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The Development of the Eocene Platform Carbonates from Wells in the Middle Adriatic Off-Shore Area, Croatia

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Key words: Eocene, Platform carbonates, Wireline logs, Adriatic off-shore, Croatia.

Abstract

In the Middle Adriatic deep off-shore wells the following sedimentary facies exist: fenestral and Charophyte limestone facies (X); facies of foraminiferal wackestone-packstone, ostracod marls and fine grained breccia conglomerate (A); facies of foraminiferal packstone-grainstone (B) and miliolidal mudstone-wackestone (C); facies of porous limestone?, grainstone? (Y); facies of fossiliferous mudstone-packstone (D); algal boundstone/bindstone and wackestone facies (E); facies of the foraminiferal mudstone-packstone (F); *Nummulites-Discocyclina* floatstone-packstone and grainstone-rudstone facies (G). The sediments were deposited close to the carbonate platform margin. Beds of facies X have an uncertain stratigraphic position; younger than the Cretaceous but older than the Cuisian. A transgressive sequence that is composed of facies A, B, C and Y was formed during the Cuisian, whereas the others belong to Lutetian (and Biarritzian). At the end of the Middle Eocene they were tectonically compressed and covered by flysch deposits. Good stratigraphic correlation between the wells along the Dinaric strike strongly suggests that the facies are laterally extensive in this direction. Perpendicular to the trend they are considerably reduced. Oil shows in the Kate-1 well originated from the Lower Cretaceous source rocks (evaporite complex).

1. INTRODUCTION

The Eocene platform carbonates, although of relatively limited extent in the Adriatic off-shore, became an interesting exploration project when some oil shows in the wells Jadran-3, Jadran-9 and Kate-1 were discovered.

This work is a study of the sedimentary platform facies development and the cessation of platform conditions during the Lower (Cuisian) and Middle Eocene (Lutetian to Biarritizian). In the North and Middle Adriatic, the Eocene platform carbonates were drilled only in the wells Kate-1, Jadran-3, Kornati More-4, Jadran-9 and Susak More-1. Figure 1 shows the well locations together with the north-eastern part of the Tertiary (Dugi Otok) Depression and the south-eastern part of the Istrian Platform.

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2. METHODOLOGY

The interpretation of the Eocene carbonate platform facies is based on analysis of the wireline log facies compared with the geological information acquired during drilling and by the transformation of the physical characteristics of the sediments (wireline log facies) into geological entities (sedimentary facies). This method was scientifically developed by Selley from 1970 to 1985 and since then it has been widely used in the oil industry, especially as the basis for building facies models and reconstructions of sedimentary environments.

The wireline log facies interpretation was carried out on the logs which primarily reflect the lithological characteristics of the observed sediments, i.e. the natural radioactivity (gamma rays and spectralog) and porosity logs (neutron, density and acoustic logs).

The technique is primarily qualitative and relies heavily on the visual identification of the coherent units. The criteria used for separating the units depends on the geological data acquired by drilling. There is no standard procedure for separating certain wireline log facies, although it would be logical to separate the obvious coherent rocks first, and then in correlation with neighbouring wells, gradually perform more detailed separation.

The sedimentary facies interpretation is based on the detailed study of the cored intervals and sedimentological core descriptions according to the micro-analyses (litho- and biostratigraphic data).

For the cored intervals their constituent sedimentary facies were determined and added to the appropriate wireline log facies. For the wireline log facies which were not cored, sedimentary facies were determined from mud cuttings and by comparison with similar wireline log facies that were cored in the same or in the neighbouring wells.

3. EOCENE CARBONATE FACIES IN THE KATE-1, JADRAN-3, KORNATI MORE-4, JADRAN-9 AND SUSAK MORE-1 WELLS

The Eocene platform carbonates in the examined wells are subdivided into ten wireline log facies of consistent intervals (X, A, B, C, Y, D, E, F, G and H). For

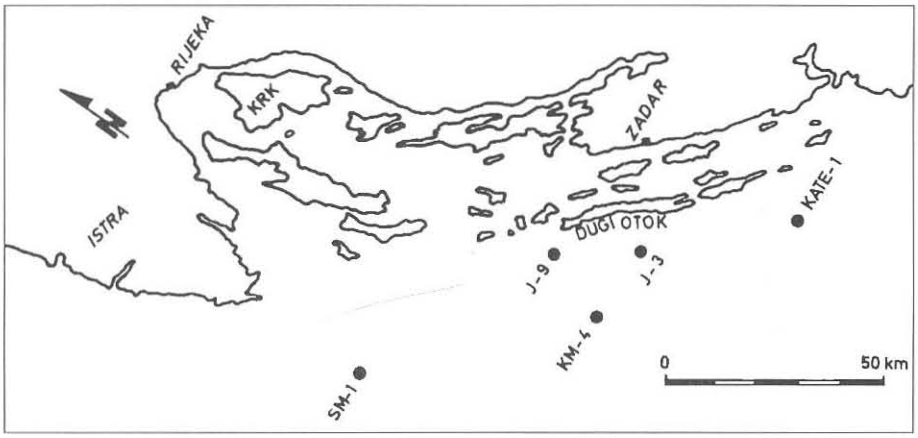


Fig. 1 Location map.

each of the wireline log facies the geological information acquired by drilling, determined the corresponding sedimentary facies.

3.1. Facies X - sedimentary facies of fenestral and Charophyte limestone (salt and brackish marshes, tidal flat)

This is the oldest Palaeogene facies deposited on the karst plane formed of different units of the Upper Cretaceous (Cenomanian to Maastrichtian), after emersion and erosion during the Palaeocene. It is clearly shown on the wireline log diagrams by the high values of compensated density log (from now on referred to as density) 2.45 - 2.70 g/cm^3, by the low values of compensated neutron log (from now on referred to as porosity) 4-10%, by low values of borehole compensated acoustic log (in further text acoustic) approx. $230 \cdot 10^{-6}$ s/m (70 mcs/ft) and by low radioactivity (in further text gamma ray intensity) 10-20 API. The thickness varies laterally from 7-17 m.

Mud logging identified the following lithologies: bauxitic ooids of tangential concentric construction and pelitic clay with abundant pyrite in Kornati More-4 (Fig. 2), fenestral and Charophyte limestone with vugs filled with mosaic drusy calcite in Kate-1 (Fig. 3), pyritic fenestral limestone in Jadran-9 (Fig. 4) and fenestral limestone with desiccation cracks, ostracods and miliolids in Jadran-3 (Fig. 5).

These sediments were deposited on a low energy tidal flat or salt and brackish marshes under anoxic conditions. The proximity of the coast with beaches is typified by deposits in the area of the Kornati More-4 well. Due to the lack of index fossils, it is impossible to determine the age of these sediments. It is certain that they represent a short transgressive sequence before the Middle Cuisian (the approximate age of sediments from the next transgressive cycle). If the transgression was caused by eustatic sea level rise, it could be the result of maximal flooding by the end of the Ilerdian (HAQ et al., 1987). The subsequent emersion until the next transgression was relatively short, 1-2 million years.

3.2. Facies A - sedimentary facies of foraminiferal wackestone-packstone, marl with ostracods and fine-grained breccia conglomerate (coastal environment with repeated shallowing and emersions)

The main wireline log characteristic of this facies is the very high gamma ray intensity. The gamma radiation curve has the typical expression easily spotted on all examined wells ("hot streak" marker). The gamma ray intensity is highest at the lower part of the interval, from 70 API in the Kate-1 well up to 220 API in the Susak More-1 well (Figs. 3 and 6). In the upper part of the interval the values are considerably lower, up to 50 API. Spectra log analysis from Kate-1 proved that the uranic component has more influence than either the thorium or potassium radioactive group. The coal from the Lower Eocene mines in Raša, Istria, also has an uranium content up to 300 ppm (FERTL, 1979). This uranium enrichment should be of the same origin because the sediments are of the same age and from closely related environments. According to the literature (FERTL, 1979) a high uranium level in carbonate sediments can indicate the presence of organic or phosphate rich deposits or permeable zones through which there is a circulation of underground waters enriched in uranium salts.

The density, porosity and acoustics values are almost identical to the previous facies, except for the first few metres (Fig. 7). The higher porosity value, gamma ray intensity, higher speed of acoustic wave spreading and density depend on the presence of clay and breccia-conglomerate in the argillaceous matrix.

Facies A was studied in cores from the wells Jadran-3 (Figs. 5 and 11) from 1764-1766 m, and Jadran-9 (Fig. 4) from 1324-1327.3 m. The lowest 10 cm of the core in Jadran-3 is a fine grained limestone breccia conglomerate with weakly rounded clasts in a matrix of skeletal detritus. These are followed by organic rich limestone, ostracods marl with burrows, desiccation cracks and fenestral milolid-coskinolinid limestone. The lithofacies of foraminiferal wackestone-packstone limestone prevails. Fractures and intergranular porosity

