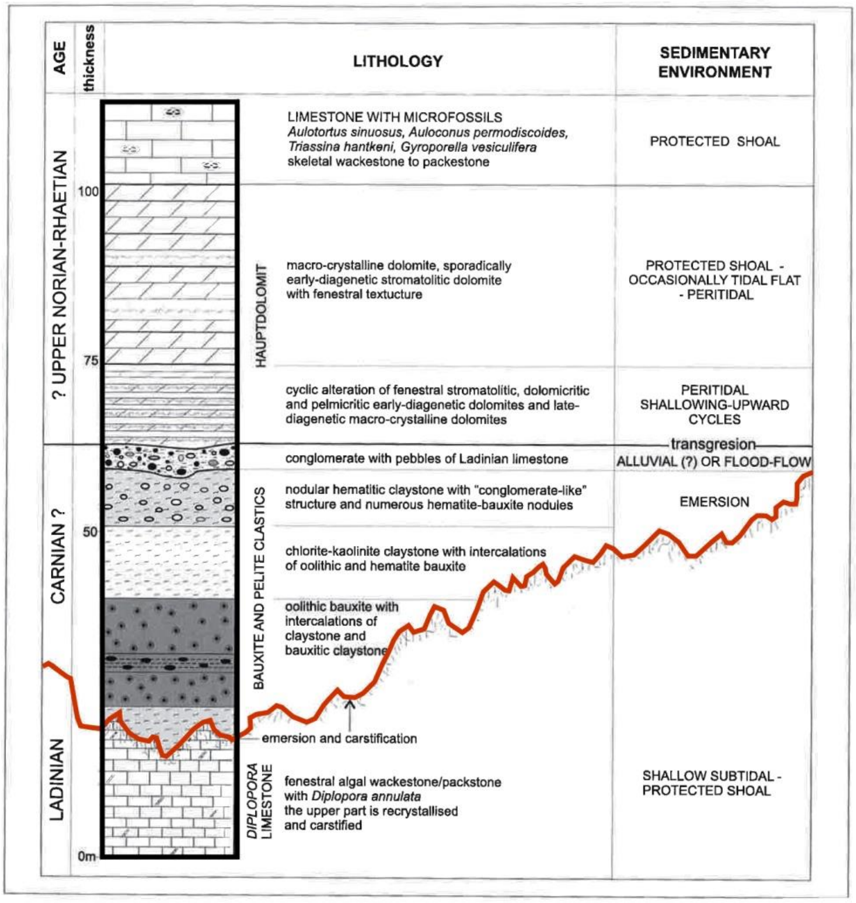


Fig. 2-7. Shematic geological column of Vrance locality (c. 12 km to the east, near Gračac; see Tišljar et al., 2007 for details).

Fig. 2-8. Outcrop of red clastics c. 40 km to the NW (locality of Jadovno).

Stop 3:

Hauptdolomite formation—Norian-Rhaetian (c.208.5-201.3 Ma)

After Middle Triassic continental phase, gradual ingression of the Late Norian sea resulted in deposition of dolomite sequence of “Main dolomite” or Hauptdolomite (**Figs. 2-9** and **2-10;** Velić, 2007*a*). This sequence of distinguishable light and dark grey layered early-diagenetic and late-diagenetic dolomites represent peritidal alternation that is in some places c. 250 m thick. Early-diagenetic dolomites are characterized by stromatolitic texture, whereas late-diagenetic dolomites are characterized by recrystallized structure. Within the Hauptolomite formation there are also sporadic occurences of interlayered bioclastic calcarenitic strata with peudoolitic-oolitic texture. In the Mt. Velebit area, haupdolomite formation age is primary dated by preseved fragments of Norian carbonate algae *Gyroporella vesiculifera* and secondly by superposed position in relation to early Jurassic limestone and dolomite succession (Sokač et al., 1976).

Fig. 2-9. Outcrop detail of Hauptdolomite formation along the Mali Alan pass succession with light and dark grey laminas.

Fig. 2-10. Outcrop detail of early-diagenetic dolomites within Hauptdolomite formation along the Mali Alan pass succession.

Stop 4:

Lower Jurassic limestones and dolomite succession—Hettangian-Sinemurian (c. 201.3-190.8 Ma)

The Hettangian and Sinemurian limestone and dolomite succession occur c. 100 m from the milestone on Mali Alan Pass (**Figs. 2-11** and **2.12**), in the direction of Obrovac (Sokač, 2001). Well-bedded, grey, Lower Liassic (Hettangian - Lower Sinemurian) limestones that resembles alternation of skeletal-intraclastic grainstone and mudstones (micrite) were deposited in shallow subtidal with periodic emersions into the vadose zone. In this transition zone microcrystalline dolomite interchange with well layered micrites, oncoid and peloid wackstones,oolitic grainstones and rare intraformational breccia. Going towards younger parts of succession dolomite disapear. At the stop 4 we can find alternation of mudstones, fossiliferous wackstones, peloidal grainstones and oncoidal-bioclastic, gastropod rich grainstones.

Limestones are rich in algal remnants and gastropods. Fossils (**Fig. 2-13**). are primary dominated by algae *Paleodasycladus* (e.g, *P. meditereaneus, P. mediterraneous var. heraki, P. mediterraneous var. illyricus,* , *P. mediterraneous var. elongatus,* , *P. alanensis, P. benecki,* etc.) and foraminiferal assamblage (e.g., *Lituosepta recoarensis, Orbitopsella primaeva, Orbitopsella praecoursor*, etc.)(see Sokač, 2007 for details). In the area of Mali Alan pass the total thickness of Lpwer Jurassic limestone and dolomite succession reach 210 m (**Fig. 2-14**).

Fig. 2-11. Outcrop of Lower Jurassic limestone and dolomite succession along the road Sv. Rok-Mali Alan-Obrovac near the highest point of Mali Alan pass (1044 m).

Fig. 2-12. Outcrop details of Lower Jurassic limestone strata with c. 30-100 cm strata thickness. 20 m from Mali Alan pass (1044 m).

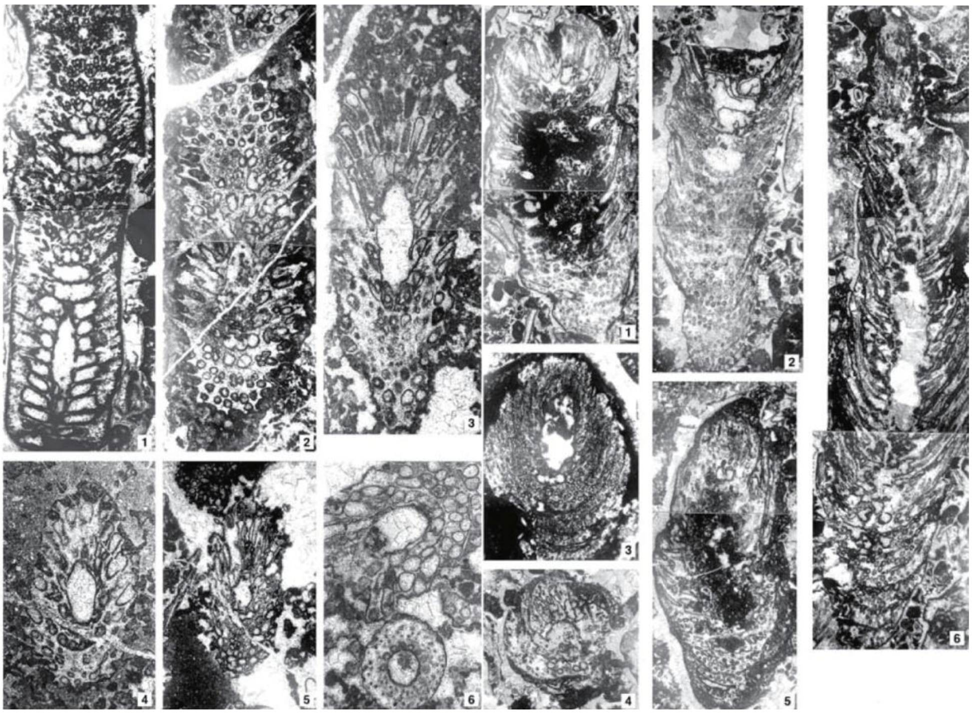


Fig. 2-13. Microscopic section of microfacies of *Palaeodasycladus mediterraneus* var. *heraki, Palaeodasycladus mediterraneus* var. mediterraneus, *Palaeodasycladus mediterraneus* var. *gracilis.*. Bundles of secondary branches are clearly visible. Sample localities and ages--VT: Mali Alan Pass, central Mt. Velebit, Lower Liassic; JD: Jadièevac, central Mt. Velebit, Lower Liassic; TG: Mt. Trnovski Gozd, western Slovenia, Middle Liassic (after Sokač, 2001).

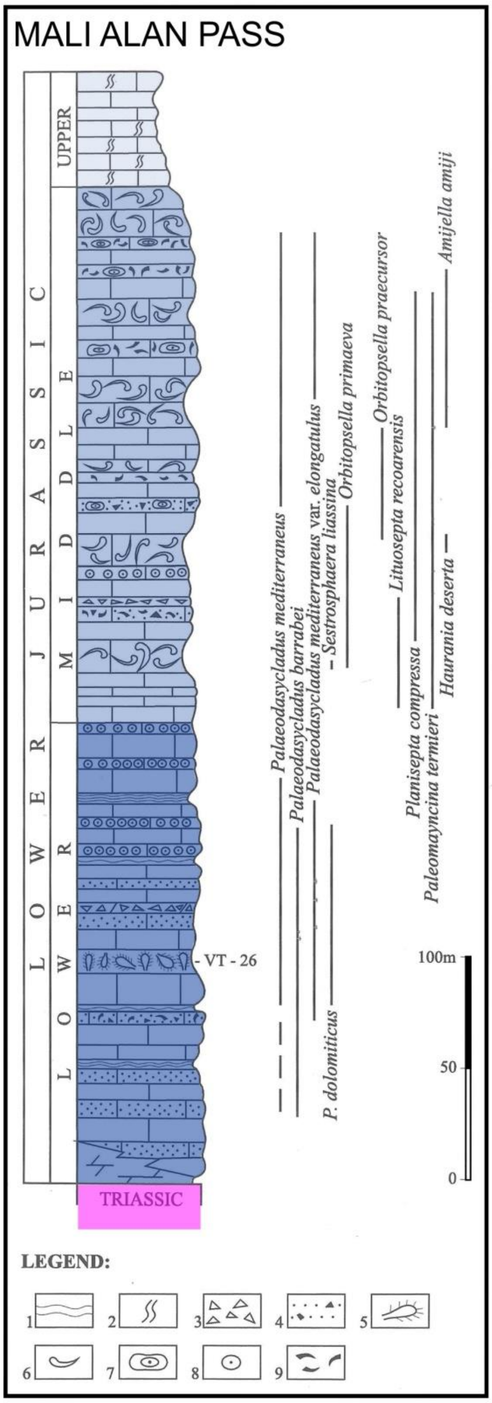


Fig. 2-14. Geological column of the Lower Jurassic deposits of the Mali Alan locality (Velebit Mt.). Legend: 1) stromatolites; 2) bioturbations; 3) peritidal breccia; 4) peloids and intraclasts; 5) dasyclad algae; 6) bivalve *Lithiotis problematica*; 7) oncoids; 8) ooids; 9) bioclasts; VT 26 – sample with algae.

Stop 5:

Lithiotides limestone unit—Plinsbachian-Toarcian (c. 190.8-174.1 Ma)

In the upper portion of Lower Jurassic limestone and dolomites we find mud-supported limestones (**Fig. 2-15**). This 215 m thick limestone succession (**Fig. 2-14**). represent fossiliferous, skeletal-bioclastic mudstones, wackstones, floatstones and rudstones alternating with mudstones, wackstones, peloidal packstones in shallowing upward sequence

(Velić, 2007). Int the top hangingwall sequences submarine slides and slump folds could be found. Lithiotides shells (**Fig. 2-16**) are transported, often current-oriented resembling 2 m thick cocina beds. Lithiotides shells could be found either resedimented or in primary positon. Beside macroscopic fossils of Lithiotides, Brachiopodes and Gastropods, in this limestone units many microfossils could be found. Calcareous algae and bentic foraminifera *Orbitopsella primaeva and Orbitopsella praecoursor* prevail (see **Fig. 2-17;** Velić
, 2007b, c).

