Depositional conditions during Pliocene and Pleistocene in Northern Adriatic and possible lithostratigraphic division of these rocks

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ORIGINAL SCIENTIFIC PAPER

In the area of Northern Adriatic Neogene and Quaternary sediments have relatively large thicknesses. Those are deposited in some depressions located inside Adriatic Basin, where is the largest Po Depression. Recent borders of Po Depression are located in Italian and Croatian offshore where hemipelagic sequences of Pliocene and Pleistocene were interrupted by Po palaeodelta progradations, and to a lesser extent of Adige and Piave Rivers. These sediments include important reservoirs with significant quantities of hydrocarbon gas, and it is why they are well explored in areas of Italian and Croatian gas fields by deep wells as well as different methods for subsurface imaging, mostly by reflective seismic. Sequence of Pliocene and Pleistocene sediments can reach thickness of 6 000 m, and it is divided in lithostratigraphic system with units in rank of formation. On Italian side Cenozoic sediments up to Mesozoic basement are divided in twelve formations, but on Croatian side has been described only one formation. It is Susak Formation that encompasses all Cenozoic rocks. It is why in Croatian part of Northern Adriatic in proposed introducing of the following lithostratigraphic units 8in rank of formation): Dinaridi Formation (Mesozoic rocks), Susak Formation (Palaeocene-Miocene rocks), Istra Formation (Pliocene sediments) and Ivana Formation (Pleistocene and Holocene sediments).

Key words: lithostratigraphy, Pliocene, Pleistocene, Po Depression, North Adriatic, Croatia

1. INTRODUCTION

Republic of Croatia territory included more than 54 000 km² of Adriatic Sea. According to bathymetry the offshore can be subdivided into four areas. Looking from the north toward south these are:[21] (1) area between Istra and Po River delta, where is sea bottom slightly jagged with maximal depth up to 39 m, (2) from line Ravenna-Pula to line Ancona-Zadar with average depths up to 70 m, (3) transitional zone between Central and Southern Adriatic with depths between 70-200 m, (4) from line Monte Gargano-Mljet-Pelješac toward south with depths 200 - 1 000 m and strongly jagged.

During geological history depositional conditions and tectonic activity in Adriatic offshore had been significantly changed. Adriatic Sea is eventually formed in Holocene after Flandrian transgression.[3,6,16] However, deposits that today are incorporate in Adriatic Basin are significantly older. The oldest rocks proven in wells are Permian and Triassic, which are up to Ladinian series deposited at epeiric carbonate platform, as part of so called Adria-Apulia plate located on the north-eastern margin of Gondwana. It is followed by rocks of intra-oceanic, isolated Southern Tethyan Megaplatform (STM) from end of Ladinian to late Early Jurassic (Toarcian). It is covered by sediments of Adriatic Carbonate Platform (AdCP) from Toarcian to the end of Cretaceous.[23] During Permian period clastics, evaporates and carbonates had been deposited, and in Lower Triassic clastites and carbonates. Locally part of

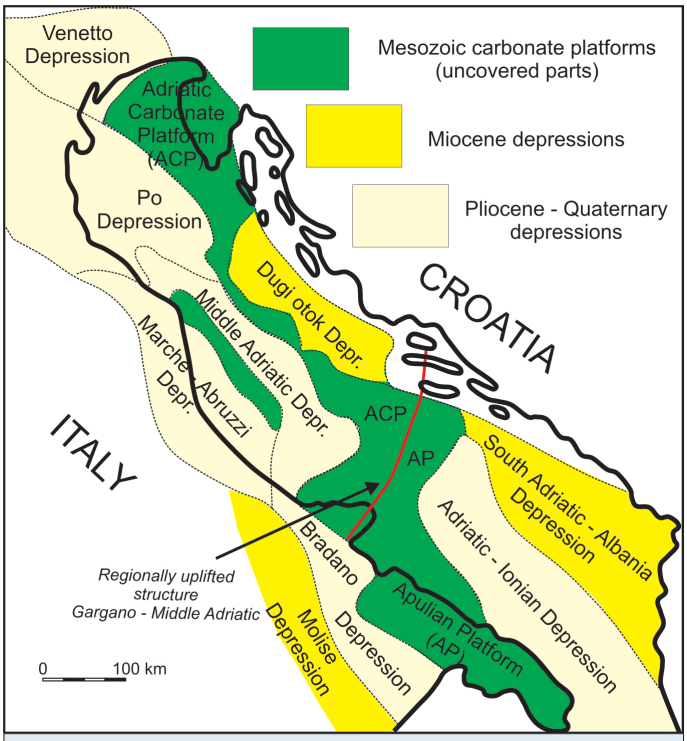

Fig. 1. Depression in Adriatic offshore (modified after 13)
Sl. 1. Depresije u Jadranskom podmorju (modificirano prema13)

these rocks had been deposited in sabkha environment. Strong tectonic displacements were recorded along deep faults through entire lithosphere during Middle Triassic. It caused basin extension and volcanism. Large AdCP had been gradually disintegrated and uplifted at the end of Cretaceous. Transgression in Early Palaeogene only locally reactivated marine of fresh water sedimentation. Uplifting was accompanied with clastic sedimentation[10], which lasted also in Miocene, Pliocene, Pleistocene and Holocene, but with different detritus sources. In analysed area of North Adriatic, sediments from Palaeocene to Miocene age can be found only locally and mostly in deeper parts, represented by carbonates. On contrary, Pliocene, Pleistocene and Holocene deposits have covered entire area with significant thicknesses and consist of marlstones, clay (stones), siltstones, silts, sandstones and sands.[13]