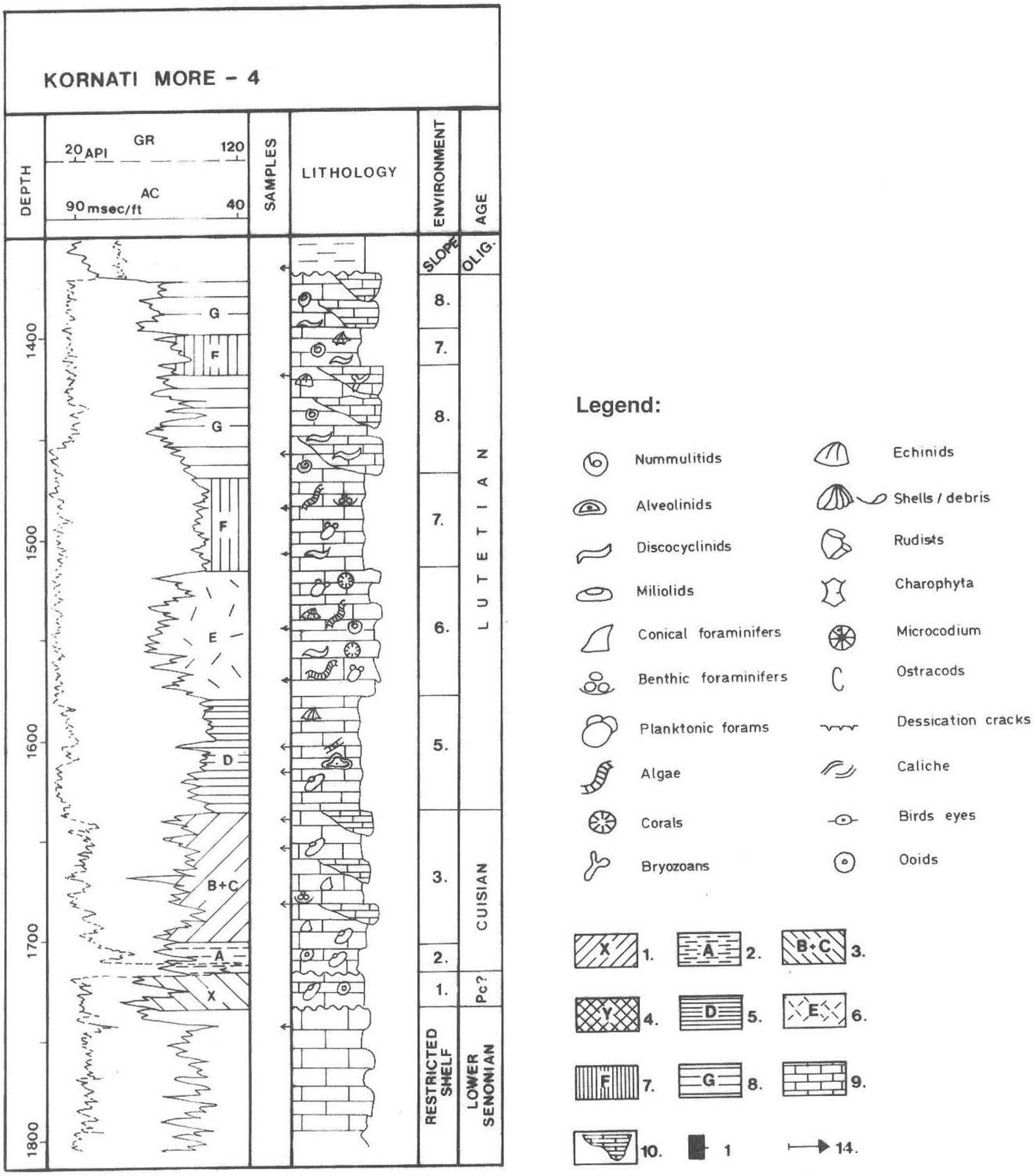


Fig. 2 Sequence of Palaeogene carbonates in the deep well Kornati More-4. Legend: 1) facies of fenestral and *Charophyta* limestone (X); salt and brackish marshes, tidal flat environment; 2) facies of foraminiferal wackestone-packstone, marl with ostracods and fine grained breccia conglomerate (A); coastal environment with repeated shallowing and emersions; 3) facies of foraminiferal packstone-grainstone limestone and miliolidal mudstone-wackestone limestone (B and C); coastal environment with repeated shallowing and emersions; 4) facies of porous limestone - ?grainstone (Y); ?beaches; 5) facies of fossiliferous mudstone-packstone limestone (D); shallow platform and mud mounds environment; 6) facies of algal boundstone (bindstone) and wackestone (E); platform margin buildups; 7) facies of the foraminiferal mudstone-packstone (F); foreslope environment; 8) facies of *Nummulites-Discocyclina* floatstone-packstone and grainstone-rudstone (G); foreslope environment; 9) shallow marine mudstone-wackestone; 10) shallow marine packstone-grainstone; 11) core samples; 12) mud samples.

are filled with bitumen. The sediments were deposited in a pericoastal environment with repeated shallowing and emersions.

In the Jadran-9 well core microcodium and pisolitic wackestone-packstone alternate with some bauxite and fossiliferous packstone-wackestone with shell debris, bryozoans, red and green algae and benthic foraminifers in argillaceous mudstone and caliche. Microcodium is developed by mycorrhizal calcification (symbiosis of fungi and cortical cells of the plant roots) and caliche typical of the limestone palaeosoil (KLAPPA, 1978), so they often occur together in the sediment.

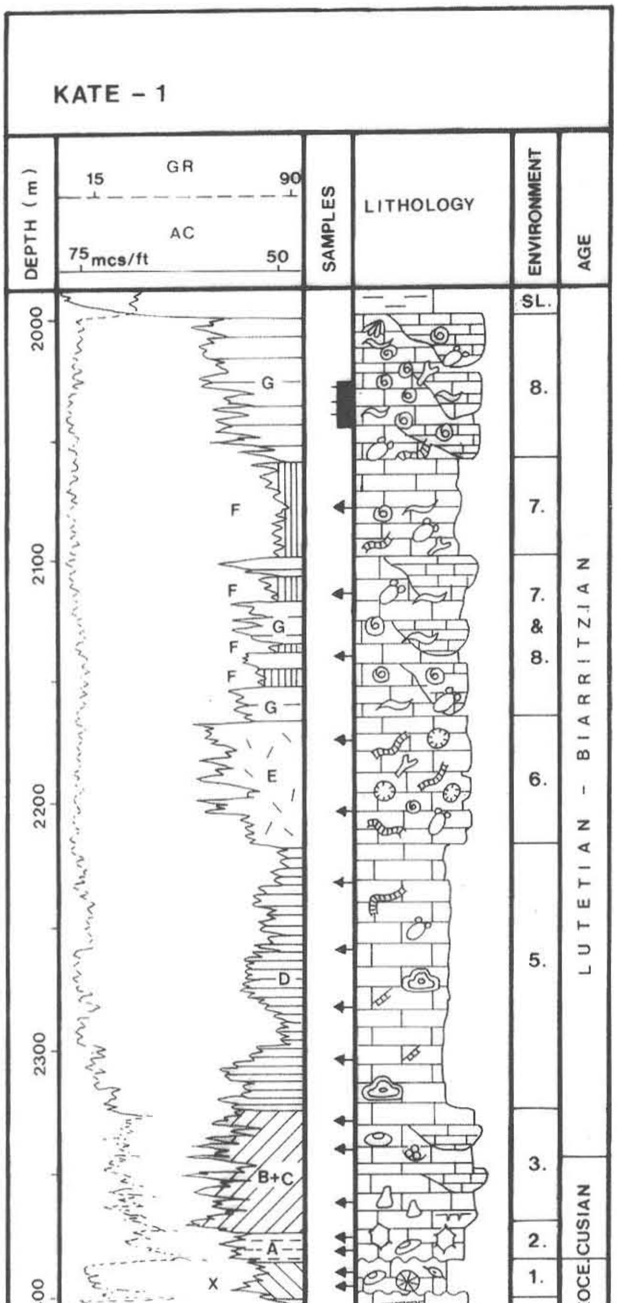


Fig. 3 Sequence of Palaeogene carbonates in the deep well Kate-1. For legend see Fig. 2.

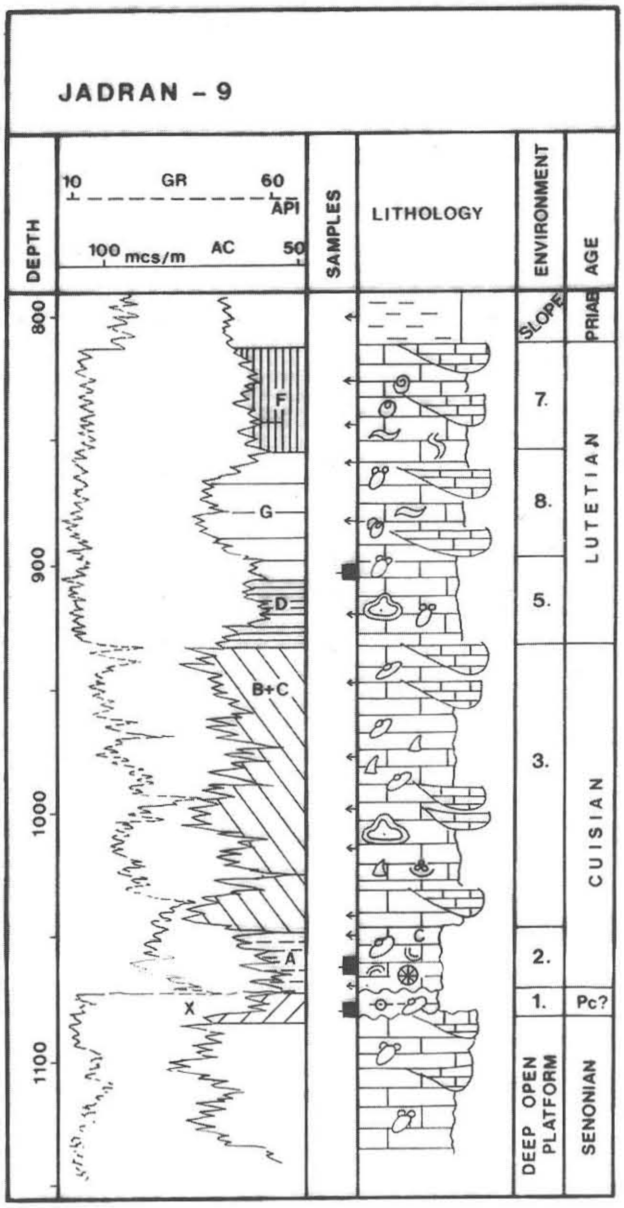


Fig. 4 Sequence of Palaeogene carbonates in the deep well Jadran-9. For legend see Fig. 2.