Fig. 2-15. Strata of Middle Lower Jurassic Lithiotides limestone unit inclined towards SW in the vicinity of Mali Alan pass.

Fig. 2-16. Middle Lower Jurassic Lithiotides limestone detail with Lithiotis shells.

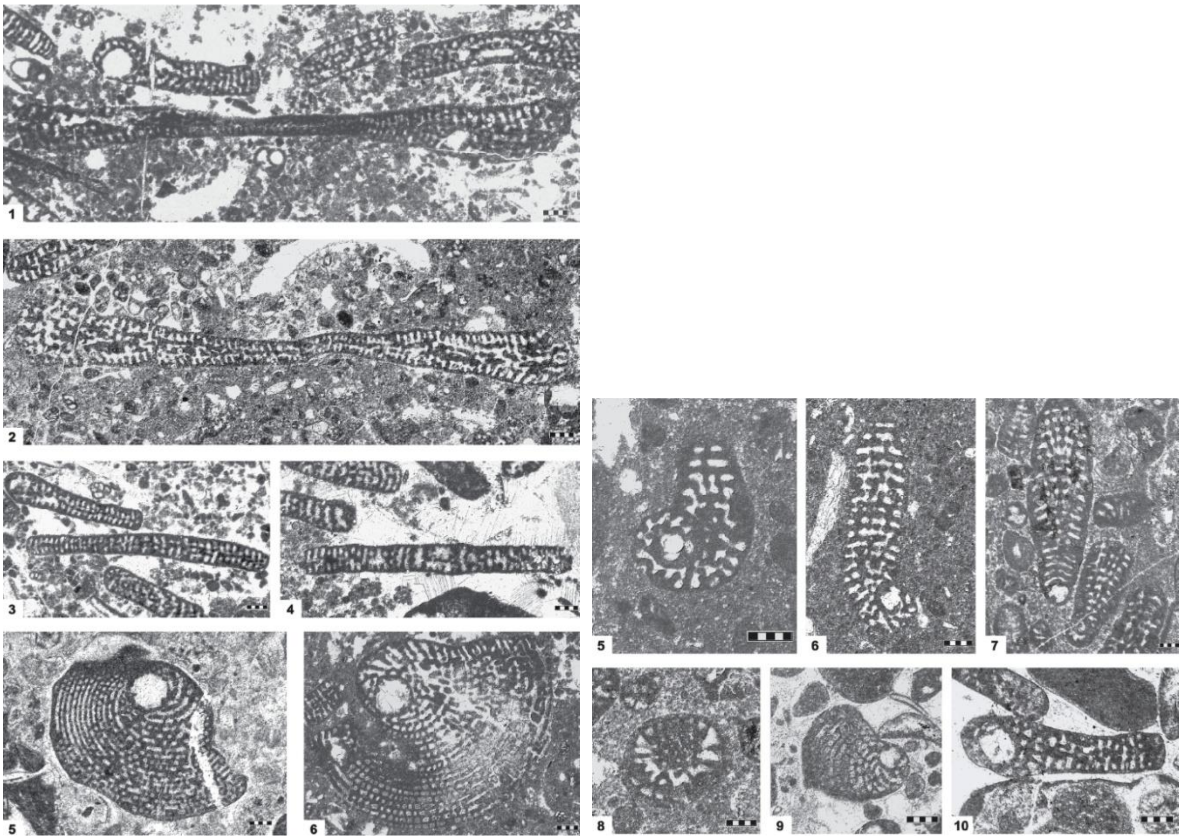


Fig. 2-17. Microscopic section of 1–4 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; 1 – megalosphaeric and microsphaerc forms, 2–4 – microsphaeric forms; 1, 3–4: North Velebit Mt., 2: Central Velebit Mt., Croatia. 5–6 Orbitopsella praecursor (GÜMBEL), Pliensbachian; megalosphaeric forms, 5: Central Velebit Mt., 6: Plitvice, Croatia. 5–8 Lituosepta recoarensis CATI, Late Sinemurian–Early Pliensbachian; 5–6: Central Velebit Mt., 7–8: Gornje Jelenje, Croatia. 9–10 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; megalosphaeric forms, 9–10:South Velebit Mt., 11: North Velebit Mt. Scale bars – 0.2 mm (after Velić, 2007).

Stop 6:

Fleckenkalk, “Spotty” limestone unit—Toarcian (c. 182.7-174.1 Ma)

At the stop 6, immediately after last beds of Litiotides limestone unit we follow Fleckenkak or “Spotty” limestone unit (**Figs. 2-14** and **2-18**). With total thickness of c. 120 m, this thin bedded strata (10-60 cm strata) represent intensively bioturbated mudstone/wackstones (**Fig. 2-19**). This resulted in “spotty” limestone pattern that is in German “Fleckenkalk”. Fleckenkalk also contain biclasts and ooids.

This unit deposited predominatly in deeper subtidal and lagunal enviroments, under oxgen reduced conditions. This deposition correlate with Toarcian Oceanic Anoxic Event (Velić, 2007c). With respect to its erosion-prone characteristic the relief in fleckenkalk are low than in surrounding Jurassic rocks.

Fig. 2-18. Fleckenkalk, “Spotty” limestone unit at stop 6 where is its contact with Lithiotides limestone unit.

Fig. 2-19. Fleckenkalk, “Spotty” limestone unit in detail with fossil bioturbations.

Stop 7:

Middle Jurassic massive limestone unit—Aalenian-Callovian (c. 174.1-163.5 Ma)

This massive Middle Jurassic limestone unit in the vicinity of Mali Alan pass, along the road Gračac-Vratce reach c. 430 m (**Fig. 2-20**). Middle Jurassic carbonates are represented by ooidic, bioclastic and intraclastic limstones deposited in high water energy enviroments (Velić, 2007c).

This limestone succession is abundant in microfossils (**Fig. 2-21)** of calcareous algae (e.g., *Selliporella donzelli, Thaumatoporella parvovesiculifera),* lituolids foraminifera, hauraniids, cyclamminids and pfenderinas (e.g., *Meyendorffina bathonica, Pfenderina salernitana)* and gastropoda. Limestones are grey-brownish and occasionally are interfingered with dolomites. The total strata thickness is in a range of 30 to 150 cm, whereas in the topmost section strata thickness can reach c. 4 m. (Ivanović et al., 1976).

Fig. 2-20. Massive limestone strata outcrop at the boundary with fleckenkalk. Beds are inclined towards SW.

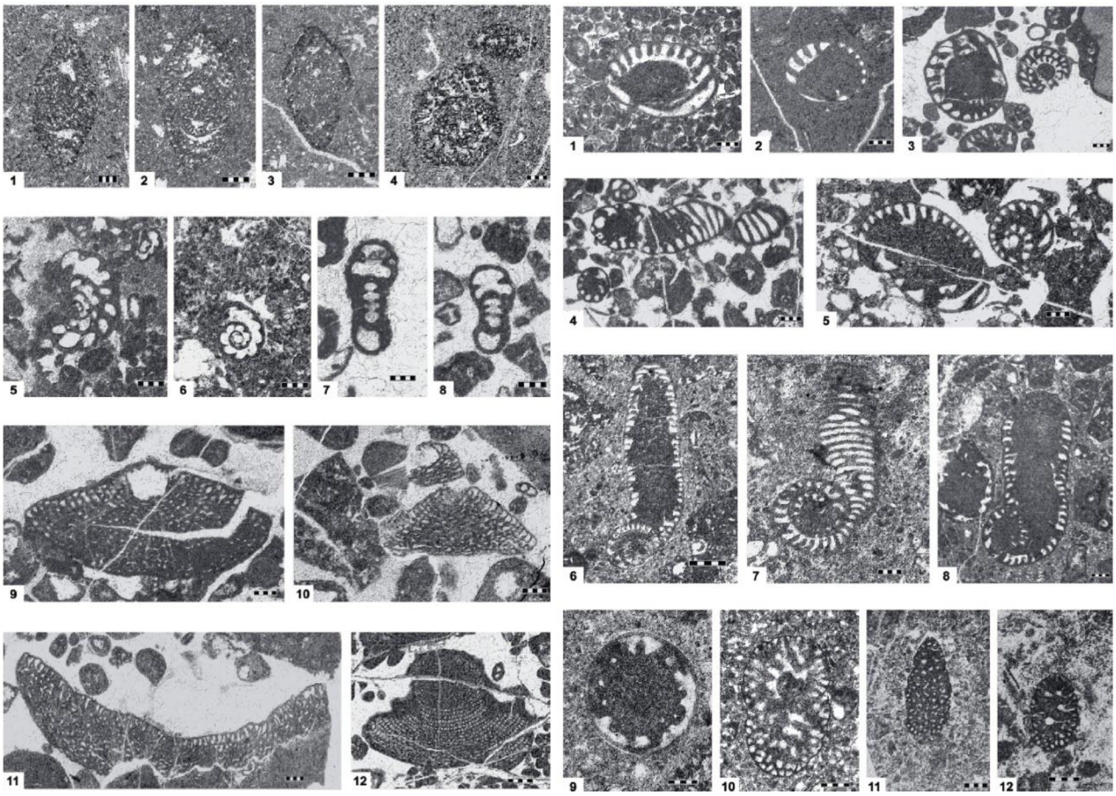


Fig. 2-21. Microscopic section. Left sections--1–4 Pseudocyclammina liassica HOTTINGER, Late Pliensbachian, Velika Kapela Mt., Croatia. 5–8 Mesoendothyra croatica GUŠIĆ, Aalenian–Bajocian; 5 – South Velebit Mt., 6–7 – Biokovo Mt., 8 Dubrovnik area, Croatia. 9–12 Gutnicella cayeuxi (LUCAS), Aalenian–Early Bajocian; 9–10 – megalosphaeric forms, 11–12 – microsphaeric forms: Dubrovnik area, Croatia.Right sections--1–5 Paleopfenderina salernitana (SARTONI & CRESCENTI), Bathonian; 1–3, 5 – microsphaeric forms, 4–5 – megalosphaeric forms; 1: South Velebit Mt., 2: North Velebit Mt., 3–5: Biokovo Mt., Croatia 6–9 Satorina apuliensis FUORCADE & CHOROWICZ, Late Bathonian, 6–7, 9: Western Istria, 8: South Velebit Mt., Croatia. 10–12 Kurnubia jurassica (HENSON), Late Callovian–Oxfordian; 10, 12: Western Istria, 11: South Velebit Mt., Croatia. (after Velić, 2007c).

Stop 8 & 8a:

Carbonate polymictic breccia unit (Jelar/Mt. Velebit breccia) —Eocene-oligocene? (c. 56.0-23.03 Ma)

The Jelar/Velebit polymictic breccia is know to cover W and SW slopes of Mt. Velebit, c. 2 km wide amd 100 km long area. In the vicinity of the Sv. Rok tunnel Jelar/Velebit breccia are in tectonic contact with Upper Jurassic and Lower Cretaceous limestones (**Fig. 2-22**). Jelar/Velebit carbonate breccia are composed of various angular to subangular clasts, clast-supported eith grey or reddish matrix (**Fig. 2-23**).

Clast size is extremely variable depending of degree of tectonization and mechanical disintegration, from several mm to several dm in size. In relation to source rocks clasts of breccia prevail (Velić et al., 2007). The age of Jelar/Velebit breccia is estimated in accordance to the source clasts that in vicinity of Baške Oštarije (c. 55 km NW) are Eocene in age (i.e., foraminiferal limestone). In te SE large amounts of tectonically fragmented material were transported by alluvial systems that yielded also thick sequences of Promina conglomerates (Velić et al., 2007).

Fig. 2-22. Carbonate polimiknic breccia at Romanovac quarry in the vicinity of Sv. Rok.