Adriatic Basin is divided on particular depressions of different ages regarding beginning of creation. Three depressions are formed in Miocene: Dugi otok, South Adriatic-Albania and Molise. Later, in Pliocene, sinking of sea basin bottom caused forming of other depressions: Venetto, Po, Marche-Abruzzi, Middle Adriatic, Bradano and Adriatic-Ionian[13] (Figure 1). The largest depressions are Po and South Adriatic-Albania, but no one has continuous borders and depositional environments through geological past. it is reflected in different sediment thicknesses and areas as well as unconformities among particular lithological units. Depressions are mostly asymmetrical. Croatian part includes entire Dugi otok Depression, eastern parts of Po and Middle Adriatic Depressions and northern part of Southern Adriatic-Albania Depression.

The goal of presented analysis and proposed lithostratigraphic division is area of Po Depression. The largest part is today located onshore, between Southern Alps and Apennines, which in Pliocene was under sea level (Figure 3). The rest is in northern Adriatic offshore ranging to margins of Istrian part of AdCP. Numerous Croatian gas fields are discovered in the eastern part of depression. Generally Po Depression is fulfilled by sediments of Pliocene, Pleistocene and Holocene age. Siliciclastic detritus have origin mostly in Alps and partially from Apennines. Total thickness can locally overreach 6 000 m in Italian part. In entire Po Depression many hydrocarbon reservoirs had been discovered, mostly of gas. It pointed out the need for sediment division based on lithostratigraphy nomenclature. Moreover, the first gas discoveries had been found in Italian offshore and first lithostratigraphy units had been outlined very detail. On contrary, Croatian nomenclature mostly was based on results obtained with surface exploration of eolian sediments of Susak Island as well as of uncovered parts of AdCP located in Istra. It is why Croatian lithostratigraphy included significantly lower number of lithostratigraphy units. Today valid lithostratigraphy nomenclature in Italian and Croatian parts of Po Depression is given in Table 1.

It is clear (Table 1) that some kind of problem exists in Croatian part of Po Depression regarding dividing or describing of Cenozoic sediments, because all are incorporated in one formation Susak. It directly resulted from fact that this formation had been described before discoveries of significant quantities of gas in this part of Croatian offshore, i.e. before detail seismic profiling and well drilling. However, after almost three decades of different exploration, large numbers of data sets are available. There was possible to outline differences between Neogene and Quaternary sediments, changes in depositional environments and influence of strong climate transitions. All these data together made possible to construct more detailed lithostratigraphic division.

Table 1. Comparison of Croatian and Italian lithostratigraphy nomenclature for rank of formation

Chronostratigraphic units	Lithostratigraphic formations		
	Croatian name	Italian name	
Holocene	Recent sediments		
Pleistocene	Susak	Ravenna	
		Carola	Santerno
Pliocene	Susak	Porto Garibaldi	
		Corsini*	
		Canopo*	
		Santerno	
Miocene	Susak	Clara	
		Corinna	
		Schlier	
		Cavanella B	
		Bisciaro	
		Cavanella A	
Oligocene		Scaglia Cinerea	
Eocene (Palaeocene?)		Scaglia	
Mesozoic	Dinaridi		Calcari Del Cellina

(*characteristic lithofacieses of these formations exist exclusive in Italian part of Po Depression)

2. Palaeogeographic reconstruction of Northern Adriatic during Pliocene and Pleistocene

Reconstruction of depositional environment of Po Depression is given for Pliocene and Pleistocene epochs, when Adriatic Sea was forming up to present-day borders, mostly influenced by glacial and interglacial periods.

2.1. Northern Adriatic in Pliocene (5 332-2 588 Ma)

At the end of Miocene, approx. 6 Ma ago, glacial in Antarctic area caused

global sea-level decreasing for about 50 m. Also, the connection through Gibraltar with Atlantic was interrupted and in Mediterranean sea-level had been significantly decreased. In many shallow water environments a large quantities of evaporates had been sedimented. It is known as Messinian salinity crisis event reflected also in Adriatic (e.g. ref.[22]). Evaporates are today in the top of Miocene sediments in Mediterranean (Figure 2), what is confirmed in the 1970 by drillings performed with ship Challenger.[25] The largest part of Mediterranean represents in Messinian isolated, shallow water, evaporates basin, reduced at the less than half of previous water area. Similar event of reducing happened 10 - 11 Ma ago and little bit more to the north, when Paratethys was disintegrated in several smaller basins (Pannonian, Dacian, Black Sea, Caspian, Aral[12,15]). However, connection between Mediterranean and Atlantic was re-established at the end of Messinian and new sedimentation cycle begun in new marine environment.