Such facies indicates a coastal environment with variations of the sea level over a low lying plain. Coastal (supratidal) sediments alternate with sediments indicative of highly reductive swamps that are seasonally dried and occasionally with marine milolid limestone due to minor sea level rise (DAVIS, 1985).

Geochemical studies of the core samples determined that amorphous huminite/vitrinite kerogen (>95%) is the dominant form of organic matter (Corg 0.26-0.43%), and it is therefore assumed that it was developed by the biodegradation of a terrestrial precursor. The deposits do not exhibit the source rock characteristics as the major part of the organic matter has been oxidised (high HI) within the sedimentary environment. The maturation parameter T_{max} (407-410°C) indicates an especially low degree of thermal transformation, and therefore these sediments cannot be considered as the source rocks.

Mud samples in other intervals of Kornati More-4, Kate-1 and Jadran-9 wells (Figs. 2, 3 and 4) have similar characteristics to the rocks in the cored intervals. The thickness of this facies varies between 10-26 m.

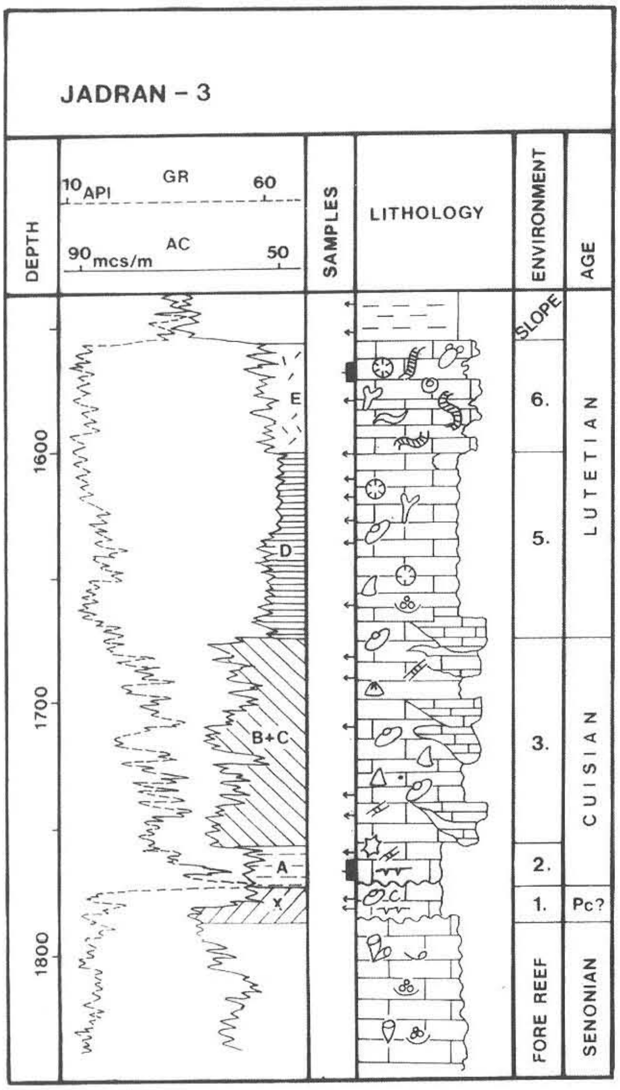


Fig. 5 Sequence of Palaeogene carbonates in the deep well Jadran-3. For legend see Fig. 2.

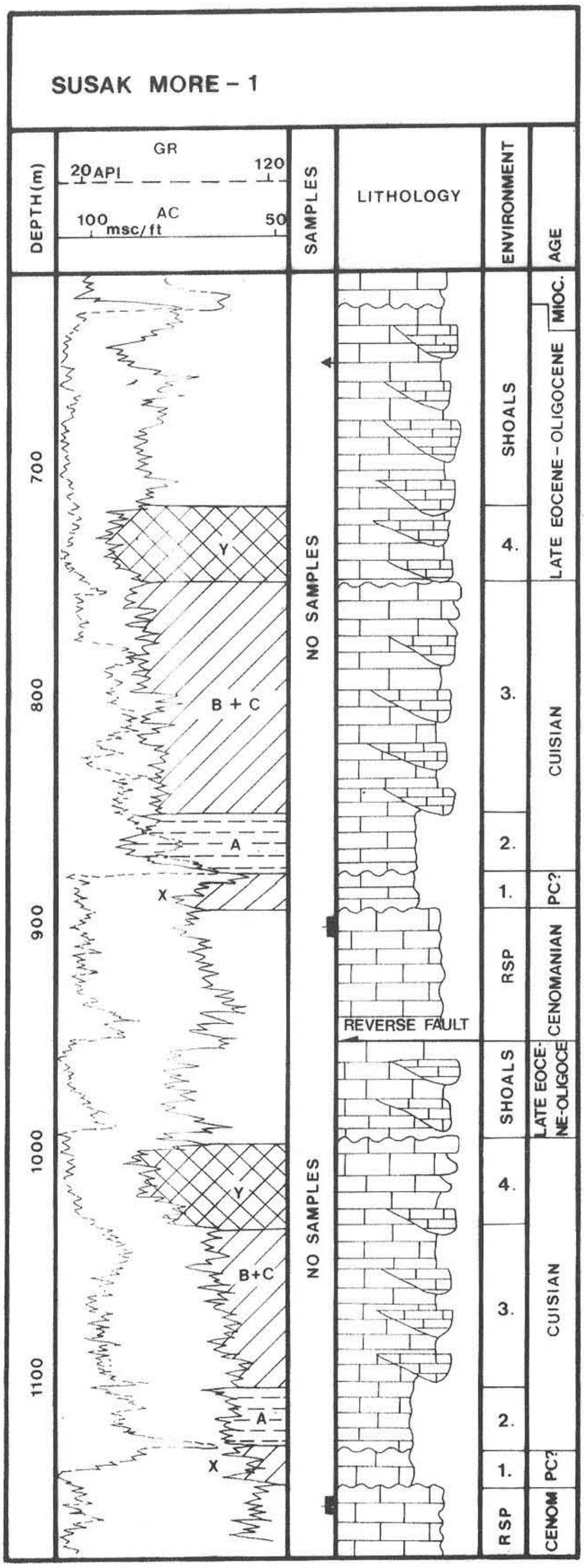


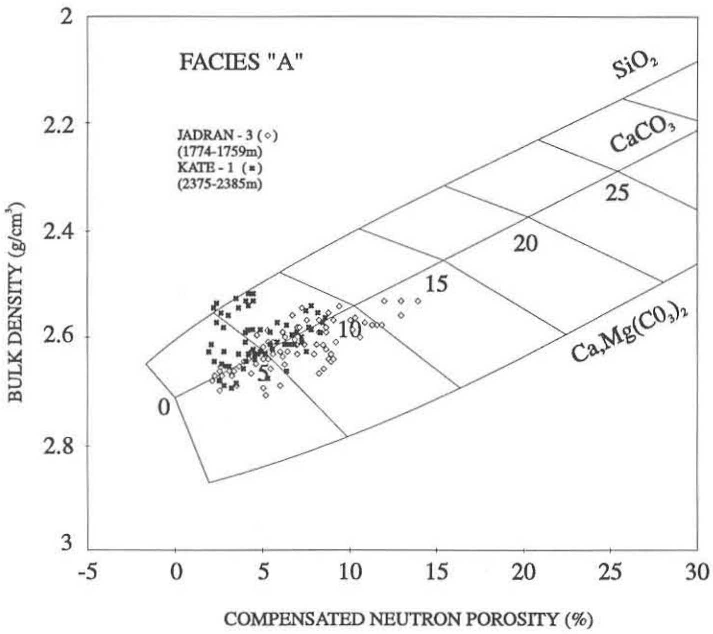
Fig. 6 Sequence of Palaeogene carbonates in the deep well Susak More-1. For legend see Fig. 2.

Sedimentary facies to which the sediments of the wireline log facies A belong to, are sediments of coastal plain with fresh water flows, swamps that occasionally dry out, and the beaches that are flooded by the shallow sea that forms shallow restricted lagoons.

Due to the lack of index fossils the age is roughly determinated as Lower and/or Middle Cuisian on the basis of *Coskinolina* sp., *Fallotella* sp., *Spirolina* sp., discorbids, rotalids, small miliolids, ostracods and green algae, and because the sediments of facies A are conformably overlain by younger sediments of a determinable age without any sedimentation break.