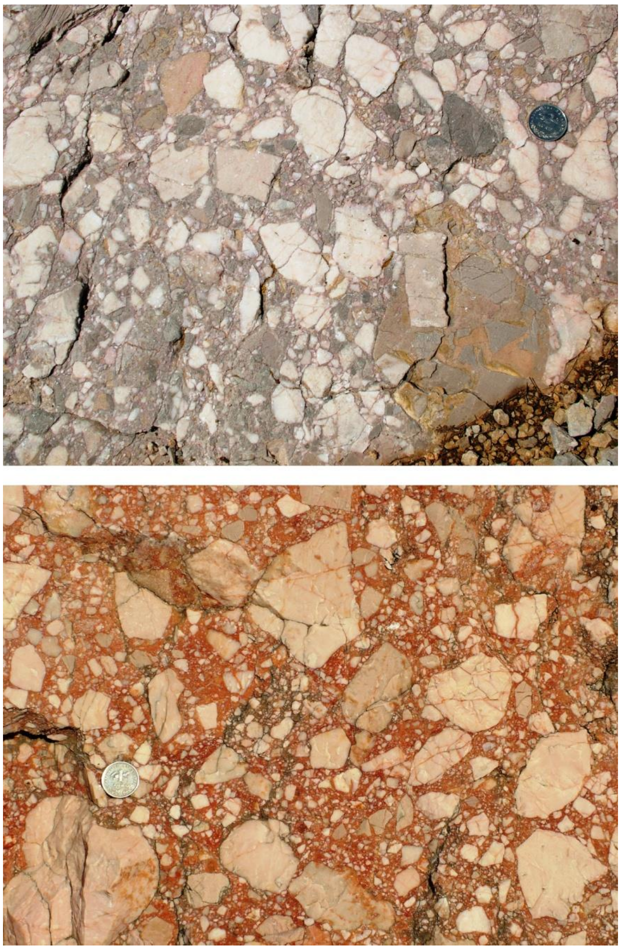


Fig. 2-23. Jelar or Velebit polimiknic breccia examples.

***3. DAY** (06. 07. 2016.)* **–** External Dinaridic Units**--**

National Park Paklenica -

Text, map and photos were acquired while working on a project for National park Paklenica and from book Velić, I., Velić, J., Vlahović, I., Cvetković, M. (2014): Geološki vodič kroz NP Paklenica (Geological Guide trough NP Paklenica – in English). Paklenica National Park, 325 pp.

Tour of the Northern Eastern part of the National Park Paklenica will be a profile trough mainly Middle and Upper Triassic and Lower Jurassic carbonates and Triassic clastics. Approximate length of the tour is 13 km (6.5 km in on direction), approximate starting elevation is 750 m, maximum height at Sv. Brdo at 1751 m (**Fig. 3-1**).

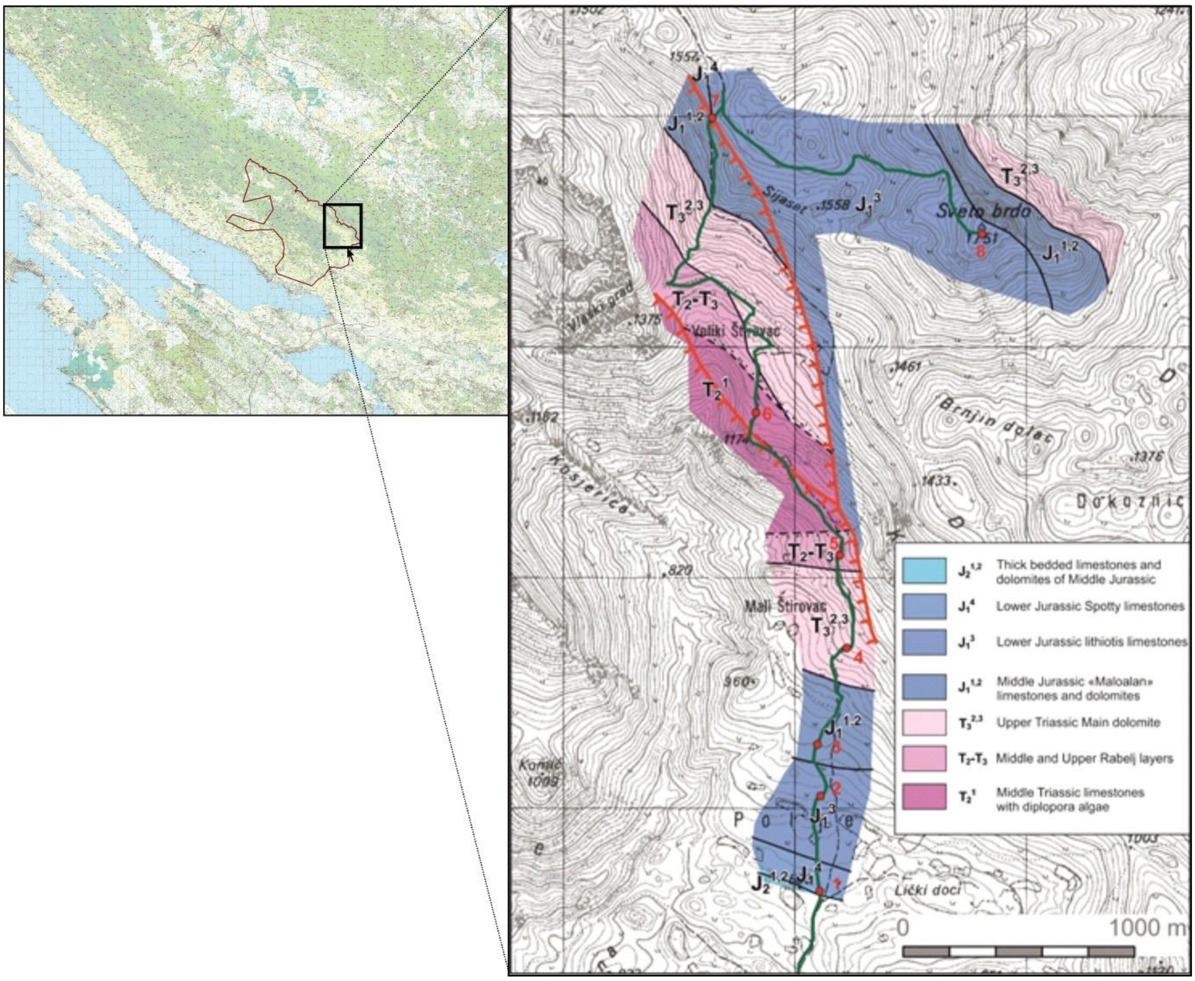


Fig. 3-1. Route through Middle and Upper Triassic and Lower Jurassic Limestones on the Eastern border of National park Paklenica

Stop 1:

Boundary of the thick-bedded limestones of the Upper Jurassic and Lower Jurassic "spotty" limestones. Approximate age of these limestones is 181 to 174 MA. Spotty limestones are mostly covered by younger, possibly glacial sediments that will be available for observation later. The "spotty" aperance of these carbonates is due to the uneven late diagenetic dolomitization and bioturbation (**Fig. 3-2**). Dominantly, they are comprised of layers of dark colored mudstones and fine grained ooide grainstones. Typically, they are thin bedded (20 – 30 cm) but occasionally the bedding can be up to 80 cm. They are deposited in deep water marine environments during an Oceanic anoxic event. At this location, thickness of spotty limestones is about 120 m.

Fig. 3-2. Classic "spotty" limestone.

Stop 2:

Lower Jurassic Lithiotis limestones – a classic facies that can be observed on many location through the Dinarides. Approximate age of these limestones is 195 to 181 Ma. It is named after the shell *Lithiotis* (**Fig. 3-3**) that in this location is abundant in coquina layers which were deposited sometimes in tempestite beds. Along with aforementioned shells, brachiopods can be found as well. Limestones are well-bedded (40 – 60 cm), dark grey to black colored and were dominantly sedimented in subtidal environment although there were periodical emersions which can be observed with emersion breccia. Thickness of these limestones is about 200 m. There number of coquina beds rich with *Lithiotis* is variable through the Dinarides.

Fig. 3-3. Lower Jurassic limestone with abundant Lithiotis shells

Stop 3:

Lower Jurassic limestones and dolomites unofficially named Mali Alan formation is based on the typical locality in Croatia at which they can be observed. Approximate age of these carbonates is 201 to 195 MA. Majority of these sediments is comprised of variation between limestones and dolomites (**Fig. 3-4**). Limestones are typically grey to dark grey colored mudstones or wackestones. Fossil detritus is frequent and mollusca chell fragments can frequently be found. In addition to the aforementioned, remains of the algae genus *Palaeodasycladus* can be found but the most important are the foraminiferae based on which these limestones were dated. These are *Lituosepta* and *Orbiopsella*. These sediments are well-bedded (20 – 80 cm) with a total thickness of about 300 m.

Fig. 3-4. Mali Alan limestone and dolomites (Velić et al., 2014)

Stop 4:

Upper Triassic Hauptdolomite – approximate age from 210 to 201 Ma. Main lithological characteristic of these dolomites is the variation between layers of lighter, laminated, early-diagenetic dolomite, and dark grey to brownish late-diagenetic dolomite with large crystals (**Fig. 3-5**). Bedding is usually well-developed (avg. 50 cm), except in fault zones. These sediments were deposited in shallow water marine environment. Average thickness of these dolomites is around 350 m at surrounding locations.

Fig. 3-5. Variation of late and early-diagenetic dolomite in Upper Triassic main dolomite (Velić et al., 2014)

Stop 5:

Clastic deposits of middle and upper Triassic – “Rabelj” layers. These sediments are a result of the weathering of the palaeokarst environments that was developed in Triassic diplopora limestone. They are comprised of red colored, sandy tufitic slitsones, tufitic sandstones and carbonate clast rich conglomerates and microbreccias (**Fig. 3-6**). The tufitic are a direct result of volcanic activity which was present at that time but more to the North, at present locations of Baške Oštarije, Fužinski Benkovac and Senjska Draga. Red color of the clastics is due to the oxidized iron from devitrified volcanic ash. Thickness of the sediments is around 80 m and approximate age from 235 to 215 Ma.

Fig. 3-6. Microbreccia from Rabelj layers

Stop 6:

Diplopora limestones of Middle Triassic – “***Klimenta***” limestones. These limestones are prone to karstification and their characteristic morphology after karstification can be easily observed trough the field. They are massive, often without bedding. The special features (prone to karstification) is derived from the fact that they were subjected to karstification previously in the geologic history (at the end of middle Triassic). They are light grey to grey colored and resemble marble on a fresh opened surface. Fossil assemblage can be various but most abundant are the fossil algae from genus *Diplopora.*

Fig. 3-7. Vlaški Grad peak in Diplopora limestones

Stop 7:

Northern Paklenica reverse fault – overlook of the fault zone.

Stop 8:

Peak Sv. Brdo – overllok of the Paklenica are and Lika. From stop 7 to here there are good outcrops of Lithiotis limestone. Also some glacial features can be observed – circs.

Fig. 3-8. Overview from Sv. Brdo peak towards the NW

***4. DAY** (07. 07. 2016.)* **–** External Dinaridic Units**--**

National Park Northern Velebit

National park Sjeverni Velebit encircles the highest elevation zone of Northern Velebit and the northernmost part of Middle Velebit (**Fig. 4-1**). Established in 1999, NP Northern Velebit covers an area of 109 km^2. It is strongly affected by karstic processes, with many varieties of karst landscape and landforms that by its diversity, presents *locus tipicus* for karstic terrains.

As a result of interaction between thick carbonate succession (c. 8000 m), active tectonics and climate, many surface karst phenomena (**Fig. 4-2**) make this area exceptionally interesting, whereas subsurface karst features (**Fig. 4-2**)., of which the most impressive are caves address the NP Northern Velebit as one of the most interesting speleological localities in the world . Climate influence is especially important in the area due to interchange of glacial and interglacial during Würm period, prominent freezing processes, frequent rainfalls and longlasting snow cover, that in overall increase concentration of dissolved carbon dioxide which cause intense chemical dissolution of carbonates (Velić and Velić, 2009; Perica and Lozić, 2002).

Fig. 4-1. Karstic landcscape in area of peak Crikvena, at elevation of 1641 m.

Fig. 4-2. Karstic surface phenomena called "škrape" (left). Right figure depicts entrance in one of the deepest karstic caves (Lukina jama) with bottom at 1392 m.