In the beginning of Miocene global sea-level rising was happened. This level was higher in Lower Pliocene than today. Adriatic Sea then covered much larger area, especially at the side of present-day Italy (Figure 3), what can be concluded from distribution of marine Pliocene sediments in the foot hills of Northern Apennines and in the delta of Po River.[21]

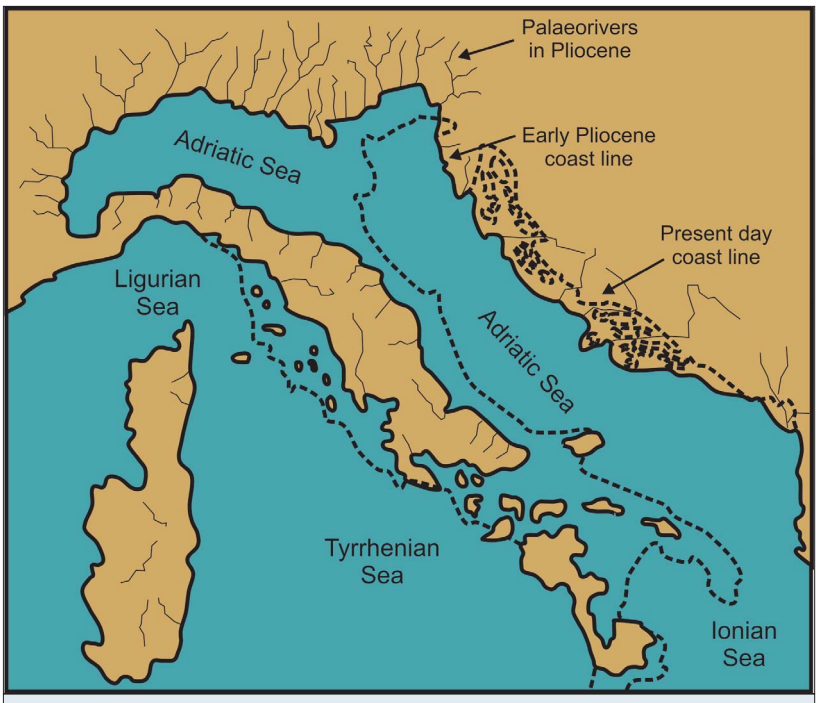

Fig. 3. Adriatic Sea borders in Lower Pliocene (modified after[26])
Sl. 3. Granice Jadranskog mora u donjem pliocenu (modificirano prema[26])

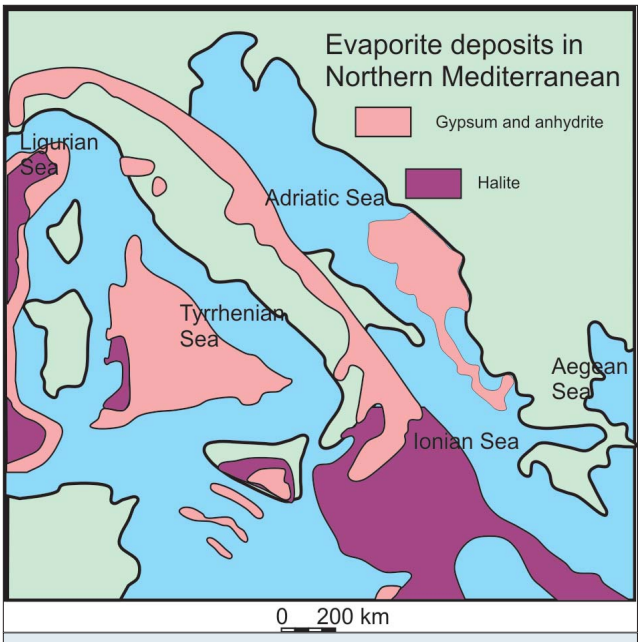

Fig. 2. Distribution of Messinian sediments of halite, gypsum and anhidrite in Mediterranean (modified after[25])
Sl. 2. Rasprostanjenost mesinskih naslaga halita, gipsa i anhidrita u Sredozemlju (modificirano prema[25])

Sediments of Lower Pliocene in Croatian part of Adriatic are characterised by numerous samples of marine planktonic and benthic foraminifera, which palaeontologically indicate on warm climate and sedimentation in deeper and open sea, i.e. in outer shelf.[2,17] Upper Pliocene sediments indicate on decreasing in species number and larger quantity of planktonic foraminifera[8] what describe moderate-cold climate as result of glaciation. Benthic foraminifera in Northern Adriatic are indicator of lower, epibathial environment with average depth 600–1 000 m. These sediments that today have larger permeability are mostly deposited at Italian side of basin slope in the area that was relatively fast sinking during Upper Pliocene, i.e. 3.0-2.2 Ma ago.[14] Foraminifer's species also indicate that large mass of organic matter had been transported in this area. It was held in upper part of water column thanks to eutrophic conditions or deposited with sands.

2.2. Northern Adriatic in Quaternary (2 588 Ma – present)

Quaternary period is divided in Pleistocene epoch (2 588-0.011 7 Ma) and Holocene epoch (0.011 7 Ma to recent). It is characterized by climate changes that caused many changes of life evolution and relief forms. Marine Pleistocene sediments had been deposited both in cold, moderate and warm conditions of open and middle shelf to lithoral. In some place periodically land existed. In the northern Earth hemisphere six glacial periods had been registered, with warmer interglacials among them. According to Alpine division glacial are called *Biber, Donaü, Günz, Mindel, Riss, Würm* (Table 2).