3.3. Facies B and C - sedimentary facies of foraminiferal packstone-grainstone (Facies B) and miliolid mudstone-wackestone (Facies C) (the tidal flat environment)

This facies is composed by alternation of facies B and C in all the wells. The density, porosity and acoustic logs show the good correlation of the two facies in all wells except in the Kate-1 well (Figs. 3 and 8) where the exchanges are more frequent in relation to the thickness of both facies. Porosity in facies B varies from 10 to 25%, density 2.35-2.60 g/cm^3 and acoustics



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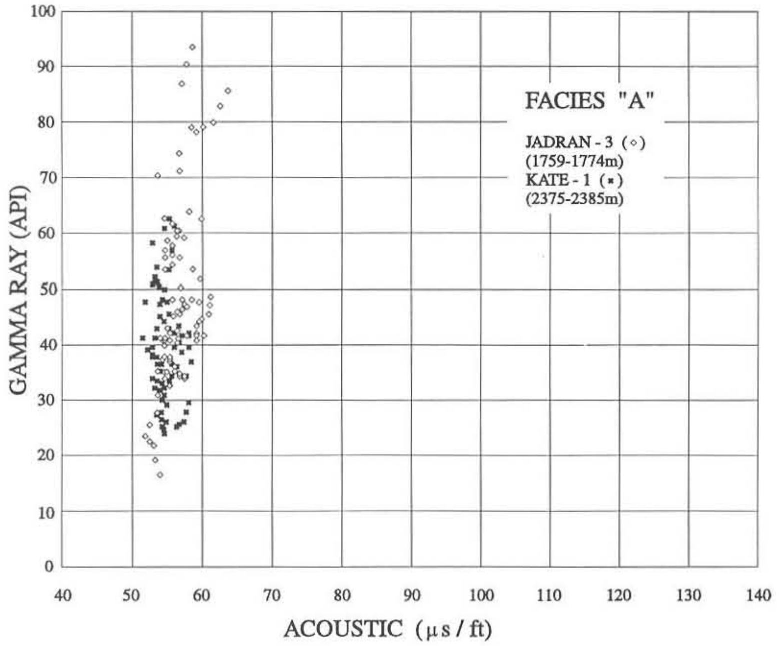


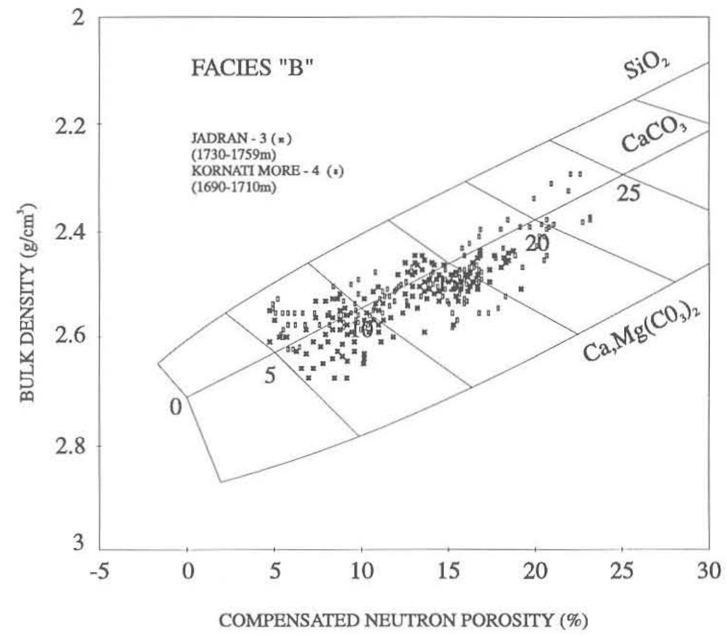
b

Fig. 7 Facies A: a) cross plot response showing carbonate point distribution; b) GR/AC cross plot response.

from 197-230·10^{-6} s/m (60-70 mcs/ft). The values of these parameters in the Susak More-1 well (Fig. 6) are not reliable because of the cavernous borehole, but the characteristics of the B and C facies are still visible. The gamma ray curve does not reflect the changes in these facies in any of the wells. In the lower part of the interval the values are higher between 30 and 70 API. In the upper part, they do not exceed 30 API units. Only in the Susak More - 1 well the values are very high, among 50 and 100 API units.

The facies was cored only in the Jadran-9 well, but in the tectonicaly repeated section in the interval 1342-1345.2 m. Bauxite oolites point to emersion and/or the vicinity of karstified coast, while fossiliferous wackestone-packstone and grainstone limestone with benthic foraminifers and echinids, algae and shell debris indicate high energy shallow water environment. Facies C was cored in the interval 1029-1032 m. Light brown miliolid wackestone-packstone alternates with dark grey and brown fenestral wackestone with gastropods. Fenestrae are filled with internal sediment and mosaic drusy calcite cement. Shallow karstified surfaces and geopetal fabrics were also noted. The environmental energy was low. The mud samples of the same facies in the Kate-1 well also contain ostracods and oncoids.

Both facies are typical for the tidal flat, their appearance and development can be connected to the alternation of the sediments deposited in tidal channels (facies B) with those from the sheltered lagoons (ponds) of higher salinity (facies C). The regularity of the alternation of both facies in all the wells (except the Kate-1 well) is curious. It is impossible to determine whether



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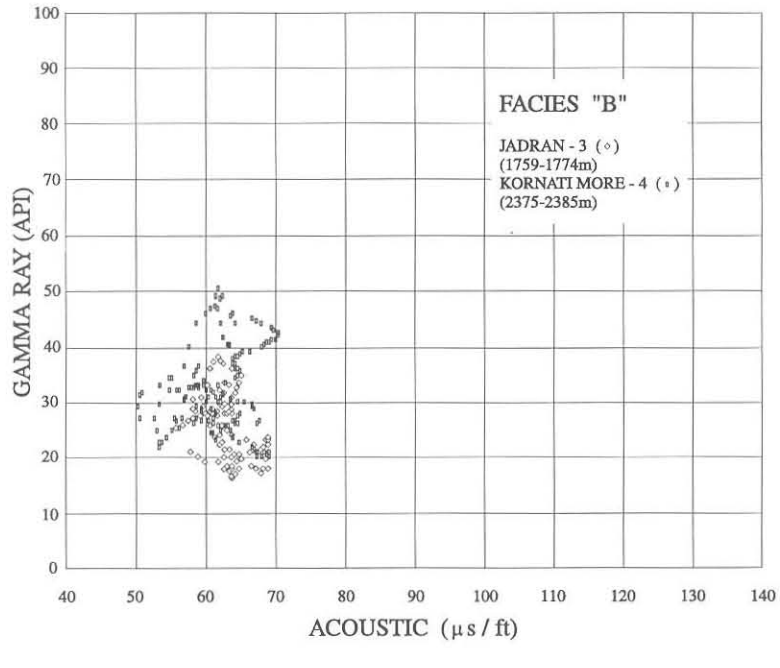

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Fig. 8 Facies B: a) cross plot response showing carbonate point distribution; b) GR/AC cross plot response.

they represent shallowing upward cycles or storm tide deposits.

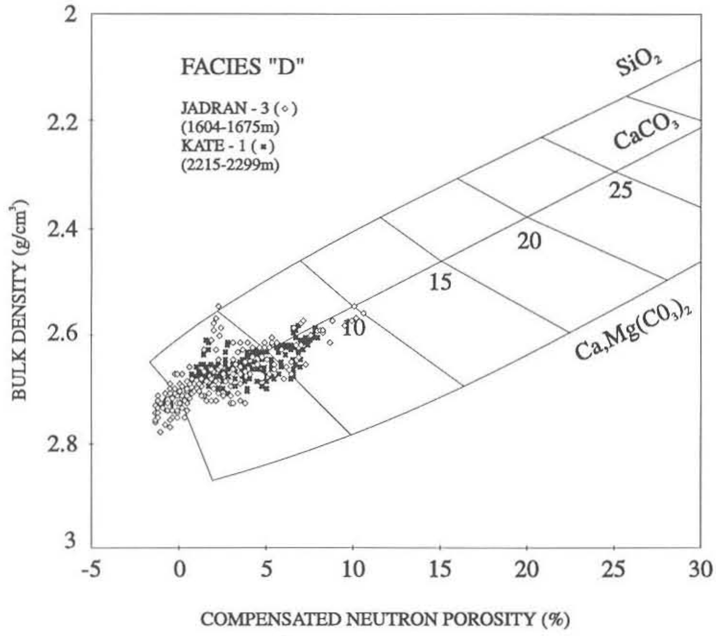
Only in the the Kate-1 well are facies B and C also recognised below facies X (Figs. 3 and 17). According to LUČIĆ (1993) this presents the only known Palaeocene tidal flat deposit in the Adriatic off-shore.

The foraminiferal association with *Coskinolina perpera* HOTTINGER & DROBNE and *Chrysalidina makarskae* (van SOEST), determined the age as Lower Eocene (Middle - Upper Cuisian).

3.4. Facies Y - sedimentary facies of porous limestone - ?grainstone (? beaches)

Facies Y was isolated only in the Susak More-1 well (Fig. 6), only on the gamma ray and acoustic logs, because during the drilling at the depth of 775 m (in the top of this facies), the complete loss of mud occurred, and due to cavernous borehole the porosity and density values are invalid.

As the well samples were not available the determination of the facies characteristics and the sedimentary environment was not possible. Although, the physical characteristics of sediments enable certain assumptions. The decrease of gamma radiation is visible as well as the increase in acoustic value in relation to the facies B in the base. Such characteristics corespond to the porous limestone (?grainstone) developed in the high energy environment, where the mud component was washed out. If that is the case, following the Walter's low (WILSON, 1975) on the lateral and vertical changes of the facies, these deposits could be interpreted as the beach sands deposited over the tidal flat facies



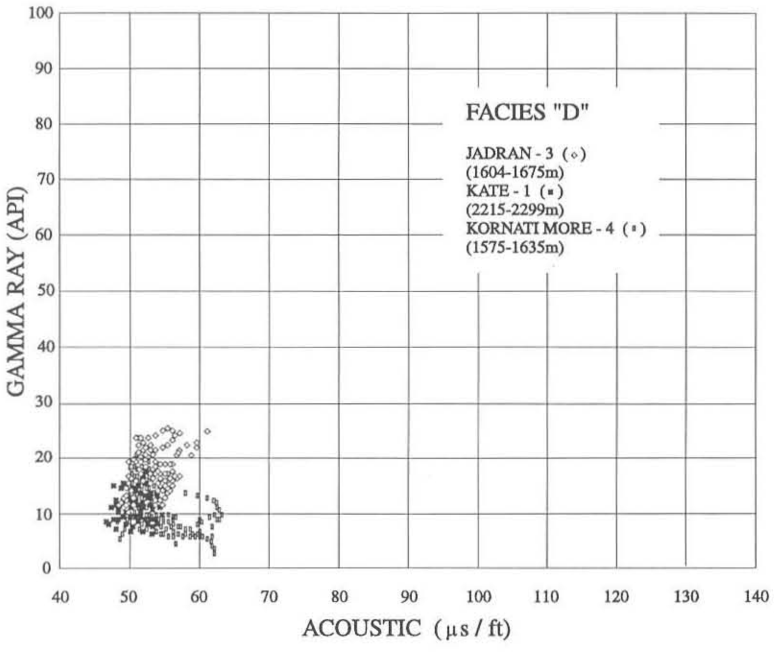


Fig. 9 Facies D: a) cross plot response showing carbonate point distribution; b) GR/AC cross plot response.