Major stratigraphic units in area of NP Northern Velebit (**Figs. 4-3** and **4-4;** Velić et al., 2005):

- ***Middle Triassic*** *(Ladinian) -- Diplopora limestones* are the oldest unit in the Park. Strongly karstified, they occur as massive blocks without observable stratification and bedding. Fossil compostion is related to calcaeous algaes *Diplopora annulata* that is index-fossil for Ladinian. The thickness of these limestone unit in the Park area is between 400-500 m.
- ***Upper Triassic*** -- this succession onset with Carnian and Norian red clastic sediments terrigenous in origin. This clastic sediments starts with reddish, sandy and tuffitic siltstones, tuffitic sandstones, conglomerates and microbreccias. Rhaetian succession is characterized by dolomites, known as *Hauptdolomite (*German) or *Dolomia Principale* (Italian). Main characteristics of this dolomites are alteration of early-diagenetic laminated dolomites with late-diagenetic dark to brownish coarse grained dolomite. The thickness of Hauptdolomite unit in the Park area is between 250 m, whereas the clastic sediments are about 200 m thick.
- ***Jurassic*** succession begins with Lower Jurassic alteration of limestones and dolomites. Limestones are grey to dark grey-colored micrites, with sporadic occurences of bioclasts of molluscs, gastropoda, and shellfishs but most important are microfossil remains of calcareous algae *Paleodasycladus*, index-fossil for Hettangian and Sinemurian. Dolomites are mostly late diagenetic, coarse grained, dark brown and grey. Conformably on this unit overlies the Lower Jurassic limestones Pliensbachian in agre with bivalves and foraminiferas from which the most important

are *Lituosepta* and *Orbitpsella* that are index-fossils for this age. Upper portions of Pliensbachian limestones are characterized by Lithiotides limestone unit. This limestone unit is characterized by fossils of *Lithiotis problematica*, *Cochlearites loppianus, Lithioperna scutata* and others. Beside Lithiotides in this succession we find also brachiopods. Lower Jurassic succession ends with Toarcian Fleckenkalk i.e., "spotty" limestones. With spotty pattern, this limestone unit are very well stratified, platy abundant in ichnofossils. Deposition of these sediments characterize regional tectonic movements and uprising of sea level. Within the area of NP Northern Velebit Lower to Middle Jurassic boundary is characterized with deposition of late-diagenetic dolomites. Middle Jurassic succession resembles thick, stratifed dark grey limestones with very poor fossil content, often karstified. Aalenian and Bajocian limestones however are characterized by foraminifera findings from genus *Praekurnubia and Pseudoeggerella.* In the upper portions of these limestone unit occasionally we can find limestone breccias and Bathonian limestones rich in fossil finding of calcareous algae *Heteroporella anici* (NIKLER & SOKAČ) and *Selliporella* with species of *Satorina, Paleopfenderina, Orbitammina and Pseudoeggerella*. The Upper Jurassic (Oxfordian and Kimmeridgian) limestones are the the most fossiliferous stratigraphic unit. Abundant in macrofossil of *Cladocoropsis,* foraminifera (*Kurnubia*, *Chablaisia, Nautiloculina, Labyrinthina*, *Karaisella*, *Trocholina*, etc.) and algae (*Salpingoporella*, *Griphoporella, Clypeina, Parurgonina)* this unit have high organic content, "bitumen-smell-like" and as such could be considered as potential hydrocarbon source rock. The thickness of Jurassic carbonate succession unit in the Park area is c. 1800 m.

- ***Lower Cretaceous*** is only sporadically present within the NP boundaries. Lower Cretaceous succession is composed of platy, medium thick stratifed limestones. Limestones are characterized by numerous cracks and breccia-like habitus. According to foraminifera content, genus *Campanellula* indicate age of the lowermost part of Lower Cretaceous. Emersion breccia's are also found, indicating shallowing up cycle which ends at the end of Hautervian. Upper Cretaceous sediments are not identifed within the Park boundaries.
- ***Paleogene*** breccia's covers approx. 2/3 of the NP area. This cataclastic breccia are characterized by angular clasts, mostly with dimensions from 1 to 5 cm, sometimes up to 20 or 30 cm and sporadically up to 70 cm in parameter. Clasts are unsorted, polymicnic, different in size and origin, without clear stratification. The total thickness of these breccias variable, up to 400 m. Tectonically deformed and displaced by numerous faults and fractures, these breccias are crushed in several stages that finally resulted in surface and subsurface mechanical and dissolution erosion. As a result, these breccia complex is often characterized by numerous karst phenomena, from which the most distinctive are deep caves. Some of them are the deepest in the Dinarides. Area around Hajdučki and Rožanski kukovi is proclaimed in 1969. as strict reservation with highest degree of protection.
- **Quaternary** deposits are represented by glacial, glaciofluvial and fluvial sediments.

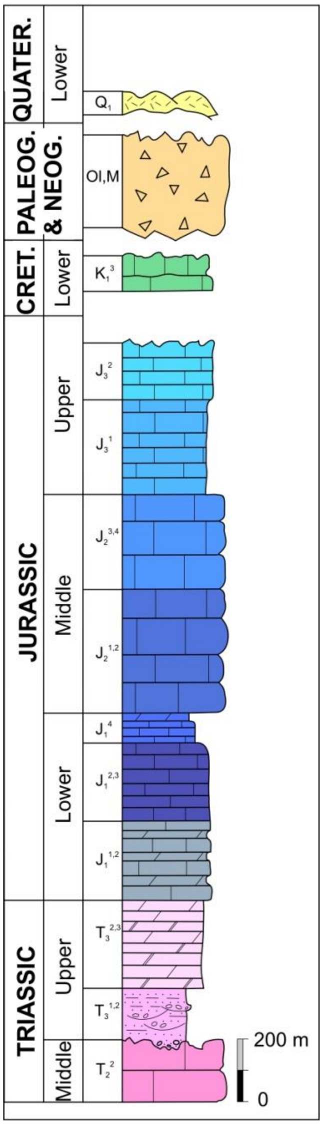


Fig. 4-3. Shematic geological column of carbonate and clastic succession in NP Northern Velebit (Velić et al., 2005).

Structural setting of NP Northern Velebit area:

In the area of NP Northern Velebit five structural units are identifed: Apatišan and Štirovača anticlines, Bakovac-Rožan syncline, and fault zones of Bakovac and Štirovača faults. Fracture system analysis shows existence of multiple oriented set of fracture systems from which the most dominant is fracture system parallel to the strike of main structural units. This furthermore means that formation of the dominant fracture systems were associated to the zones of maximum curvatures where strata were exposed to compressional and extensional stresses. As a result, due to fracture density and its widness in the most convex and concave areas stronger corrosional effect and faster karstification at certain locations has been identified. It is considered that dominant fracture system in the NP area is genetically linked with strata folding and formation of anticline and syncline system during the Dinaridic orogenic phase (Tomljenović et al., 2015).

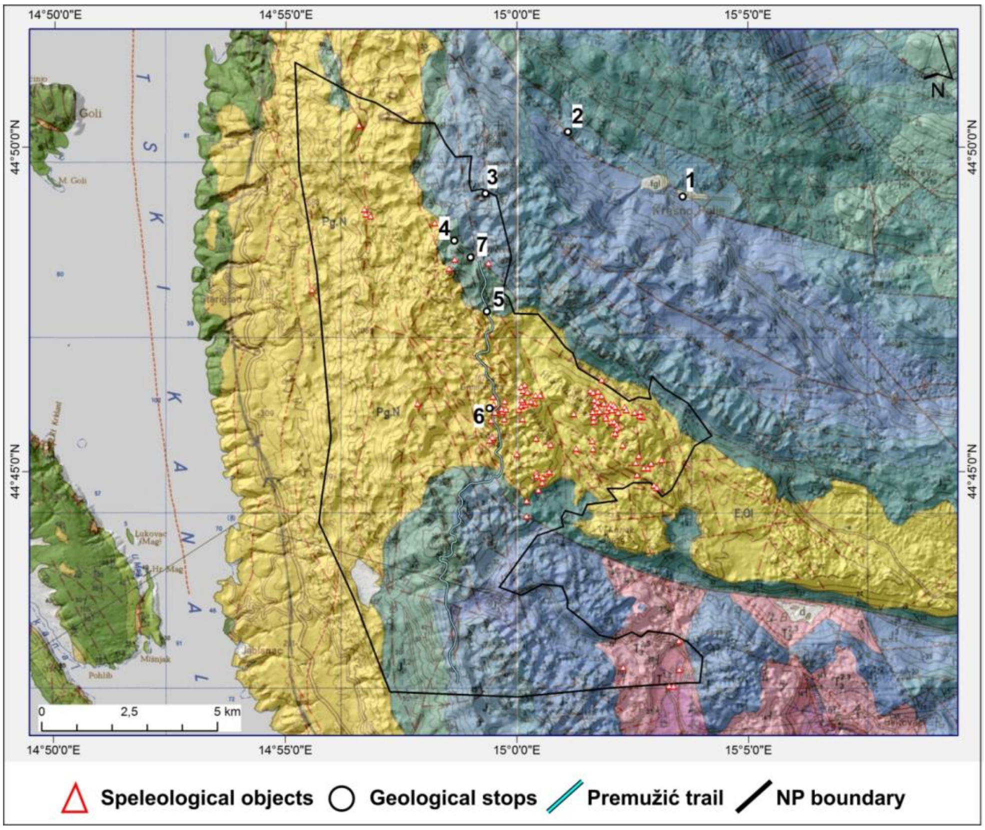


Fig. 4-4. Geological map with numbered stops within the NP Northern Velebit.

Stop 1:

Administration of NP Sjeverni Velebit – multimedia presentation about the NP Sjeverni Velebit.

Location: Krasno polje (**Fig. 4-5**) positioned in central part of WNW – ESE striking 12 km long valley. Krasno polje is characterized by tectono-glacio-fluvial origin along the WNW striking normal fault.

Fig. 4-5. Overview to Krasno polje. Line of sight is from NE towards SW.

Stop 2:

Lower Jurassic: Lithiotides limestones (**Figs. 4.6** and **4.7**) and “Spotty” limestones
Location: Southern slopes of Nadžak bilo that belongs to the NE limb of Apatišan anticline

Fig. 4-5. Brachiopod shells in Lithiotides limestone unit.

Fig. 4-6. Lithiotides cocina detail in Lithiotid limestone unit.

Stop 3:

Middle Jurassic: karsted outcrops of massive Middle Jurassic limestones succession (**Fig. 4-7)**

Location: Blatne doline

Fig. 4-7. Middle Jurassic massive limestone unit

Stop 4:

Upper Jurassic: Oxfordian fossiliferous limestones and Kimmeridgian limestones.

Location: Vučjak- meteorological station and Velebit botanical garden (**Figs. 4-8 and 4-9**).

Fig. 4-8. Meterological station at Vučjak.

Fig. 4-9. Entrance in Velebit botanical garden in the vicinity of meteorological station.

Stop 5:
Kimmeridgian limestones (**Fig. 4-10**) and Velebit breccia's boundry.
Location: 1250 m from entrance in to Premužićeva Trail.

Fig. 4-10. Massive Kimmeridgian limestones with prominent foliation related to active tectonics.

Stop 6.

Paleogene Velebit cataclastic breccia's (**Fig. 4-11**).

Location: Middle part of Strict reservation of Hajdučki and Rožanski kukovi (**Fig. 4-12**).

Fig. 4-11. Velebit polymicnic cataclastic breccia that covers approx. 2/3 of NP area.