Table 2. Glacials and interglacials during Pleistocene (modified after[27])

Names	Glacials and interglacials	Age (years)
Würm	Glacial	11 700 - 110 000
Riss- Würm	Interglacial	110 000 - 130 000
Riss	Glacial	130 000-200 000
Mindell-Riss	Interglacial	200 000 - 300/380 000
Mindell	Glacial	300/ 380 000 - 455 000
Günz – Mindell	Interglacial	455 000 - 620 000
Günz	Glacial	620 000 - 680 000
Günz – Donaü	Interglacial	850 000 - 1300 000 (?)
Donaü	Glacial	1300 000 - 1 550 000
Donaü – Biber	Interglacial	2 100 000 - 2 500 000
Biber	Glacial	2 500 000- ?

During Pleistocene glacials volume of ice was three times larger than today, and ice covers had average thickness about 2 km. Huge amount of ocean water was iced what decreased sea-level more than 120 m in comparison with present-day. On contrary, inter-glacial periods resulted in sea-level rising, and sometimes it overreached present level for several meters. Such sea-level changes during Pleistocene and Holocene had been reflected in palaeogeography of Adriatic Sea, which after last glacial[7] (Würm) obtained recent borders (Figures 4, 5).

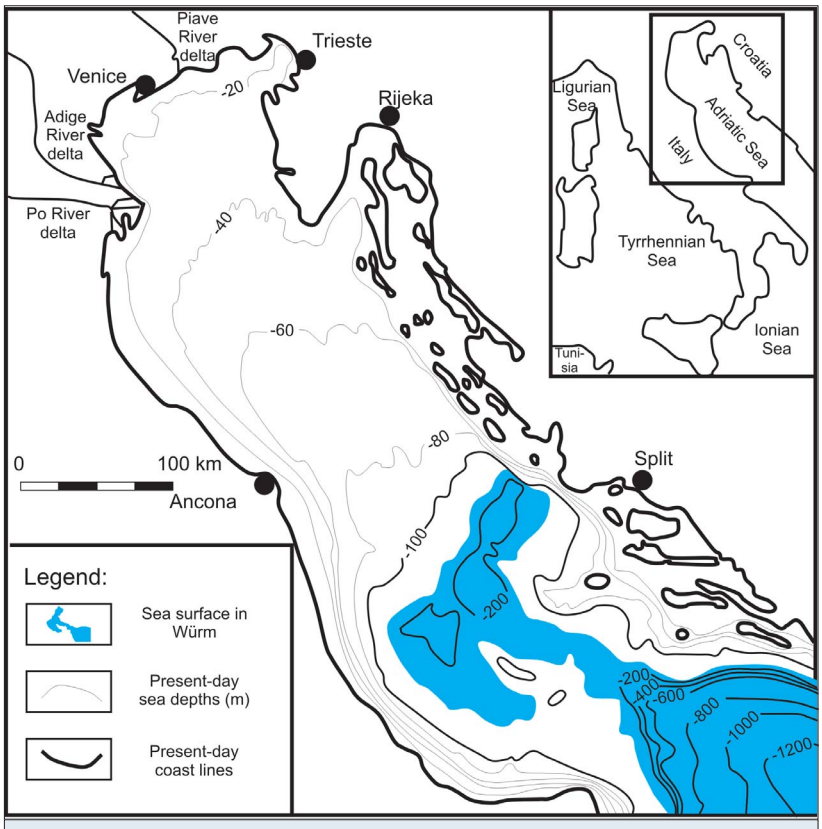

Fig. 4. Borders of Adriatic Sea during Würm (modified after[4])
Sl. 4. Granice Jadranskog mora tijekom virma (modificirano prema[4])

2.3. Depositional characteristics during Pliocene and Pleistocene

During Pliocene and Pleistocene material in Po Depression was mainly transported by Po River, including subsidiaries (Figures 4, 5). Together with Po River, probably influence had Adige River (Figures 4, 5) that also still today transport detritus in Po Depression. The third transport mechanism could be Piave River (Figure 4, 5), located northern from Venice. This river is mostly source of detritus for Venetto Depression and is the shortest from all three mentioned rivers, but part of material from distal part of its delta could reach north part of Po Depression.

Pliocene turbidites are mostly formed in river deltas and represented by clastic deposits. It is silt and sad in Italian part of Po Depression. In Croatian part sediments of delta and prodelta existed only in Pleistocene when border of Adriatic Sea was moved toward east, while periodical sea-level decreasing due to glacial events several times moved to south. Turbidites transported majority of material in relative shallow, hemipelagic environment, with depth up to 200 m. This environment can be represented by distal part of delta, i.e. prodelta. Mostly fine-grained sediment indicated on turbidites of low density[10], i.e. currents with dominantly distal facies of Bouma sequence[1], like Tc, Td and Te. These sediments are distant from proximal delta area and it is why they are interbedded with interturbiditic, hemipelagic interval Tf[19]. Such interval can indicate on absence of re-sedimentation processes or delta moving due to retrogradation caused by sea-level increasing (alocyclic process) or lateral (autocyclic process). Just alteration of turbiditic intervals and hemipelagic facies represents main property of depositional sequences in Croatian part of Po Depression during Pliocene and Pleistocene.