B and C presenting regresive part of the sequence.

3.5. Facies D - sedimentary facies of fossiliferous mudstone - packstone limestone (the shallow platform and mud mounds environment)

In the north-western part of the carbonate platform the sedimentary sequence ends with the emersion by the end of the Lower Eocene (facies Y in the Susak More-1 well). In the other areas the sedimentation continues during the gradual sea level rise. Facies D follows conformably on the facies B in the Kornati More-4, Kate-1, Jadran-9 and Jadran-3 wells (Figs. 2, 3, 4, 5 and 9).

The lower part of the interval is composed of sediments with porosity varying between 3-18%, density of 2.50-2.65 g/cm and acoustics between $197\text{-}230{\cdot}10^{-6}$ s/m (60 and 70 mcs/ft). In the upper part of the interval, which has been developed in all the wells except the Jadran-9 well, the sediments are of higher density (2.60-2.70 g/cm), lower porosity (1-8%) and acoustics ($184\text{-}197{\cdot}10^{-6}$ s/m, i.e. 56-60 mcs/ft). Gamma ray intensity is low: 10-20 API. In the Jadran-9 well the thickness of these sediments is 8-22 m, while elsewhere is 58-80 m.

The facies has not been cored. According to the analysis of mud samples, mudstone, wackestone and packstone containing miliolids, conical and large foraminifers and shells and corals debris, were deposited in the subtidal zone beneath the normal wawe base on the shallow platform. The fragments of corals and shells probably originate from distant shoals (facies E) or from the mud mounds.

In the upper part of the facies D of the Jadran-3 well (Fig. 5), mostly in the mudstone and wackestone/float-

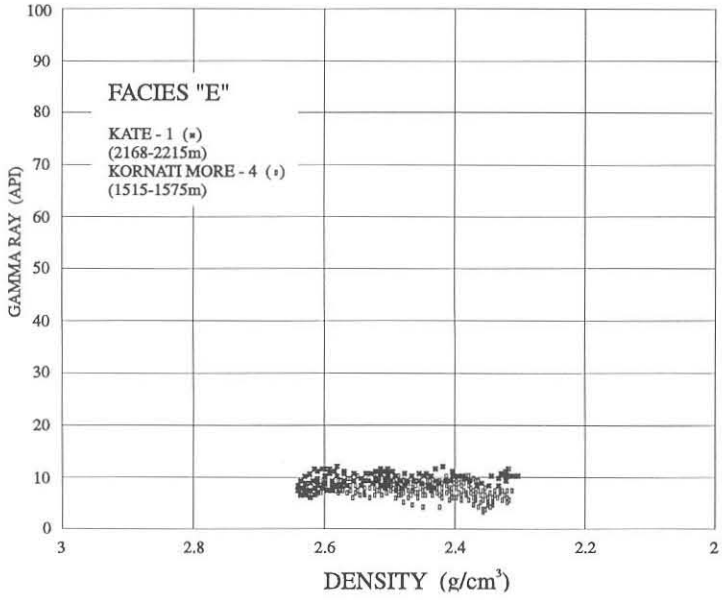


Fig. 10 Facies E: GR/DEN cross plot response.

stone, new faunal elements appear: corals and planktonic foraminifera. These sediments can be compared with the mud hummocky cross lamination in the reef base (ELLOY, 1982) where they are actually located.

It is important that the foraminiferal community changes in this facies. *Nummulites* sp., *Operculina* sp., *Assilina* sp., and *Discocyclina* sp. of the Middle Eocene (Lutetian) age appear for the first time. The boundary between the Cuisian and Lutetian coincides with the change of facies B and C into facies D.

3.6. Facies E - sedimentary facies of algal boundstone (bindstone) and wackestone (marginal platform buildups)

The sediments of this facies are developed in the Kornati More-4, Kate-1 and Jadran-3 wells (Figs. 2, 3, 5 and 10). On the wire-line logs the typical serrated curve shows acoustics 56-90 mcs/ft, porosity 3-30% and density 2.35-2.70 g/cm^3. The gamma ray value is less than 10 API.

The facies in Jadran-3 well was tested by the mechanical core in the interval 1565-1565.3 m (Fig. 12).

The rock is classified as algal boundstone (bindstone) and wackestone according to the classification of EMBRY & KLOVAN (1971). It contains large foraminifera (*Nummulites*, *Discocyclina*, *Amphistegina* and *Operculina*), fine benthic foraminifers, planktonic foraminifers, bryozoans, corals, shells, echinids and encrusting red algae. As only a small interval of the facies was tested by coring (30 cm), it is difficult to determine is that the true reef or some other kind of marginal platform buildup. According to the regional position and the appearance on the seismic lines, and also to the vertical and lateral spreading of the considered facies, it may be determined as the marginal platform buildup.

The changeable porosity is typical for reefs and also for peri-reefal facies. The literature describes in detail the complex processes that destroy primary and/or form the secondary porosity (LAPORTE, 1974; BABIĆ & ZUPANIČ, 1979; TOOMEY, 1981; ELLOY, 1982; SELLEY, 1985). In Kornati More-4 according to the mud cuttings the sediments are dolomitized (also expressed on the density and porosity logs). In the Kate-1 well, the karst development and open active

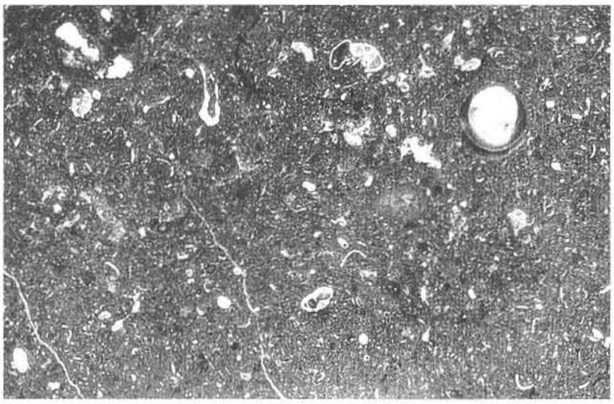


Fig. 11 Ostracode mudstone-wackestone, facies A, Early Eocene (Cuisian), Jadran-3, 1764 m, 25X.

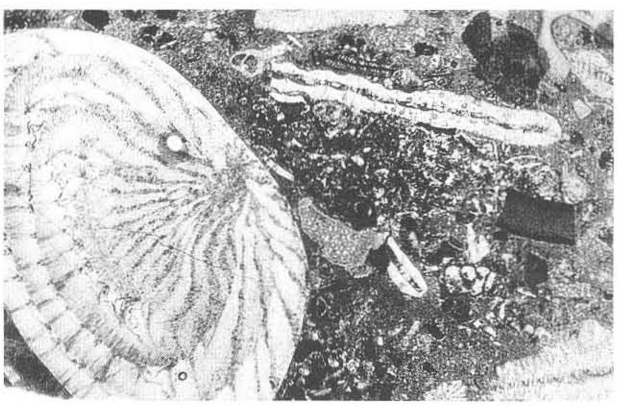


Fig. 12 *Nummulites-Lithothamnium* bindstone-floatstone, facies E, Middle Eocene (Lutetian), Jadran-3, 1565 m, 28X.

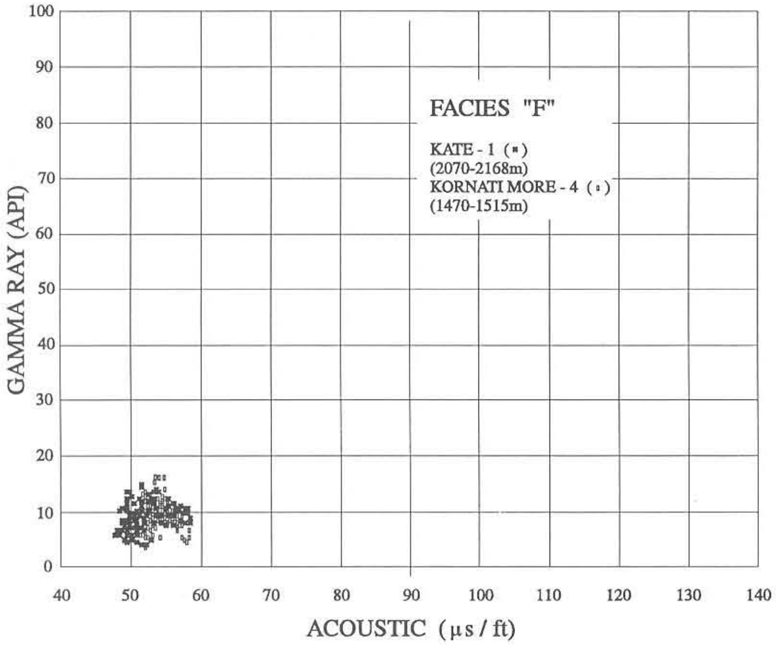


Fig. 13 Facies F: GR/AC cross plot response.

fracture systems are visible on the photo-electrical absorption curve (PEF). The rise of the curve value PEF from 5 (limestone) to 7-9 in a few intervals was caused by baroid drilling mud infiltration.

In the Jadran-3 well this facies is the final member of the carbonate succession. The sedimentation continues with siliciclastic turbidites, in the deeper sedimentary environment.