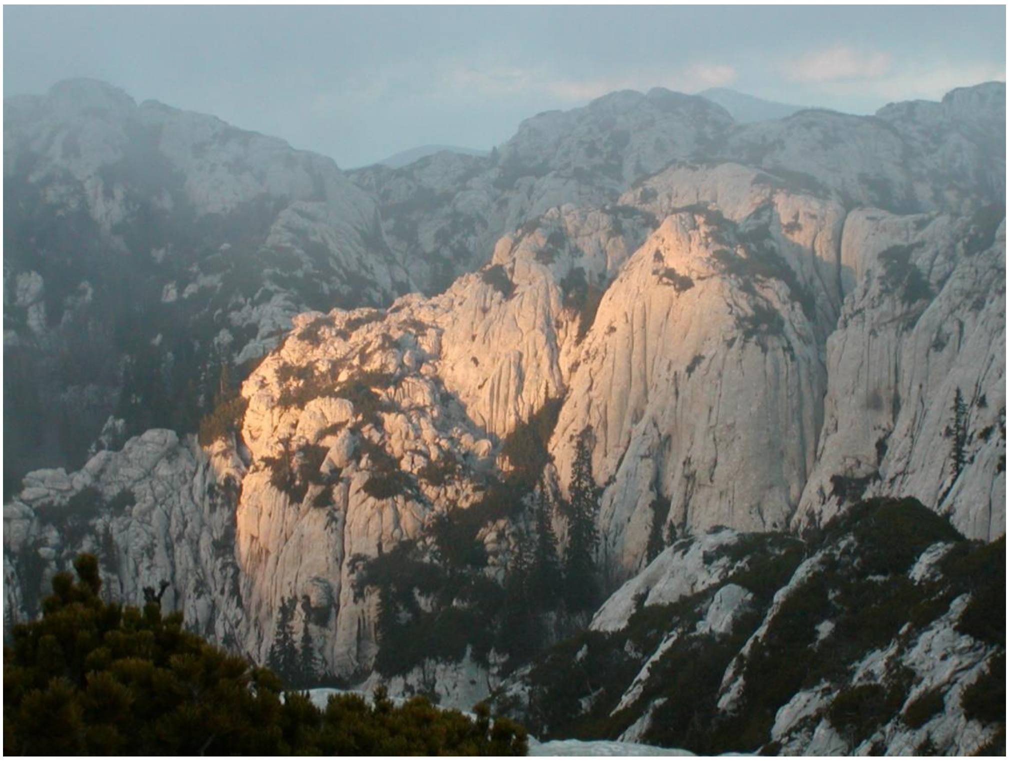


Fig. 4-12. Panoramic view to Strict reservation of Hajdučki and Rožanski kukovi.

Stop 7:
Geological 3D model of the Mt. Velebit with rocks samples from different locations in NP Northern Velebit (**Fig. 4-13**).
Location: Zavižan, Ripište

Fig. 4-12. Geological 3D model of NP area in the vicinity of Zavižan.

***5.** and **6. DAY** (08.-09. 07. 2016.)* - Undeformed Adriatic Carbonate Platform-- **Istria peninsula**

The geological and tectonical overview of Istria as well as description of stops given in this fieldtrip guidebook is based on VLAHOVIĆ, I. & TIŠLJAR, J. (eds.): Evolution of Depositional Environments from the Palaeozoic to the Quaternary in the Karst Dinarides and the Pannonian Basin. 22nd IAS Meeting of Sedimentology, Opatija – September 17–19, 2003, Field Trip Guidebook A1, 1–64. Zagreb.

Geological settings of Istria

The geology of Istria is desribed in the six sheets and explanatory notes to the 1:100,000 scale Basic Geological Map, of Pula (Polšak, 1970), Cres (Magaš, 1973), Rovinj (Polšak and Šikić, 1973), Labin (Šikić and Polšak, 1973), Trieste (Plentičar et al., 1973) and Ilirska Bistrica (Šikić and Plentičar, 1975). Beside geological maps and explenatory nots, the geology of Istria with special focus on lithofacies and biofacies investigations of shallow water carbonates has been studied and investigated by many authors (e.g., Salopek, 1954; Polšak, 1965a, 1965b, 1967; Šikić and Blašković, 1965; Šikić et al., 1969; Magdalenić, 1972; Tišljar, 1976, 1978a, 1978b; Sokač and Velić 1978; Tišljar and Velić, 1986, 1987; Velić et al., 1995a, b; Tišljar et al., 1995; Gabrić et al., 1995; Biondić et al., 1995; Velić et al., 2000; Vlahović et al, 2000a, b; Tišljar et al., 2000a, b; Tunis et al., 2000, Matičec et al., 2000, Sakač and Gabrić, 2000; Šparica et al., 2000; Korbar et al., 2002; Moro et al., 2002; Tišljar et al., 2002a, b; Velić et al., 2002; Vlahović et al., 2002a, and others). This detailed studies we motivated by quite well preserved stratigraphic records at certain localities in Istria, within undeformed part of Adriatic Carbonate Platform, that enabled recognition of important events in the geological history of the Adriatic Carbonate Platform.

Considering the geological peculiarites, stria can be subdivided into three regions (**Fig. 5-1**):

a) the Jurassic–Cretaceous–Eocene carbonate plain of southern and western Istria,
b) the Cretaceous–Eocene carbonate–clastic zone, characterised by overthrust structures in eastern and north-eastern Istria (from Plomin and Učka to Ćićarija), and
c) the Eocene flysch basin in central Istria.

These three Istria's regions are named as : ***Red Istria*** – the southern and western Istrian plain named after the *terra rossa* covering a large part of the younger Mesozoic and Eocene carbonates; ***White Istria*** – in eastern and north-eastern Istria, characterised by karstified outcrops of "white" Cretaceous–Eocene limestones; and ***Grey or Green Istria*** – in central Istria, characterised by Eocene flysch.The Istrian sedimentary succession consists predominantly carbonate rocks ranging in age from Late Dogger to Eocene, with subordinate Eocene siliciclastic rocks, flysch and calcareous breccia, and Quaternary terra rossa and loess (**Fig. 5-2**).

Istria's Late Dogger to Eocene succession can be subdivided into four sedimentary units or megacycle depostional sequences bounded by important discontinuities – emersion surfaces that are covered by Quaternary deposits:

1) Bathonian–lowermost Kimmeridgian;

2) Upper Tithonian–Lower/Upper Aptian;
3) Upper Albian–Upper Santonian;
4) Eocene;
5) Quaternary.

5.1. Bathonian–lowermost Kimmeridgian megacycle depostional sequence (Figs. 5-1 and 5-2)

This sequence is characterised by a shallowing-, and coarsening-upward trend, which in the uppermost part is expressed by the appearance of a regressive breccia (the ***Rovinj breccia*** – Velić and Tišljar, 1988), and a final emergence surface with bauxite deposits. The Bathonian–Lowermost Kimmeridgian succession is represented by types of shallow-water limestones that crops out in western Istria, between Poreč and Rovinj (**Fig. 5-1**).

In the Bathonian and Callovian, shallow subtidal and lagoonal environments were characterised by deposition of of medium- to thick-bedded mudstones and fossiliferous wackestones (the ***Monsena Unit*** – Velić and Tišljar, 1988). Similar depositional environments prevailed during the oldest Oxfordian, with deposition of peloidal packstones and wackestones (the ***Lim Unit* –** Velić and Tišljar, 1988). During the Middle and Late Oxfordian, ooidal sandbars and bioclasts were formed in high-energy shallows and the marginal parts of lagoons, which gradually prograded (tidal bars – Velić and Tišljar, 1987; the ***Muča Unit*** – Velić and Tišljar, 1988). The shallowing-upward tendency continued to the end of the Oxfordian, and during the earliest Kimmeridgian resulted in the formation of the regressive ***Rovinj (Vrsar) breccias*,** representing the end of this megacycle depostional sequence. With emersion and karstification intense relief was formed with accumulation of clayey bauxites. In some places important quantities of bauxite have been formed, e.g. near Rovinj, Rovinjsko selo, near Gradina, as well as between Vrsar and Funtana. The emergence with bauxite deposition in Istria corresponds to the level characterized by significant palaeo-karstification in large part of the AdCP (e.g. Kimmeridgian of Biokovo Mt. – Tišljar et al., 1989; Velić and Tišljar, 1991; see Field trip A2, Stop 8 – Benček et al., this Vol.; NNE part and the platform margin in central and SE Slovenia – Dozet & Mišič, 1997; NW Bosnia – Vrhovčić et al., 1983; E Herzegovina – Natević & Petrović, 1967; W and N Montenegro – Vujisić, 1972; Mirković and Mirković, 1987). Contemporaneously, in the central part of the AdCP, in deeper troughs we have deposition of limestones with cherts and ammonites (Furlani, 1910; Chorowitz and Geyssant, 1972; Velić et al., 1994; Bucković, 1995)

5.2. Upper Tithonian–Lower/Upper Aptian megacycle depostional sequence (Figs. 5-1 and 5-2)

Different types of peritidal deposits predominate, especially pelletal limestones and LLH-stromatolites, with subordinate emersion breccia with clayey matrix (Tithonian, Hauterivian, and Barremian), early- and late-diagenetic dolomites (Berriasian), and grainstones (bioclastic sand bar deposits in the Upper Valanginian and Upper Barremian). Deposits of this large-scale sequence crop out from Poreč, in the form of an arc (Fig. 2), near Kanfanar and Bale, to the coast from Rovinj to the island of Veli Brijun.

The megacycle started in the younger Tithonian with transgression, i.e. shallowing-upward cycles deposited in subtidal, intertidal and supratidal environments. Used as an architectural-building stone called ***Pietra d'Istria*** or ***Kirmenjak***, these limestones are composed of black-pebble breccia/conglomerates, mudstones and fenestral mudstones with desiccation cracks nad dinosaur tracks (see Mezga et al., 2003).

Shallowing during the Berriasian and older Valanginian resulted in the deposition of limestones in subtidal and intertidal environments that were completely late-diagenetically dolomitised, though with early-diagenetic dolomites forming in supratidal environments. This alternation of late and early-diagenetic dolomites is known as ***Fantazija dolomites*** (Velić and Tišljar, 1988). In the younger Valanginian, Hauterivian and a major part of the Barremian numerous short-lasting emersions are observed, with shallowing-upward and frequent LLH-stromatolites and peritidal breccia. Footprints of dinosaurs have been found on the island of Veli Brijuni, as well as bones on the sea floor near the western coast of Istria.

The transition to the Aptian was characterised by a change in the depositional system, that involved relative deepening, into restricted lower subtidal and/or lagoonal environments with sporadic pelagic influences. The Lower Aptian is characterised by massive floatstones with oncolites, ***Bacinella*** and r**equieniids** (*Toucasia* sp.), which are well-known as the architectural-building stone ***Istarski žuti*** (*Yellow Istrian* – named after its yellowish colour). Upper Aptian is characterized by rapid shallowing and emersion. The regional emersion is result of relative fall in sea-level caused by the interaction of eustatic changes and synsedimentary tectonics on the Istrian part of the Adriatic Carbonate Platform. The end of the large-scale sequence was marked by deposition of emersion breccia and conglomerates, with clay and black swamp deposits, which are well exposed in a complete zone in western Istria, from Punta Furlan, Baderna, Heraki, Selina, Kanfanar, Bale, Negrin and Barbariga to Veli Brijun. In the vicinity of Baderna there are traces of bauxite on Barremian limestones, besides emersion breccia.

5.3. Upper Albian-Upper Santonian megacycle depostional sequence (Figs. 5-1 and 5-2)

This megacycle depositinal sequence is very thick (**Fig. 5-2**) with a very variable facies succession. After emersion during the late Aptian and early Albian, complete ingression occurred during the late Albian. The shallow-water platform carbonate system was re-established over the whole of the AdCP with depositon of *peritidal and foreshore sedimentary system (middle and late Albian), sedimentary systems during the Vraconian and Cenomanian, drowned platform system during Cenomanian and early Turonian, and shallow-water sedimentary system during late Turonian, Coniacian and Santonian*.

Albian deposits are characterised by transgression in the Middle Albian, covering the completely emerged area of Istria. In the late Albian a thick sequence of thin-bedded (5–20 cm) grainy limestones was deposited in peritidal and foreshore environments (i.e., fine-grained intraclastic-peloidal packstone/grainstones alternating with foraminifer-peloid packstones/wackestones, and less frequent LLH-stromatolites). The uppermost part of the Albian deposits is commonly represented by limestone breccia and grainy limestones with gently inclined cross-bedded sets and current ripples, and diagenetic quartz sediments.