Accordingly, there is good base for selection of Pliocene and Pleistocene depositional lithofacies as separate lithostratigraphic units in Croatian part of North Adriatic. Data from several published papers, mostly about typical facies and lithological properties that characterised them as lithostratigraphic units, are used for detail presentation of both lithofacies.

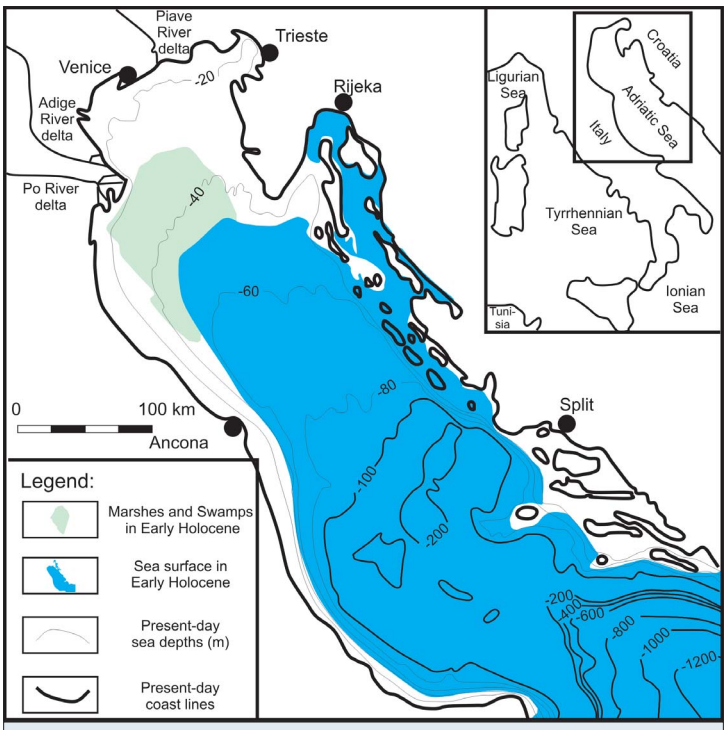

Fig. 5. Borders of Adriatic Sea in beginning of Holocene (modified after[4])
Sl. 5. Granice Jadranskog mora početkom holocena (modificirano prema[4])

Fig. 6. Schematic map of Croatian gas fields in Northern Adriatic
Sl. 6. Shematski položaj hrvatskih plinskih polja u Sjevernom Jadranu

3. Typical lithofacieses of Pliocene and Pleistocene sediments as base for selection new lithostratigraphic units in Northern Adriatic

In the next paragraphs lithofacieses are described in south-eastern and eastern parts of Po Depression. Analyzed locations mostly correspond with positions of Croatian gas fields, i.e. these are parts where sequences of Pliocene, Pleistocene and Holocene are explored in details (Figure 6).

3.1. Pliocene and older lithofacieses

During Pliocene borders of Adriatic Sea started to form. It is especially valid for border in Alpine region (Figure 3), and in the area of Gargano Peninsula. Here is important palaeogeography of Alps, which represented area of glaciers forming and advancing as well as source of many rivers with Po as the largest. Po River has recent delta in area of Ravenna town and in Quaternary it was the largest transport mechanism of detritus from the land to Northern Adriatic. The second source is delta of Adige River, and the third of Piave River. Depositional area of Po Depression is mostly determined by Po River delta, and eastern part of area is located in Croatia, mostly south-western from Istra Peninsula and Kvarner islands (Figure 1). But, in Pliocene deltas of all mentioned rivers, especially Po, had been moved toward west and northwest about 200 km. It is why its influence in Pliocene in Croatian part was probably very low and such was remained at least to Upper Pliocene, when Adriatic coast line started to move toward recent borders. Also, Alpine region covered larger areas in Upper Pliocene then in Middle and Lower Pliocene. It is why Pliocene sediments in Croatian offshore are mostly represented by basin pelites – clays and silts. Such facies can be easiest recognized at the very southeast margin of Po Depression, and those are Katarina and Marica Fields, located close to border between Po and Dugi otok Depressions (Figure 6).

The oldest sediments in Marica Field are limestones and dolomites of Cretaceous age, which belongs to lithostratigraphic unit-formation Dinaridi. But, some analysis pointed out that part of carbonates could be selected in Italian formations Scaglia, Scaglia Cinera, Cavanella A, Bisciaro, Cavanella B, Schlier, Corinna and Clara, i.e. belongs to period from Palaeocene to Lower Miocene. Also, in wider area of Katarina Field, toward Italy (border between AdCP and Adriatic-Ionian Basin), the oldest rocks are described as Middle and Upper Eocene limestone (equivalent of Italian formation Scaglia). In Katarina Field Pliocene sediments are consisted of highly fine-grained sediments like hemipelagic marlstones and clayey marlstones as good isolator rocks. There is no evidence of sands or silts. Only in Pleistocene deposits in Marica Field are discov-

ered 10, and in Katarina Field 5 gas reservoirs in sands, silty sands and silts.

3.2. Pleistocene lithofacieses

These lithofacieses is significantly different from Pliocene due to often intervals of sands and silts. How Croatian part of Po Depression had been closer to Po River delta, more and more sands and silts had been transported in depressions. In Croatian part such facies can be easiest recognized in the largest gas field Ivana (Figure 6). There is proven sequence of Pleistocene sediments[5,24], with thickness between 900 and 1 500 m. Toward deeper basin part thicknesses can be even larger. Particular sandy Pleistocene gas reservoirs can overreach thickness of 20 m.