3.7. Facies F - sedimentary facies of the foraminiferal mudstone-packstone (foreslope environment)

Facies F overlies on the reefal limestone in the Kornati More-4 and Kate-1 wells (Figs. 2, 3 and 13). It appears in the Jadran-9 well (Fig. 4) between the two intervals of the facies G, while in the Kate-1 well (Fig. 3) it alternates with facies G. The wire-line log facies almost looks like facies D. Porosity varies between 1-6%, density from 2.55-2.70 g/cm^3 and acoustics approximately 60 mcs/ft. The value of gamma ray intensity doesn't exceed 15 API units.

This facies hasn't been cored. According to the mud samples (Fig. 14) there are foraminiferal mudstone, wackestone-floatstone and packstone with corallinacean and bryozoan debris. Its thickness is 46-98 meters.

Sediments from this facies are of Lutetian age (*Sphaerogypsina globula* (REUS), *Asterigerina rotula* KAUFMANN, *Discocyclina sella* D'ARCHIAC, *Lepidocyclina* sp., *Nummulites* sp., *Turborotalia cerroasulensis possagnoensis* (TOUMARKINE & BOLLI), *Globigerina senni* (BECKMANN)). They developed on the very edge of the platform toward the slope and basin, and they are laterally and vertically (Walter's Law) the first neighbouring member of facies E and G of the transgressive sequence.

The main criterion for determining the sedimentary environment was the fossil content. Bioclastic deposits in which the association of *Discocyclina*, *Nummulites*, *Astericyclina* and *Sphaerogipsina* dominate, with the significant presence of planktonic foraminifers, undoubtedly shows the foreslope and toe of slope envi-

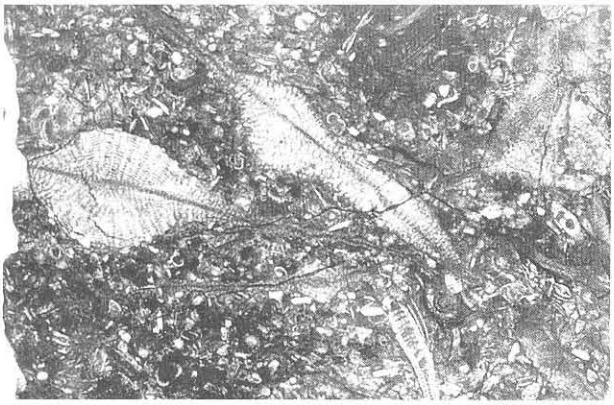


Fig. 14 *Discocyclina* grainstone-packstone, facies F, Middle Eocene (Lutetian), Jadran-9, 1445 m, 25X.

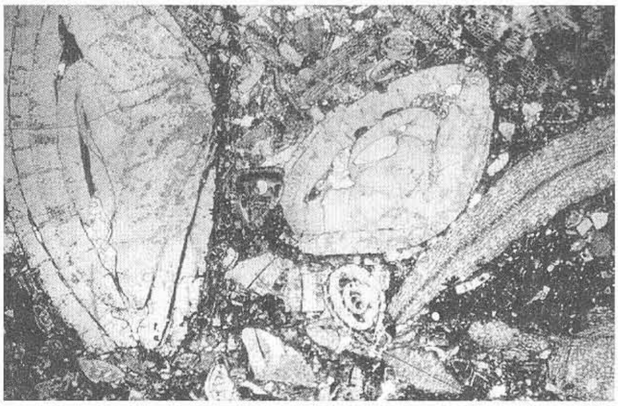


Fig. 15 *Nummulites-Discocyclina* grainstone, facies G, Middle Eocene (Lutetian), Jadran-9, 921 m, 28X.

ronment beneath the wave base (BIGNOT, 1972; GHOSE, 1977; DROBNE et al., 1991).

3.8. Facies G - sedimentary facies of *Nummulites-Discocyclina* floatstone-packstone and grainstone-rudstone (open platform shoals)

Facies G overlies facies D in the Jadran-9 well (Fig. 4). In Kornati More-4 and Kate-1 wells (Figs. 2 and 3) it succeeds facies F. In the Kornati More-1 and Jadran-9 wells it cyclically alternates facies F.

The wire-line log characteristics of facies G are porosity of 3-10% in the Kate-1 well, up to 25% in Kornati More-4 well and up to 19% in the Jadran-9 well. The density varies from 2.35-2.55 g/cm^3 and acoustics from $164\text{-}197 \cdot 10^{-6}$ s/m (50-60 mcs/ft). Gamma ray intensity is approximately 10 API.

Facies G was studied in mechanical cores in Kate-1 well between 2028-2046 m. According to the lithofacies and sedimentological interpretation the rock is composed of *Nummulites-Discocyclina* floatstone/packstone with occasionally higher content of corallinaceans and bryozoans and fragments of echinoderms and shells. The matrix contains fine-grained fossil fragments and carbonate mud, and rarely mosaic drusy calcite cement. Grainstone/rudstone types appear very often. Primary intraskeletal porosity is high but it was diminished because of the cementation of intraskeletal cavities. Oil shows are connected with fractures or stylolitic surfaces and tectonic fabrics with variable impregnation of the surrounding rock, especially where there are dissolution holes developed. Limestone of this facies was sedimented in the open platform shallow water environment.

In the Jadran-9 well, the same facies was studied between 915-921 m. According to petrographic and lithological analyses, the rock is foraminiferal grainstone-packstone (Fig. 15) and occasionally glauconitic. Because of the high energy environment, there are only a few planktonic foraminifera, while large foraminifers (mostly *Nummulites*) are abundant.

In the vertical sequence, the sediments of facies G in the wells Kate-1, Kornati More-4 and Jadran-9 aggradationally alternate with facies F of the forereef environment, like the reflection of platform pulsing before its final drowning under the siliciclastic flysch deposits. Sediments of the facies G are of the Lutetian age, and in the Kate-1 well they are somewhat younger - Lutetian to Biarritzian (*Operculina biaricensis* OPPENHEIM, *Nummulites millecaput* BOUBEE, *Nummulites dufrenoyi* D'ARCHIAC & HEIME).

4. DISCUSSION

4.1. Correlation in Wells

A schematic correlation cross section (Fig. 16) shows the extent of the considered deposits along the Dinaric structural trend, from the Susak More-1 well in the north-west to the Kate-1 well in the south-east. They represent the older (carbonate) part of the transgressive megasequence of the Palaeogene and Neogene beds.

Facies X, A, B and C are easily correlatable across all the wells. They were deposited in the coastal environment (facies X and A), and in the tidal flat (facies B and C). In the Susak More-1 well area, the sedimentary sequence of the Eocene carbonates was interrupted at the beginning of the Lutetian because of the uplifting of the carbonate platform, causing the emersion which lasted till the end of the Upper Eocene, when the deposition of carbonate sediments continues again. The sediments of the Upper Cretaceous, Eocene and Lower Oligocene were repeated twice in the well due to a reverse fault at the depth of approximately 945 m. The total thickness of the Eocene sequence in the thrusted part is 140 m and in the autochthon 142 m.

Toward the south and south-east the rest of the carbonate platform was oscillating and slowly drowning, with the tendency of increasing thickness of regarded deposits. The transgressive sequence continues through the Lutetian with facies D, E, F and G, and the environment changes from internal shallow platform toward platform edge. The thicknesses of the Lutetian deposits in Jadran-9 well are 276, 132 and 157 m (tectonically repeated sequences), in the Jadran-3 well is 288 m, in Kornati More-4 well 369 m, and in the Kate-1 well 395 m.

In the Jadran-3 well area facies E (platform margin buildup) completes the calcareous part of the transgressive megasequence, which continues with flysch sedimentation. Facies G and F in the Jadran-9, Kornati More-4 and Kate-1 wells are repeated cyclically. Shoals of open shallow waters pass into sediments of the forereef environment. Such an alternation of facies is the result of multiple, relative oscillations of sea level (Fig. 17) that do not correspond with the eustatic curve of the sea level change (HAQ et al., 1987). This reflects the pulsing of the platform before its final drowning (SCHLAGER, 1981) because of the subsidence in front of the growing thrust structures of the Dinarides in the East.

Because of folding (recumbent fold) and thrusting, in the Jadran-9 well, the same Palaeogene carbonate sediments were drilled in three intervals, with the middle interval being inverse. In all three intervals the sequence of facies from X to G is identical. The thickness of the inverted interval (132 m) is smaller in relation to the other two intervals because of the overburden compaction and the structural dip of deposits.

4.2. Correlation with On-shore Sediments

According to their facial characteristics, off-shore facies X, A, and B can be compared to the Liburnian and miliolidal limestone (ŠIKIĆ & POLŠAK, 1973; BIGNOT, 1972; DROBNE, 1979) in Istria (Fig. 17).