The transition from the Early to the Late Cretaceous was marked by the establishment of different sedimentary environments in northern and southern Istria (Vlahović et al., 1994). In northern Istria stable peritidal conditions continued into the earliest Cenomanian. The younger part of the Early Cenomanian and the older part of the Middle Cenomanian facies differentiation was along the inclined inner carbonate ramp. Subtidal mudstones, peloid wackestone/packstones with benthic foraminifera and rudist debris (mostly radiolitids – *Sauvagesia*?, *Eoradiolites*), foraminiferal-bioclastic wackestones and thinner intertidal fenestral mudstones and LLH-stromatolite were deposited. In the central part of northern Istria, near Marušići, prograding carbonate bioclastic packstone/grainstones was deposited in upper shoreface and foreshore environments. In the eastern part of northern Istria, bioclastic, occasionally storm-deposited wackestones, packstones and grainstones, sporadic relics of rudist congregations, were deposited, while in locally restricted lagoons mudstone and chert bed were deposited. In southern Istria, the latest Albian and Early to Middle Cenomanian were characterised by the establishment of a shoreface depositional system showing the effects of synsedimentary tectonics, slumps, tempestites, carbonate sand and rudist clinoforms and biolithite bodies (TIŠLJAR et al., 1998). Within rudist-bearing deposits, radiolitids (*Sauvagesia*, *Eoradiolites*), caprinids (*Caprina*, *Neocaprina*, *Schiosia*, etc.), ichthyosarcolitids (*Ichthyo-sarcolites*), polyconitids (*Polyconites*) and requieniids have been found. The boundary between these deposits and the Middle to Upper Cenomanian limestones is sharp with change from massive clinoformal bioclastic bodies into thin-bedded (5–25 cm) limestones deposited in low energy shallow-water environments. Peloid-bioclastic wackestone/packstones and peloid grainstones predominate, with rudist biostromes and chondrodontid coquinas. Middle to Upper Cenomanian shallow-water deposits also contain reptile tracks on the island of **Fenoliga** (Gogala, 1975).

Facies characteristics of the Cenomanian and Turonian was associated to the drowned platform depositional system which was established in southern Istria. As a resul, „limestones with ammonites" were deposited, i.e., mudstone/wackestones with planktonic fauna (including ammonites). This deepening was not recorded in northern Istria; Upper Cenomanian beds became emergent and covered by bauxites and transgressive Eocene deposits. The succession of Cenomanian deposits in northern Istria compared to southern Istria indicate the role of synsedimentary tectonics (Vlahović et al., 1994).

During the Late Turonian, Coniacian and Santonian a shallow-water platform depositional system was re-established over the entire region of modern-day Istria. It was represented by well-bedded limestones with an alternation of thin layers of mudstone, bioclastic wackestone/packstone and stromatolite laminae in the older part, and mostly thin-bedded rudist coquinas/microcoquinas/lithosomes and bivalve rudists coquinas (*Distefanella*/*Biradiolites*, *Durania*, *Sauvagesia*, *Medeella*, *Radiolites*, *Praeradio-lites*, *Lapeirousia*, *Gorjanovicia*, *Bournonia*, *Vaccinites* and *Hippurites*) in the younger part of the deposits (TIŠLJAR, 1978a). The youngest part of the Cretaceous succession is missing, as a result of emersion related to Late Cretaceous tectonics.

5.4. **Eocene megacycle depostional sequence (Figs. 5-1** and **5-2)**

Istria comprises a relatively thick succession of carbonate and siliciclastic rocks. Its greatest part crops out in the Pazin Basin and neighbouring areas. With variable emersion phase duration between the Early to Late Cretaceous and Early Eocene, members of the

Eocene sedimentary succession were transgressively deposited on different members of the Cretaceous basement. This resulted in very variable Eocene deposits in the lateral and vertical sense. In general, Eocene deposits can be divided into: *Liburnian deposits, Foraminiferal Limestones, Transitional beds and Flysch.*

Liburnian deposits, locally present, were deposited in the lowest parts of the palaeorelief. They are characterised by an oscillating ingression, and are mostly represented by fresh-water to brackish, lagoonal deposits of the Early Eocene.

Foraminiferal limestones in Istria can be divided into three or four lithostratigraphic types deposited from the "Cuisian"/Ypresian to the Middle–Late Lutetian. These are *Miliolidae*-, *Alveolina*-, *Nummulites*- and "*Discocyclina*"-limestones, which specifically represent the uppermost part of the *Nummulites*-limestones. The foraminiferal limestones are mostly composed of whole and broken larger foraminiferal tests, with subordinate detritus of molluscs, ostracods, echinoderms, bryozoans and corallinacean algae, as well as glauconite grains and planktonic foraminifera in the uppermost part. The sequence of foraminiferal limestones represents a succession of different environments, from the restricted inner part of the carbonate platform (Miliolidae-limestones), through shallower and deeper parts of shoreface environments (*Alveolina*- and *Nummulites*-limestones) to deeper parts of relatively open carbonate ramps ("*Discocyclina*"-limestones). The sequence depends upon local palaeogeographic properties resulting in the lateral changes, the mixing of different types, etc.

Transitional beds are typical shallow marine and deep marine deposits. They consist of the "*Marls with crabs*" and "*Globigerina Marls*". "*Marls with crabs*" are well developed in the lower part of the transitional beds as a thin (not more than 5m) zone of nodular-shaped deposits, consisting clayey limestones, calcitic marls, composed of fine-grained carbonate and a siliciclastic matrix with glauconite. The fossil content is composed of planktonic foraminifera, bioclasts of benthic organisms and the often well preserved shells of crabs and echinoderms. The upper part of *the Transitional beds* consist of thick (few to several tens of m), massive "*Globigerina Marls*", sometimes with rare thin sandstone beds.

Istrian flysch deposits (Istrian Eocene clastics) crop out in the Trieste–Pazin, Labin and Plomin basins, Mt. Učka, and partly on Mt. Ćićarija. They are characterized by an alternation of hemipelagic marls and gravity-flow deposits. The prevailing turbidite succession of hybrid carbonate-siliciclastic sandstones and marls is randomly intercalated with several thick carbonate beds of debrite origin, i. e. megabeds. The depth of deposition was concluded to be of bathyal range based on morphotype associations of smaller benthic foraminifera (Živković, 1996). The total thickness of Istrian flysch deposits is estimated as up to 350 m.

5.5. Quaternary deposits

Quaternary deposits represent a relatively thin cover of all the four aforementioned large-scale sequences of Istrian carbonates and flysch deposits. The most important are loess and terra rossa although there are also other types of palaeosols and soils.

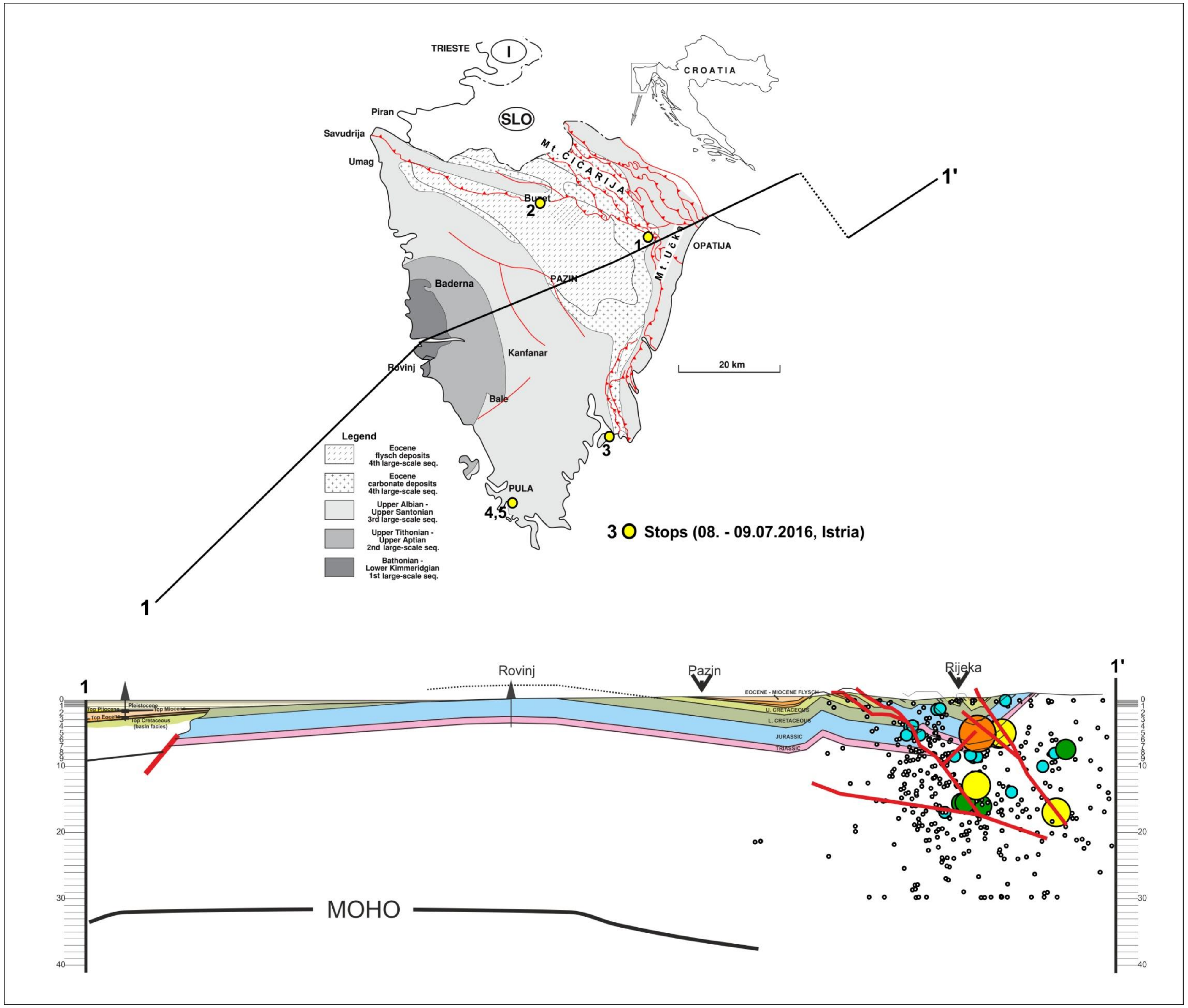


Fig. 5-1. A. Map showing the schematic distribution of large-scale sequences in Istria (after Velić et al., 1995a), and the location of the drawn cross-section. Deposits of all large-scale sequences of Istrian carbonates and flysch are for the most part irregularly covered by relatively thin Quaternary deposits. B. Regional scale profile across the Adriatic offshore, the gently folded block of the stable Adria and the Klana-Senj seismogenic zone based on interpretation of reflection seismics, well data and surface geology obtained from geological map of sheets Rovinj, Ilirska Bistrica, Labin, Crikvenica and Delnice (after Tomljenović et al., 2009).