In Ivana Field the oldest sediments are of Cretaceous age unconformitly followed by Pliocene clayey marlstones and Pleistocene sands, silty sands and silts (with gas reservoirs), locally interbedded by clays, marls and clayey marls. The youngest are Holocene muds, clays and sands of decametre values.[20] Entire Ivana structure is separated from AdCP racks in Istra by regional fault.[22]

4. Proposal of new lithostratigraphic units - FORMATIONS

Lithostratigraphic nomenclature today applied in Northern Adriatic has 13 lithostratigraphic formations on Italian side covering geological scale from Mesozoic to Pleistocene. However, for the same time period there are only 2 formations on the Croatian side. So, Dinaridi Formation includes rocks of AdCP and Susak Formation sediments of Palaeocene, Eocene, Oligocene, Miocene, Pliocene and Pleistocene series. Sediments of this long time period belongs only to one formation, although can locally in Italian part reach 6 000 m.

Obviously, there is need for additional selection of these sediments in several lithostratigraphic units, here formations, which can be consider as informal with purpose of exploration new hydrocarbon reservoirs. Like other Croatian lithostratigraphic units, especially in Pannonian Basin and somewhere in Dinarides, it can be believed that new units with start to use as formal lithostratigraphic units in rank of formation. According to North American Stratigraphic Code[11], which is the most detail and often document, i.e. instructions, for selection of stratigraphical units (and of course lithostratigraphic), the new lithostratigraphic units-formations in Northern Adriatic can be selected regarding the following criteria (ref. [11], p. 1567):

a) Formation is fundamental unit… in describing and interpreting the geology of a region… based on lithic change… that give it the greatest practicable unity of constitution;

b) Formation should posses some degree of internal lithic homogeneity… it may contain… (1) rock of one lithic type, (2) repetitions of two or more lithic types, (3) extreme lithic heterogeneity that in itself may constitute a form of unity when compared to the adjacent units.

Accordingly to listed assumptions it could be proposed the following lithostratigraphic nomenclature for Croatian part of Northern Adriatic, analysing from younger to older sediments, i.e. in direction of well drilling (Figure 7):

Pleistocene: These sediments are transgressive on Pliocene with average thickness 400-1900 m.[8] Pleistocene is divided at lower and upper. Lower Pleistocene includes marly clays, clayey marls, alterations of siltite and sands and weak consolidated sandstones. Upper Pleistocene consists of sandy and marly clays and clays with alterations of sands and silts. Coal beds can be found in lower part. The main property of Pleistocene deposits is very low compaction and sand and silt beds with thickness of several meters, which are results of deposition in Po River delta and prodelta. During Pleistocene the location of coast line in interglacials was similar to recent (Figure 5), but in glacials coast lines were moved significantly toward southeast (Figure 4). It is why sands are more often, thicker and with low portions of silts and clays at the northwest of depression (like in Ivana Field, Figure 6) then at the southeast (like in Katarina Field, Figure 6) where turbidites came only in glacials with low sea-level. So, Pleistocene lithofacies can be considered as monotonous alteration of impermeable (clay, clayey marls) and permeable (silts, sands, sandstones) sediments. It is why Ivana Field is selected as typical locality of Pleistocene delta and prodelta sediments. Consequently, it is suggested that Pleistocene sediments would be selected as **Ivana Formation**. Here is important to mention that borders between formations and chronostratigraphic units do not need to be equal, on contrary such borders very often are different except it is not reflected in lithological composition.

Pliocene: These sediments in Croatian part of Northern Adriatic, based mostly on core samples from gas fields, are described as impermeable. Of course, they are not impermeable in entire depression, i.e. they can not be such laterally, but sandstone component was deposited almost exclusively in recent Italian offshore. Typical description of Pliocene sediments in Croatian part had been given in locality Istra More[8], where it is divided in Lower Pliocene with marlstones and rare clays and silts in total thickness 10-50 m, Middle Pliocene with marly clays, siltstones and partially sands (25-250 m), and Upper Pliocene with marlstones and rarely sandstones (50-200 m). Those sediments are created in hemipelagic environment or distal part of delta (prodelta). It is considered that Pliocene lithofacies, as mostly homogeneous, can be named as **Istra Formation**.

Miocene-Palaeocene: In several gas fields carbonate sediments are drilled. In Marica Field these rocks belongs periods from Palaeocene to Lower Miocene. Similarly, the age of limestones in the wider area of Katarina Field, toward Italy, is Middle and Upper Eocene. Such sediments are, up to now, described only at western margin of Northern Adriatic gas fields zone, i.e. approximately along birder of AdCP and Adriatic-Ionian Basin. It is lithologically homogeneous carbonate lithofacies, locally determined and poorly explored. It is why we considered that all lithofacies from periods Palaeocene-Miocene would need to keep in existing **Susak Formation**.