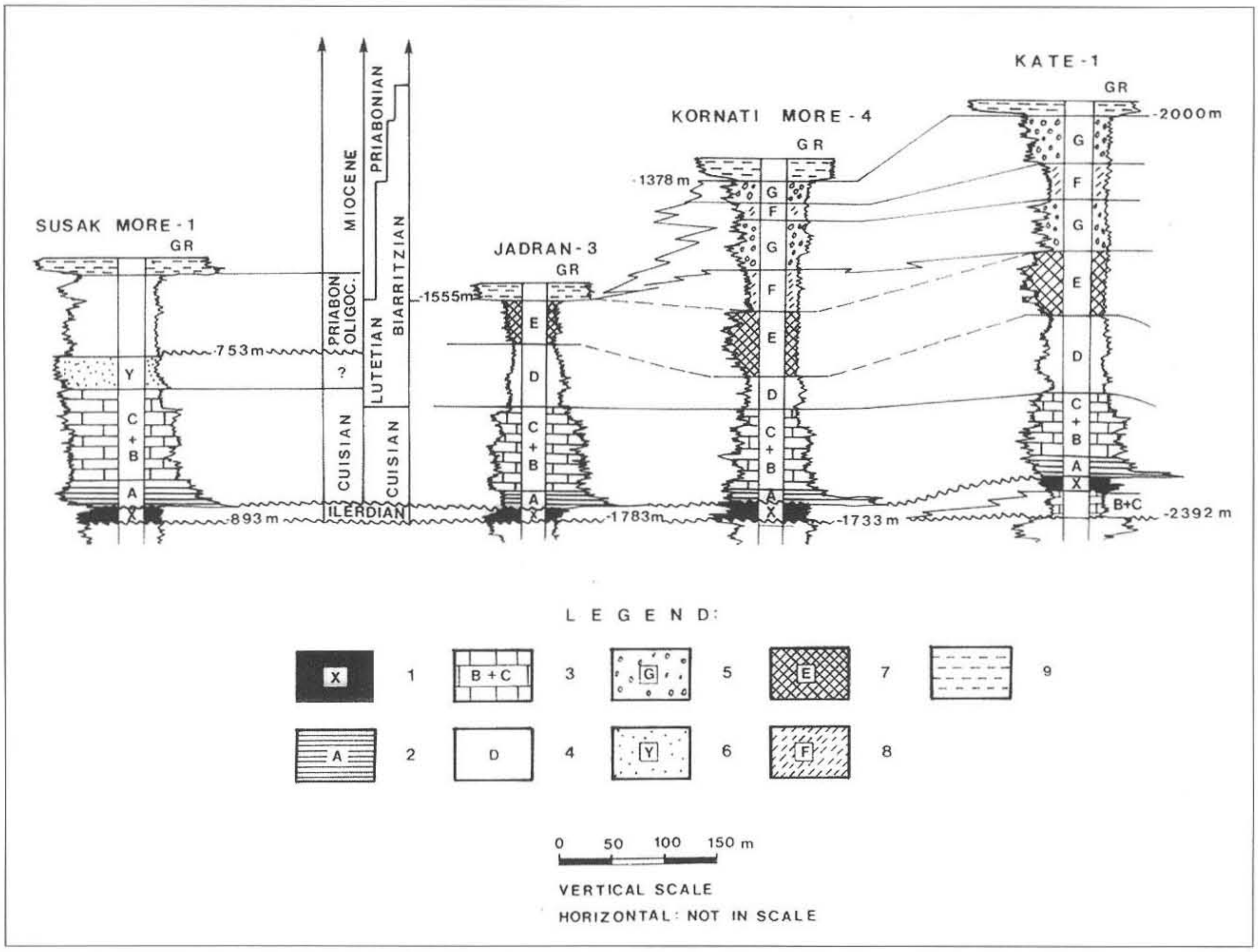


Fig. 16 Facies display: 1) peritidal deposits; 2) coastal deposits; 3) tidal flat deposits; 4) shallow platform deposits; 5) open platform shoals; 6) ?beach deposits; 7) platform margin buildups; 8) foreslope deposits; 9) flysch.

However on the Koromačno cape in the base of the Liburnian sediments, there are polimictic breccia conglomerates 15 m thick, that are also in a transgressive relationship to the Upper Cretaceous limestone. The breccia conglomerate is completely unsorted, and contains metre, decimetre and centimetre sized clasts of the Cretaceous and Palaeocene (Kozina type) limestone, and large clasts of thick dark red and orange calcite veins in the calcarenite matrix.

On the Lošinj island, in the base of the miliolid (mudstone-wackestone and packstone-grainstone) limestone, there are also transgressive breccias, approximately 1 m thick, with clasts of Cretaceous limestone.

The position of the breccia conglomerate is identical for both outcrops, so it is possible that they were formed during the same event as the facies X in the off-shore Adriatic.

On the islands of Pašman, Ugljan and Kornati the facies A, B and C are reduced to a thickness of 3 m. MAMUŽIĆ & NEDĚLA-DEVIDÉ (1973) describe this as a transgression expressed by basal breccias in the "terra rossa" or red clay matrix up to 20 cm thick. The unconformity is almost unnoticeable. Brown platy limestone that is similar to the Liburnian beds, with abundant small gastropods and miliolids is deposited on this transgressive material. Even this level is not thicker than 20 cm. The following 2.5 m consists of light brown, slightly chalky limestone with miliolids and some gastropods. There is a similar development of the same sediments on the islands of Ugljan and Lošinj.

The transgressive contact between the Cretaceous and Eocene in the Ravni Kotari area is characterised by a karstified surface with bauxite or by supratidal fenestral and intertidal miliolid limestone virtually concordant with the underlying deposits (DROBNE et al., 1991); so facies X and A are reduced (Fig. 18). Facies B and C are of similar thickness to those from the Jadran-9 well (approx. 100 m). Alveolina and Nummulites limestone of the Middle Eocene, by their sedimentological and biostratigraphic characteristics, can be compared with the sediments of facies D, F and G in the off-shore.

Platform margin limestone in the wells Jadran-3, Kornati More-4 and Kate-1 (Figs. 17 and 19) is developed on the very western edge of the carbonate platform. The scarse cored samples of the wireline log facies on the buildup, well expressed on the seimic cross sections, do not allow determination of the reef *sensu stricto*. Recently published papers (DRAGIČEVIĆ et al., 1992) and well data from the Southern Adriatic indicate that the reefs are not the exotic elements in that area. In the Jadran-3 well the platform

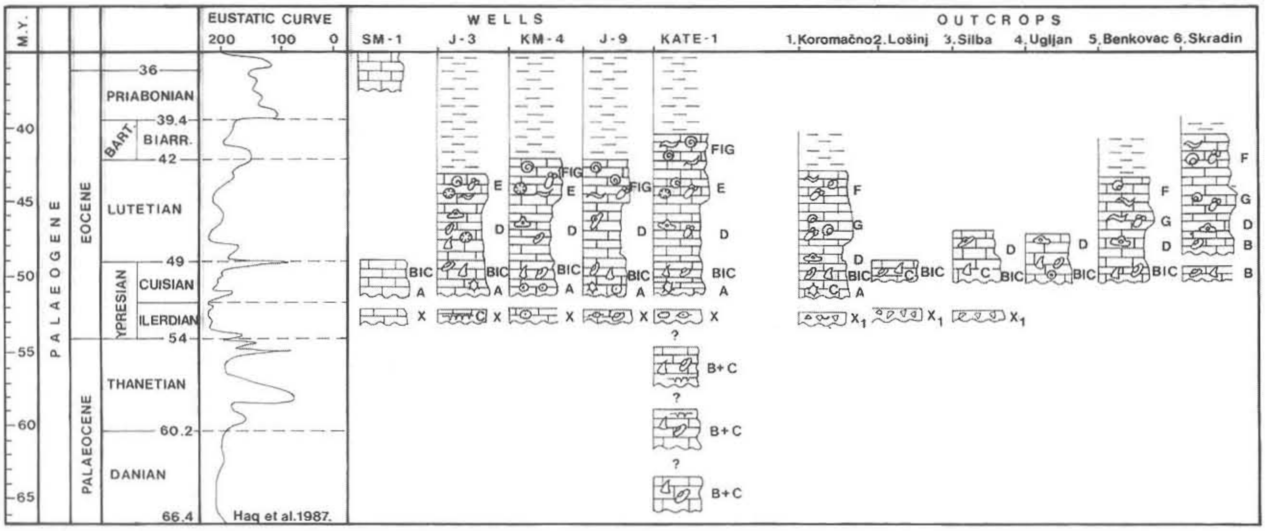


Fig. 17 Correlation of the on-shore and off-shore deposits. Legend: X) peritidal deposits; X_1) subfacies of the facies X in the outcrops; A) coastal deposits; B+C) tidal flat deposits; D) shallow platform deposits; E) platform margin buildups; F) foreslope deposits; G) open platform shoals; Y) ?beach deposits.

margin was drowned during the Lutetian, slightly earlier than in other wells, because of the sudden tectonic subsidence. At the same time in the Kornati More-4 and Kate-1 wells, buildups first migrate toward the land in prograding transgression, and then they were replaced by shoals that indicate the relative shallowing of the sea level (tectonic uplift).

Drowning of the platform beneath the flysch deposits is timed by nannofossils at the upper part of the Middle Lutetian: NP-15/16 nannofossil zone in Istria, in Ravni Kotari somewhat later (NP-16) and in the Split area NP-17 (BENIĆ, 1991). Therefore the carbonate sediments of Biarritzian age in the Kate-1 well can be compared only to the sediments south of the Krka river (in the surroundings of Skradin), and Southern Dalmatia (Pelješac and Cavtat).

4.3. Petroleum potential

In the Eocene limestone of the Kate-1 well oil shows were traced in small intervals between 2020-5630 m. In the considered sequence of the Eocene limestone, hydrocarbon shows occur in the intervals 2020-2086 m and 2340-2450 m. Part of the interval from 2394-2450 m is of Cretaceous age. The reservoir characteristics were primarily good (facies G), but they were completely destroyed by diagenetic processes. The oil appears in poorly connected fractures and vugs (secondary, fracture and "vuggy porosity").

Geochemical analyses of the oil proved the presence of sulphur (6-6.8%), and domination of n-alkanes. The pristane/phitane ratio is less than 1. The precursor is the kerogene type II, lipids of algal and bacterial origin deposited in a highly reductive environment. The oil from the Eocene limestone is characterised by "naphtenic hump" on the gas chromatograph, which is not present in the deeper intervals of the well. This is explained by the lower katagenetic degree of transformation or by possible oil degradation compared to the mature katagenetic degree of transformation evaluated in the oil from deeper parts of the well.

It is certain that the oil does not originate from the Eocene limestone of facies A. The organic matter in the facies A originates from kerogen type III which is dominated by amorphous huminite/vitrinite of a terrestrial precursor in the immature stage of thermal transformation. In the Jadran-9 and Jadran-3 wells, because of the conditions in the sedimentary environment (peritidal environment with occasional brackish water), most of the organic matter is oxidised.