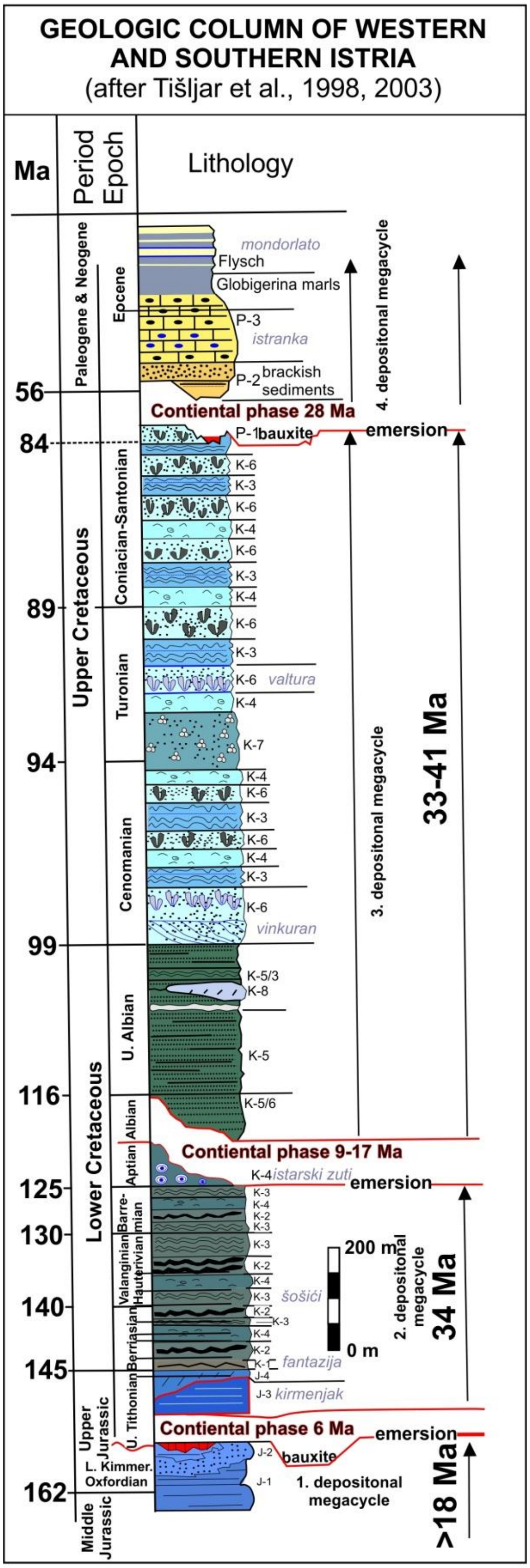


Fig. 5-2. Geological column of western and southern Istria

Tectonic characteristics of Istria

The tectonic pattern of Istria is composed of three structural units (**Fig. 5-1B**). The Western Istrian anticline comprises the largest part of western and southern Istria that is composed of carbonate deposits of the Middle and Upper Jurassic in its oldest part, and surrounded by Cretaceous and Eocene carbonates. The second structural unit, the Pazin Flysch Basin, is composed of relatively thin Eocene limestones and thick flysch deposits, cropping out in the central and NW parts of the peninsula. The third structural unit is composed of stacked thrusted structures of Ćićarija Mt. in the northern part and of eastern Istria, as well as the Učka Nappe that are composed of Upper Cretaceous and Eocene carbonates and Eocene flysch.

The oldest record of tectonic activity in Istria has been found in the Upper Bathonian depostis in the coastal area north of Rovinj, and partly in the area of the Limski kanal representing the oldest deformation in Istria.The effects of these movements were local emersion and a more intensified relief of the subtidal area. The movements were the consequence of mild compression. Until the beginning of the Kimmeridgian when the area of Istria was influenced by a regional emersion that lasted through the major part of the Kimmeridgian and Early Tithonian, relief was formed mostly by steep conjugate normal faults and extension. Tectonic activity during the Cretaceous can be identifed by synsedimentary movements that are associated to the Western Istrian anticline formed during Hauterivian. The hinge of this macrostructure remained emergent throughout the rest of the Cretaceous, i.e. until the Eocene transgression. The emerged area was inhabited by dinosaurs during the interval from (at least) the Hauterivian to the Late Cenomanian as indicated by their footprints and bones. By the end of the Cretaceous, almost the entire Adriatic Carbonate Platform, including the area of Istria, was affected by regional emersion of very variable duration. Emersion was the consequence of the final Cretaceous compression. The Upper Cretaceous tectonic events initiated the disintegration of the former carbonate platform, and marked the end of typical, productive platform carbonate sedimentation, since renewed marine conditions in the Eocene had different characteristics.The Eocene transgression was a consequence of formation of flysch basin that in Istria was associated with the beginning of subduction of the NE part of the Western Istrian Anticlinorium beneath the future overthrust structures of Ćićarija.characterised by SW vergence. The duration of this deformation phase is not definitively denoted however these movements probably are partly Miocene in age.

The neotectonic deformation in Istria and in the entire Dinarides is a consequence of the N–S oriented activity of the greatest regional stress. Neotectonic activity comprised either the formation of new, neotectonic structures, reactivation of inherited old brittle structures into the regional transcurrent faults, or rotation of already existing structures towards the new stress orientation.

Stop 1:

Mt Učka and Mt. Ćićarija- nappe system

Location: Vela Učka- Panoramic view of Mt Učka and Mt. Ćićarija

At location Vela Učka, beneath the panoramic view we see stacked thrusted structures of Mt. Ćićarija in the northern part and Mt. Učka Nappe to the east (**Fig. 5-3**).. These nappe system were formed during Dinaridic orogenic phase and are composed of Upper Cretaceous and Eocene carbonates and Eocene flysch deposits (**Fig. 5-4).** The Cretaceous limestones are rich in rudists and compose massive to thickly bedded wackestone–packstones, alternating with floatstones containing a rich radiolitid–*Vaccinites* assemblage. Besides numerous radiolitids and their bioclasts, in the predominantly para-auto-chthonous rudist congregations, numerous individuals of *Vaccinites* (Fig. 70) have also been recognized. Within these 40–60 cm thick limestone layers, radiolitids are in para-autochthonous position. The depositional environment was affected by open sea influences, and represents a general shallowing trend; from the limestones with calcispheres, through limestones with Vaccinites and radiolitids, to typical shallow-water deposits with abundant radiolitids. In the footwall of Cretaceous limestone nappes Eocene foraminiferal limestone (i.e., *Miliolidae*-, *Alveolina*-, *Nummulites*- and “*Discocyclina*”-limestone succession and flysch depostis are found. Flysch depostis resembles turbidite succession of carbonate-siliciclastic sandstones and marls intercalated with carbonate megabeds.

Fig. 5-3. Panoramic view of Mt. Ćićarija nappes. North is to the right side of picture.

Fig. 5-4. Panoramic view towards south, to the Pazin flysch basin.

Stop 2:

Eocene Istrian flysch deposits
Location: Čiritež, c. 5 km east town Buzet

Flysch deposition begin with the first occurrences of the alternation of sandstone and marl beds (**Fig. 5-5**) above the homogenous "*Globigerina Marls*" Flysch section comprises up to 350 m of flysch deposits. The lower part of the flysch unit contains carbonate and marl beds ranging in thickness from 0.3 to about 7 m, while the upper part is composed of an alternation of thin hybrid carbonate–siliciclastic beds and marls.

The carbonate beds comprise conglomerates, foraminiferal breccias, arenites and siltites. Some thick beds (megabeds) are of dual origin, i.e. debrite and turbidite. Lower parts of the megabeds of debrite origin are composed of lithic debris up to 20–30 cm in diameter. Clasts of Late Cretaceous deposits, various types of Palaeogene limestones and marl chips. Skeletal particles of large foraminifera (ortho-phragminas, nummulites), corrallinaceans, gastropods, and corals are very common. Debrites are normally graded, clast supported. Upwards, the megabeds gradually change character from debrite to turbidite, and this transition lead to the conclusion that the megabeds are the result of a single sedimentation event. Carbonate turbidites are normally graded and can be described as complete Bouma Ta–e sequences. Coarse-grained clasts (debrites) are interpreted as the products of cohesive gravity-flow i.e., debris flows and high-density turbidite currents, while the origin of carbonate turbidites is attributed to low density turbidite currents (**Fig. 5-6**). The increasing intensity of clastic deposition could be associated to instability of shelves and seismotectonic activity. Thick massive marls in the upper part of the megabeds were deposited from the ponded turbidity current tails

According to the composition of the carbonate megabeds land contributed lithoclasts of Late Cretaceous limestones, different types of Palaeogene limestones and probably "*Globigerina Marls*" was derived from a shallow-marine environment, which existed on the upper margin of the flysch trough. On the basis of palaeocurrent data collected from carbonate beds in the southern part of the Pazin Basin, the existence of a foreland high situated on the southern parts of the present-day Istrian peninsula is proposed (Babić and Zupanič, 1996).

Fig. 5-5. Eoocene flysch deposits originated as turbidite currents. Note thick marl succsession interlayered with sandstones.

Fig. 5-6. Eoocene flysch deposits with preserved folding of more competent sandstone layers within the surrounding marl.

Stop 3:

Cretaceous-Paleogene succesion boundary
Location: Koromačno bay

In the Koromačno bay, in the hinge zone of Labin anticline we will observe Cretaceous-Paleogene boundary. Cretaceous carbonate succession here is related to thick and layered limestones (c. 1-3 m thick strata) wit dominant white color. These Cenomanian limestones in the Koromačno bay are without identifiable strata bedding, however rich in fossil rudists (**Fig. 5-7**) that sporadically ocurr as massive bars (Magaš, 1973). The total rudist limestone thickness here is ≤ 800 m.

In its topmost part, the Cretaceous-Paleogene boundary is characterized by karstifed paleosurface that is sporadically covered by breccias, bauxitic and bauxite-like deposits (**Fig. 5-8**; Magaš, 1973). Above these deposits we find Upper Paleocene to Early Eocene **Liburnian deposits** that are represented by fresh-water to brackish, lagoonal deposits. In the Koromačno bay these deposits begin with brownish and platy bituminous limestones with smaller intercalations of breccias and coal-bearing limestones (Magaš, 1973). In the upper portions Liburnian deposits resembles interchange of brownish-black bituminous and coal-bearing limestones (**Fig. 5-9**) with total thickness between 150-200 m. Liburnian limestones are rich in fossils, especially in gastropods (*Melania sp, Charydrobia sp., Hydrobia sp., Stromatopsis sp., Cosinia sp., etc.)*.

Above Liburnian deposits, in the paleodepression, we find Eocene foraminiferal limestone succession (*Miliolidae*-, *Alveolina*-, *Nummulites*- and “*Discocyclina*”-limestone) that is characterized by variable thickness (between 530 and 730 m of thickness; **Fig. 5-10**) , and Istrian flysch deposits with c. 200 m of thickness (Magaš, 1973).

Fig. 5-7. Upper Cretaceous limestone rich in macrofossil of rudist bivalves.

Fig. 5-8. Cretaceous-Paleogene boundary. Note bauxitic-colored karstifed paleorelief surface with clastics at the top of Upper Cretaceous rudist limestone. Above boundary there is thick succession of Liburnian deposits.

Fig. 5-9. Liburnian deposits with brownish to black bituminous and coal-bearing limestones.

Fig. 5-10. Eocene foraminiferal limestone succession. Detail of *Nummulitic* limestone.

Stop 4:
Cretaceous Upper Albian to Middle Cenomanian carbonate succession in southern Istria (**Fig. 5-11**).
Location: Cintinera cove, Banjole- c. 7 km south from town Pula

At this location we shall see Facies Units 2 and 3 of Cretaceous Upper Albian to Middle Cenomanian carbonate succession in southern Istria.

- Facies Unit 1 - Thin-bedded peloidal and stromatolitic limestones (Upper Albian), fine-grained, well-sorted peloidal wackestones and packstones alternating with mudstones, and sporadic LLH-stromatolites and intraformational breccias. Late-diagenetic dolomitisation is sporadic, and at some localities the deposits are almost completely dolomitised into hypidiomorphic micro- to macrocrystalline dolomites. Deposits contain small gastropods, ostracods and an assemblage of Late Albian benthic foraminifera. Limestones of this facies unit are interpreted as peri-tidal deposits, with common shallowing-upward cycles.
- Facies Unit 2 - packstones/grainstones with sliding and slumping features (Vraconian–Lowermost Cenomanian). Thin-bedded peritidal peloidal and stromatolitic limestones of Facies Unit 1 to well bedded (~20 cm) laminated wackestone/packstones with thin layers of peloidal grainstones of Facies Unit 2 is gradual. Further up the succession, stromatolites are completely absent, while the proportion of thicker (30–40 cm), medium to coarse-grained, intraclastic–peloidal grainstones containing foraminifera and infrequent large (0.5 to 4 mm) micritic intraclasts gradually increases. The microfossil assemblage is characterised by ostracods and small benthic foraminifera (mostly miliolids) are very infrequent. This unit is characterised by small slides and small-scale synsedimentary faults.

Synsedimentary tectonics represent a part of the regional compressional deformation, which resulted in the uplift of the NW hinterland of the study area (Matičec et al., 1996).

- Facies Unit 3 - Storm-generated and nodular limestones (Lower Cenomanian).