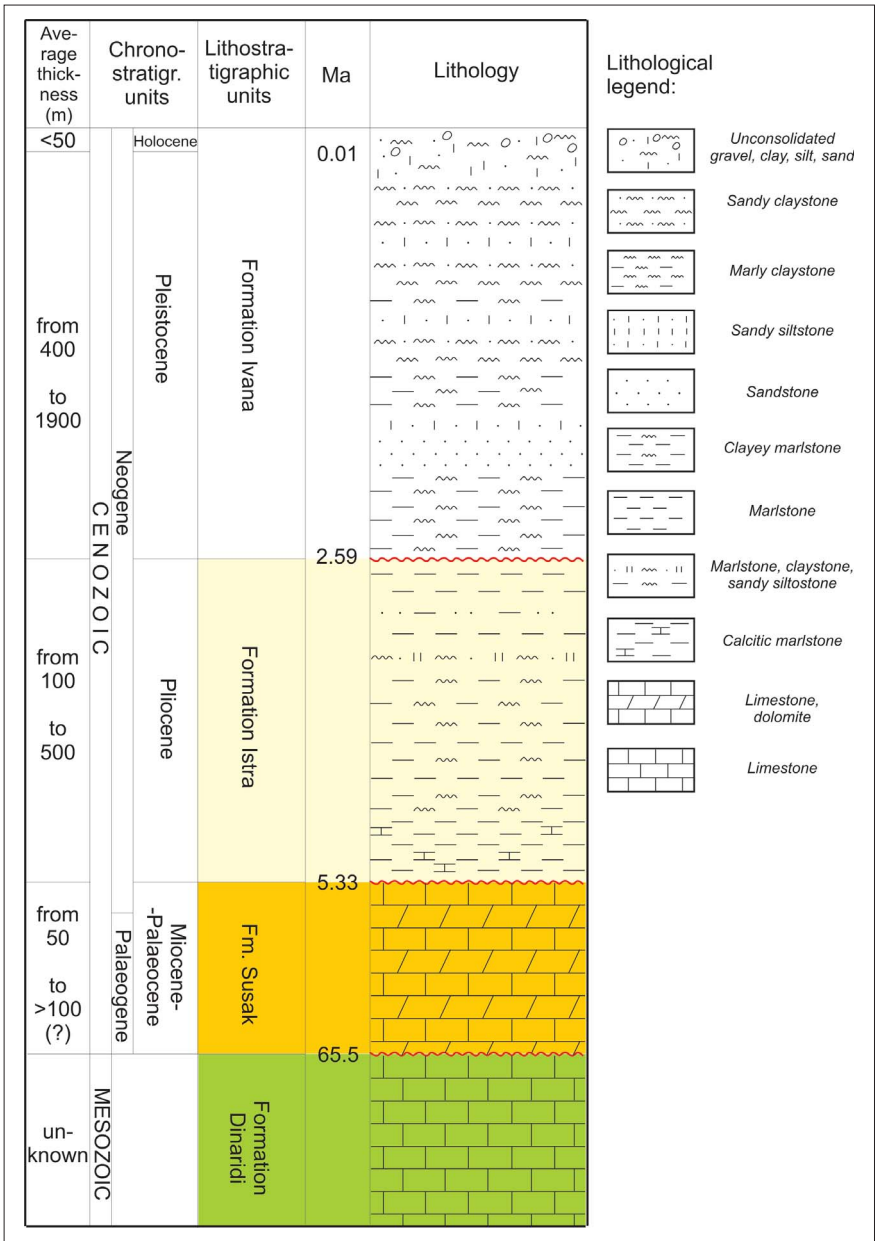

Fig. 7. Proposed lithostratigraphic nomenclature in Northern Adriatic
Sl. 7. Predložena litostratigrafska nomenklatura u Sjevernom Jadranu

Mesozoic: All possible Northern Adriatic sediments reached in top by drilling, where is assumed or proven age of Mesozoic eratem like Cretaceous rocks in Marica Field, are selected in **Dinaridi Formation**.

5. CONCLUSION

Here is presented analysis about differences between Pliocene and Pleistocene sediments in Northern Adriatic formed during creation and deposition in the area today called as Po Depression. This depression is part of Adriatic Basin, partially located in Italian and partially in Croatian offshore. Moreover, there are described locations where carbonate sediments of are drilled, mostly of Mesozoic or Cenozoic eratem. Lithological data about Northern Adriatic rocks and deposits were available in large database of published papers, which included data from deep wells.

Here are selected and named formations as the fundamental units in lithostratigraphic nomenclature. The names are given according rules about lithological homogeneity or similarity as it is prescribed in North American Stratigraphic Code. Those are: Istra Formation of Pliocene and Ivana Formation of Pleistocene and Holocene age. Pliocene sediments are impermeable, mostly represented by marlstones and rarely marly claystones, clays and siltstones. Sands and poorly consolidates sandstones are, in Croatian par of Po Depression, very rarely. It is why Istra Formation is described as mostly lithologically homogeneous sequence of impermeable sediments. The younger Pleistocene and Holocene sediments are represented by alteration of impermeable and permeable sediments. Impermeable are marly claystones, clayey marlstones and permeable are siltstones, poorly consolidated sandstones, silts and sands. It is why Ivana Formation represents monotonous alteration of impermeable and permeable sediments.