However, in the Cretaceous sediments in the Jadran-9, Jadran-3 and Kate-1 wells source rocks were determined that are in the early stage of the thermal katagenetic transformation (the beginning of the oil window) that generate oil. The Upper Cretaceous laminated mudstone of limited extent and thickness were deposited in the anoxic lagoons and contain heavy isotopes (^{13}C = 22-25%) and kerogen type I and II. The precursor is the algal-bacterial organic matter of marine origin from a very reduced environment, confirmed by the presence of heavy isotopes. The rock is also immature.

The Lower Cretaceous source rocks contain kerogene type II and subordinately type I, in the early stage of katagenetic transformation. Organic rich laminated stromatolitic mudstone was deposited in lagoons of higher salinity and sabkhas. This is confirmed by the pristane/phitane ratio which is lower than 1, the presence of sulphur rich asphaltene and by heavy isotopes ($^{13}C \approx 22\%$). On the gas chromatogram there is also a characteristic "naphtenic hump", the same as for the oil from Eocene reservoirs.

Comparing the characteristics of source rocks and oil, it is possible to conclude that oil has migrated into the area of Kate-1 well from estimated source rocks of the Lower Cretaceous evaporite-carbonate beds.

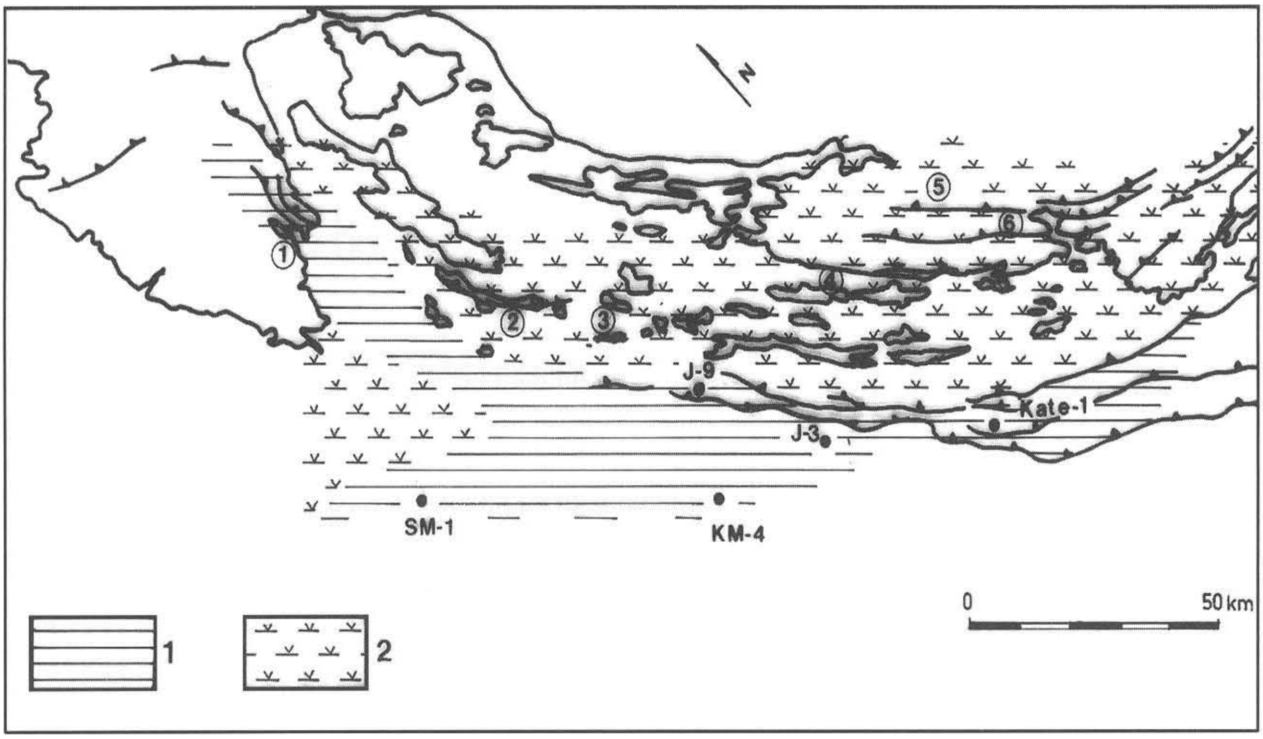


Fig. 18 Palaeogeographic map in Lower and Middle Cuisian, facies A. Legend: 1) peritidal deposits; 2) land. Position of the outcrops from the Fig. 17 are keyed by numbers.

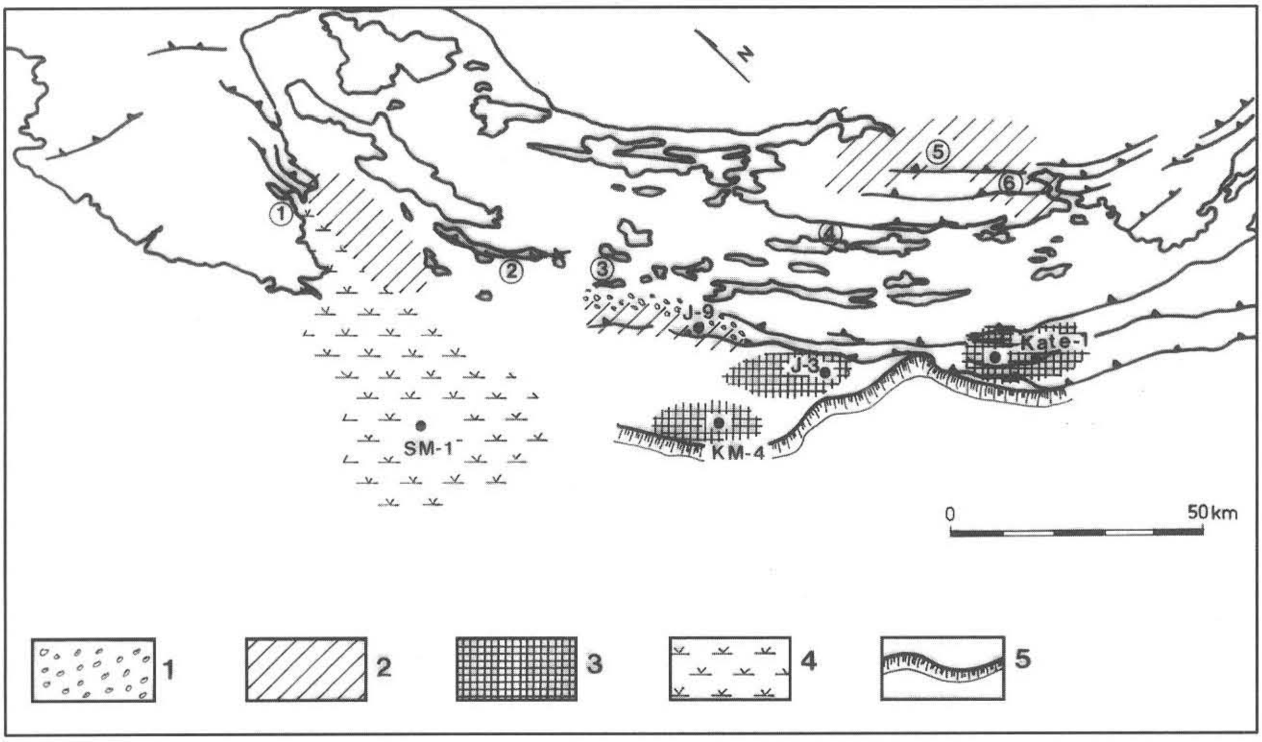


Fig. 19 Palaeogeographic map of Lutetian, facies E, F and G. Legend: 1) shoals; 2) foreslope; 3) platform margin buildups; 4) land; 5) slope. Position of the outcrop from the Fig. 17 are keyed by numbers.

5. SUMMARY

The paper is a comprehensive study of the facies characteristics of the Eocene Carbonate beds found in the Central Adriatic wells: Kate-1, Jadran-3, Kornati More-1, Jadran-9, and Susak More-1.

Considering wireline log analysis it has been possible to identify the wireline log-facies X, A, B, C, Y, D, E, F, G and H. The relevant sedimentary facies have been defined based on geological and drilling data - analysis of conventional cores and mud cuttings.

Facies X, characterised by tidal flat sediments, represents the first brief episode terminated by emersion. Facies A is the first member of the second major transgressive sequence with which eventually terminates development of the Adriatic (Dinaric) carbonate platform. It begins with a streak marker horizon within a sedimentary facies characterised by coastal lagoons, marshes and beaches. Cyclic alternation of B and C facies is characteristic for the tidal flat. Facies Y is the final member of the analysed sequence of beds on the uplifted Istrian platform. Simultaneously, the carbonate platform gradually subsided to the south-east (D facies). With further transgressions environments become more distal, thus the final members of the carbonate sequence are formed by barrier bars, buildups and foreslope deposits (facies E, F+G).

The studied beds have been affected by tangential tectonic events at the end of the Eocene period. As a result of folding and thrusting, the eastern part of the studied area is uplifted, while the western is lowered, thus forming the Dugi Otok depression which has been filled with flysch and flyschlike deposits during the younger Palaeogene and in Miocene.

Beds of the facies X have an uncertain stratigraphic position, younger than the Cretaceous but older than the Cuisian. Transgressive sequence from A to Y facies was formed during Cuisian, whereas the others belong to the Lutetian (and Biarritzian).

In correlation with surface outcrops the synchronous beds, along the Dinaric strike show an almost identical development of the sedimentary environment regardless of how distant these may be (the area of Labin in Istria and the wells in the Adriatic offshore). Much closer sediments on the Kornati islands and in Ravni Kotar outcropping in a perpendicular direction to the Dinarides are different from the offshore sediments both with regard to composition and thickness.

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