Deposits of this unit is divided into two parts: (1) thin bedded and hummocky beds and (2) biotur-bated nodular limestones. Thin bedded and hummocky beds are mostly composed of alternations of thin (<1 mm thick) laminae of mudstone/wackestone and intraclastic–peloid packstone, grainstone with sporadic small benthic foraminifera and bioclasts of molluscs. The presence of structures of probable storm origin in the overlying and underlying beds, and deeper environment of their deposition coud be regarded as additional arguments for this interpretation. Deposits of Facies Unit 3 are interpreted as being of shoreface to offshore origin, i.e. as deposited near fair-weather wave base, and might correspond to the transgres-sive systems tract.

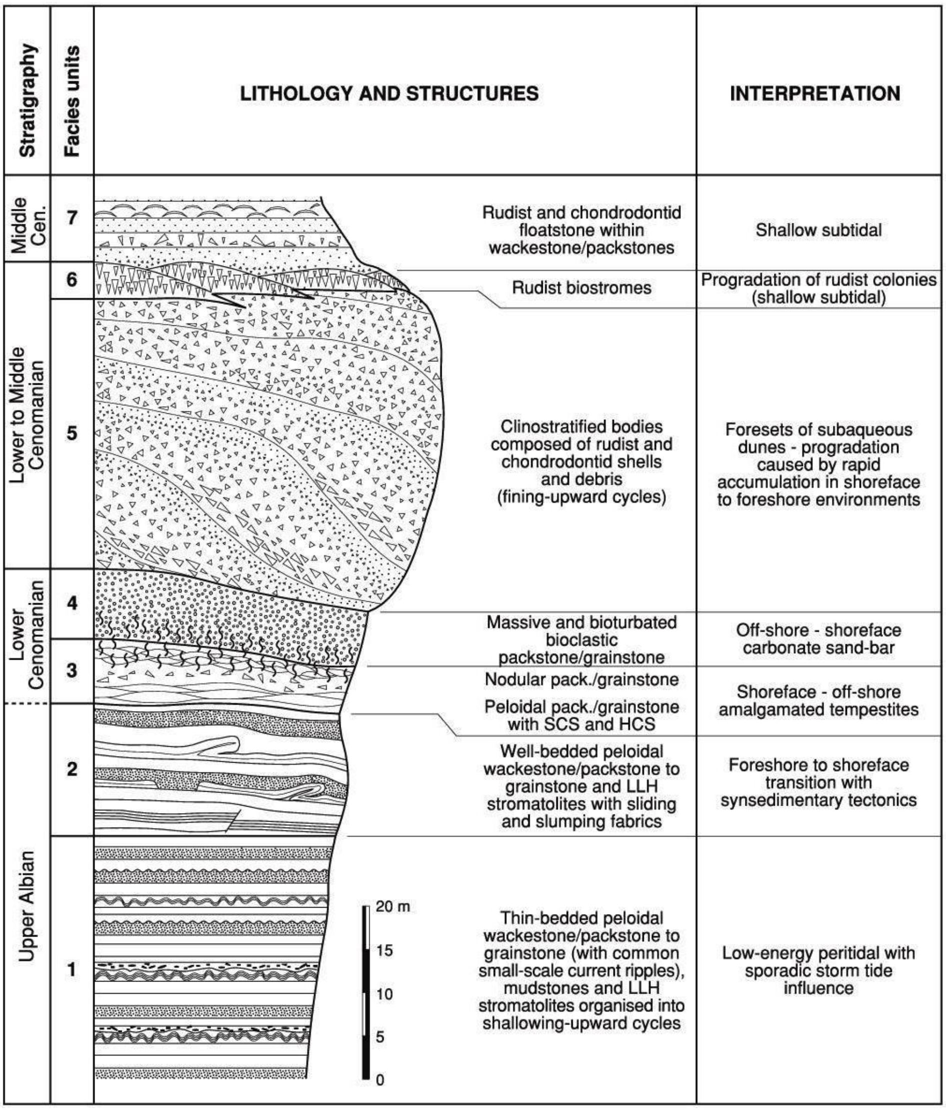


Fig. 5-11. Geological column of th Upper Albian to Middle Cenomanian carbonate succession in southern Istria (after Vlahović et al., 2003 and references therin).

Stop 5:

Cretaceous Upper Albian to Middle Cenomanian carbonate succession in southern Istria.
Location: Vinkuran quarry (c. 6 km south from town Pula) and Roman Arena in Pula (**Fig. 5-12-A** and **B)**

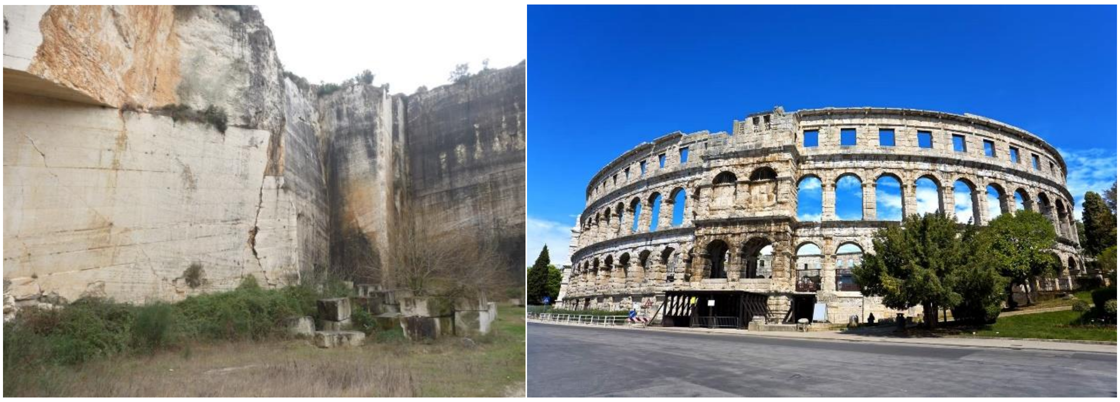


Fig. 5-12. A. Vinkuran quarry. B. Roman Arena in Pula built from bioclastic limestones exploited from Vinkuran quarry.

The Vinkuran quarry is known from Roman times, i.e. “Cava Romana” or “Roman Quarry”. Many buildings were built from the stone blocks extracted from this quarry, e.g., the Arena in Pula (69 to 79 AD). An approximately 40 m thick sequence of massive bioclastic limestones comprises three different types:

Facies unit 4 – Massive bioturbated bioclastic packstone/grainstone (6-15 m thick, ***Vinkuran statuario***; **Fig. 5-13**);

- gradual transition from shoreface to offshore enviroments to clinostratified bodies of Facies unit 5. Bioturbation might indicate period of lower sedimentation rate.

Facies unit 5 – Clinostratified bodies (fining-upward cycles) composed of rudist shells and coarse- and fine-grained debris (name ***Vinkuran fiorito*** and ***Vinkuran unito***)

- numerous clinostratified bodies (c. 2-6 m thickness), each body is characterized by fining-upward sequence. The bodies are classified as rudist-chondrodontid floatstones consisting of poorly sorted fragments of shells. FU5 are interpreted as prograding forsets of subaqueous dines

Facies Unit 6 – rudist biostromes (***Vinkuran fiorito***).

- Extensive rudist biostromesin their primary growth position. Frequent radiolitid rudist, nerineids and chondrodonts, and gastropods.

The succession of Lower to Middle Cenomanian limestones in the Vinkuran quarry represents a coarsening- and shallowing-upward sequence formed by the progradation of rudist debris and colonies towards the south-east (**Fig. 5-14**;Tišljar et al., 1995, 1998a,b).

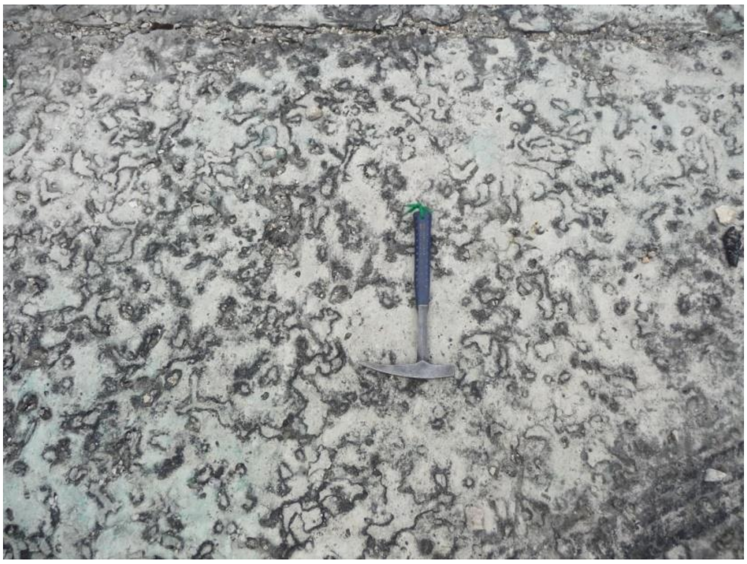


Fig. 5-13. Detail of massive bioturbated bioclastic packstone/grainstone of ***Vinkuran statuario.***

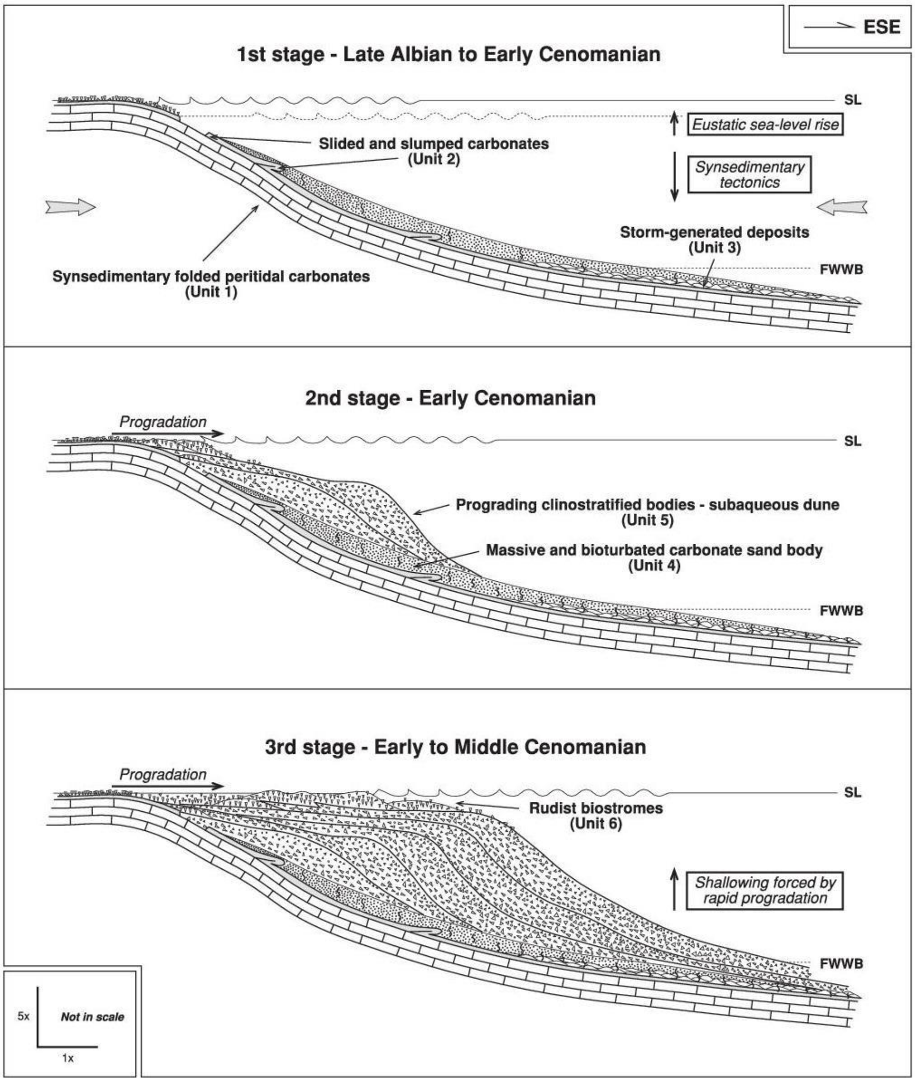


Fig. 5-14. Late Albian to Middle Cenomanian facies succession in southern Istria (after Vlahović et al., 2003 and refereces therein)

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