Logically, it can be followed by mapping of regional unconformities between and inside formations as well as defining of regional markers (key beds). Also, there is very possible to make further division of formations into lithostratigraphic members, taking into consideration results of numerous high-resolution geophysical measurements. Basic data for such procedure could be collected from logging measurements and interpreted reflective seismic, and could be used for determination and naming of EL-markers (characteristic thin beds in concordant order) and EL-borders (characteristic plane linked to unconformities).

6. REFERENCES

6.1. Published papers and books

1. Bouma, A.H. (1962) *Sedimentology of some flysch deposits: a graphic approach to facies interpretation*, Amsterdam, Elsevier.
2. Cita, M.B. and Ryan, W.B.F. (1972) *The Pliocene Record in deep sea Mediterranean sediments. Times-scale and general synthesis*, Initial Reports DSDP, Washington.
3. Colantoni, P., Gallignani, P. and Lenaz, R. (1979) Late Pleistocene and Holocene Evolution of the North Adriatic Shelf (Italy), Marine Geology, 33, M41-M50.
4. Correggiari, A., Roveri, M. and Trincardi, F. (1996) Late Pleistocene and Holocene Evolution of the North Adriatic Sea, *Quaternario*, 9, 2, 697-704.
5. Đureković, M., Krpan, M., Pontiggia, M., Ruvo, L., Savino, R. and Volpi, B. (1998) Geological modelling and petrophysical characterisation of turbiditic reservoirs of the Ivana gas field – R. Croatia, *Nafta*, 49, 7/8, 241-258.
6. Fairbanks, F.G. (1989) A 17 000 years glacio-eustatic sea level record: influence on glacial melting rates on the Younger Drayes event and deep-ocean circulation, *Nature*, 342, 637-642.
7. Herak, M. (1987) Geologija, Školska knjiga, Zagreb.
8. Kalac, K. (2008) *Biostratigrafsko-kronostratigrafska istraživanja pliocensko-pleistocenskih naslaga u podmorju Jadrana s posebnim osvrtom na klimatske promjene*, Naftaplin, knjiga 45/8, Zagreb.
9. Kuenen, PH. H. (1957) Sole markings of graded graywacke beds, *Journal of Geology*, 65, 231-258.
10. Middleton, G.V. & Hampton, M.A. (1976) *Subaqueous sediment transport and deposition by sediment gravity lows – in*: Stanley, D. J. & Swift, D.J.P. (ed.): *Marine Sediment Transport and Environmental Management*, John Wiley, New York.
11. North American Commission On Stratigraphic Nomenclature (2005) North American Stratigraphic Code, *AAPG Bulletin*, 89, 11, 1547-1591.
12. Piller, W.E., Harzhauser, M. and Mandic, O. (2007) Miocene Central Paratethys stratigraphy – current status and future directions, *Stratigraphy*, 4, 151-168.
13. Prelogović, E. and Kranjec, V. (1983) Geološki razvitak područja Jadranskog mora. *Pomorski zbornik*, 21, 387-405.
14. Rio, D., Channel, J.E.T., Bertoldi, R., Poli, M.S., Vergerio, P.R., Raffi, I., Sprovieri, R. and Thunell, R.C. (1997) Pliocene sapropels in the northern Adraiatic area: Chronology and paleoenvironmental significance, *Palaeogeography, Palaeoclimatology, Paleoecology*, 135, 1-25.
15. Rögl, F. (1998) Paleogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene), *Ann. Naturhist. Mus. Wien*, 99A, 279-310.
16. Stanley, D.I. (1995) A global sea level curve for the late Quaternary: the impossible dream?, *Marine Geology*, 125, 1-6.
17. Thunel, M. (1971) Građa tercijarnog bazena u sjeveroistočnom dijelu Jadranskog mora, *Nafta*, 22, 4-5, 275-434.
18. Tišljar, J. (1994) Sedimentne stijene, *Školska knjiga*, Zagreb.
19. Van Der Lingen, G.J. (1969) The turbidite problem, *New Zealand Journal of Geology and Geophysics*, 12, 7-50.
20. Vdović, N. & Juračić, M. (1993) Sedimentological and Surface Characteristics of the Northern and Central Adriatic Sediments, *Geologia Croatia*, 46, 1, 157-163.
21. Velić, J. (2007) *Geologija ležišta nafte i plina*, Sveučilište u Zagrebu, Rudarsko-geološko-naftni fakultet, Zagreb.
22. Veseli, V. (1999) *Facijesi karbonatnih sedimenata mlađeg mezozoika i paleogena u pučinskim bušotinama sjevernog Jadrana*, Disertacija, Rudarsko-geološko-naftni fakultet, Zagreb.
23. Vlahović, I., Tišljar, J., Velić, I. & Matičec, D. (2005) Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 220, 3-4; 333-360
24. Zelić, M., Mlinarić, Ž. & Jelić-Balta, J. (1999) Croatian Northern Adriatic Ivana gas field ready for development (Reservoir characteristics and gas inflow conditions into the well), *Nafta*, 50, 1, 19-37.

6.2. Internet sources

25. URL 1, http://records.viu.ca/čearles/messinian-crisis-apr03.htm, 8. XI. 2010.
26. URL 2, http://commons.wikimedia.org/wiki/Adriatic_Sea, 8. XI. 2010.
27. URL 3, http://en.wikipedia.org/wiki/Timeline_of_glaciation, 8. XI. 2010.

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