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Evolution and Petroleum Potential of the Ionian Basin (Northwest Greece)

1. INTRODUCTION-GEOLOGICAL FRAME.

From Triassic to Late Cretaceous the Ionian Basin (western Greece; Fig. 1) constituted part of the southern Tethyan margin, and siliceous and organic-rich sediments were often associated facies. The stratigraphy of the Ionian zone exhibits three distinct sequences (Karakitsios, 1995; Fig. 2):

a) A prerift sequence, which is represented by the early Liassic Pantokrator Limestones. These shallow water limestones overlie early to middle Triassic evaporites (more than 2000 m thick) through Foustapidima Limestones of Ladinian-Rhetian age. The "sub-evaporitte beds" of the Ionian zone do not crop out, nor were they penetrated by deep wells.

b) A synrift sequence that began with the deposition of the Siniais Limestones and their lateral equivalent, the Louros Limestones of Pliensbachian age. These formations correspond to the general sinking of the Ionian domain (formation of the Ionian basin), which was followed by an intrabasinal differentiation that separated the initial basin into smaller paleogeographic units presenting, in general, a half-graben geometry (in most cases the units did not exceed 5 km across). This is recorded in the abruptly changing thickness of the synrift formations, forming prismatic synsedimentary wedges, which, in the deeper part of the half-grabens, include complete Toarcian to Tithonian successions (from base to top: Ammonitico rosso or Lower Possidonia beds, Limestones with Filaments, and Upper Posidonia beds), while in the elevated part of the half-grabens hiatuses and unconformities are located. The directions of synsedimentary tectonic features (e.g. slumbs and synsedimentary faults) indicate that deposition was controlled both by structures formed during the extensional tectonic phase, related to the opening of the Neotethys Ocean, and the halokinesis of the Ionian zone evaporitic base.

c) A postrift sequence that is defined by an Early Barriasian breakup marked by an unconformity at the base of the Vigla Limestones. The postrift sequence (Vigla Limestones and overlying Alpine formations) largely obscures the synrift structures and, in some cases, directly overlies the Pantokrator Limestones prerift sequence. The permanence of differential subsidence during the deposition of the Vigla Limestones as shown by the strong variation in the thickness of this formation, is probably due to the continuation of halokinetic phenomena of the Ionian zone evaporitic base. This paleogeographic configuration continued with minor off- and on-lap movements along basin margins until the late Eocene, when orogenic movements and flysch sedimentation began.

The main orogenic movements took place at the end of the Burdigalian (IGRS-IFP, 1966). The Ionian basin evolution constitutes a good example of inversion tectonics of a basin with evaporitic base (Karakitsios, 1995): the double divergence of the basin (westwards in the central and western part and eastwards in the eastern part) is attributed to structures inherited from the Jurassic extensional phase, which were reactivated during the compressional phase as westwards and eastwards displacements respectively. In general, extensional faults were entirely transformed into either reverse or transcurrent faults and/or thrusts, which is consistent with the classical inversion tectonic scheme. Although, in some cases during the compressional phase, faults related to the extensional phase did not reactivate as thrusts in the way predicted by the classical inversion tectonics scheme, but due to the evaporitic base halokinesis, the most elevated footwalls have been thrusted over the preexisting hanging walls. This phenomenon was facilitated by diapiric movements promoted by the salt layer included in the evaporitic base of the basin. Field and available seismic data point out that, at list, a moderate detachment took place along the sub-surface evaporites.

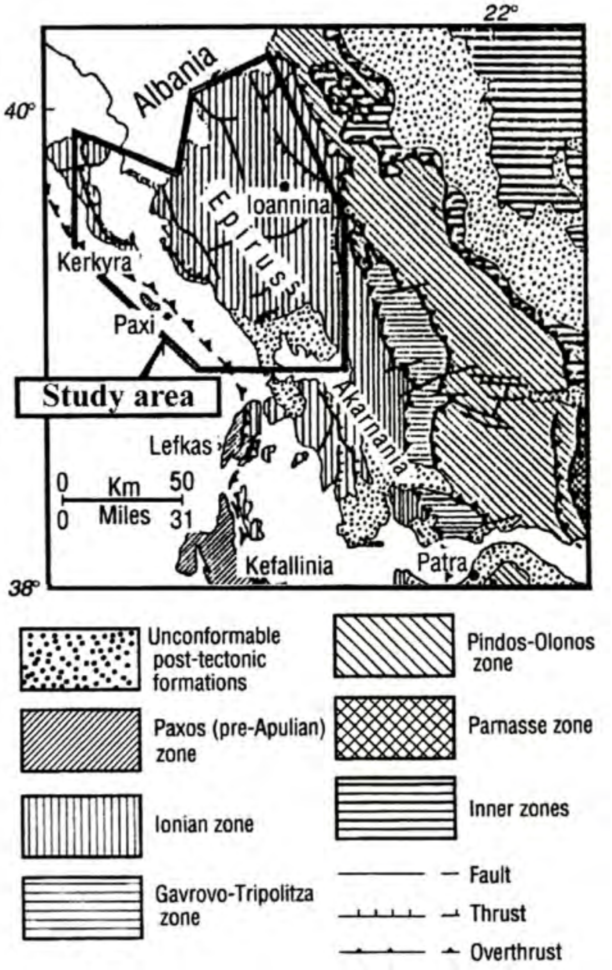


Fig. 1. Structural map of the NW continental Greece (after Karakitsios, 1995)

2. THE IONIAN ZONE SOURCE ROCKS

Five organic-rich (TOC= 1.00-28.87 wt%; Fig. 3) formations of source-rock potential have been observed: the Vigla shales or "Upper Siliceous zone" of IGRS-IFP (1966) (Albian-Turonian), the Upper Posidonia Beds (Callovian-Tithonian), the Lower Posidonia Beds (Toarcian), the marls at the base of the Ammonitico Rosso (Early Toarcian), and the shale fragments incorporated within the Triassic breccias (Karakitsios, 1995; Karakitsios and Rigakis; 1996; Rigakis and Karakitsios, 1998; Karakitsios et al., 2001; Karakitsios et al., 2002). All the above source-rock horizons have good hydrocarbon potential and their organic matter is of type I to II (Karakitsios and Rigakis, 1996; Rigakis and Karakitsios, 1998). The burial history curves have shown that the oil window, located in the central Ionian basin (Botsara sub-basin), in the interval between 3700 and 5800 m, is decreasing from west to east (Rigakis and Karakitsios, 1998). Thus, the Triassic shales have already entered the gas window in the deeper parts of the sub-basins. The Lower and Upper Posidonia Beds, and the marls at the base of the Ammonitico Rosso are mature in terms of oil generation. In the central and western sub-basins the maturity of the Vigla shales corresponds to an early maturation stage, while in the eastern areas Vigla shales are mature (Rigakis and Karakitsios, 1998; Rigakis, 1999, Karakitsios et al., 2002;). As far as the timing of the principal source-horizons maturation is concerned, the Triassic shale fragments horizons have entered the oil window in the Upper Jurassic, while the Lower Posidonia beds in the Serravalian.

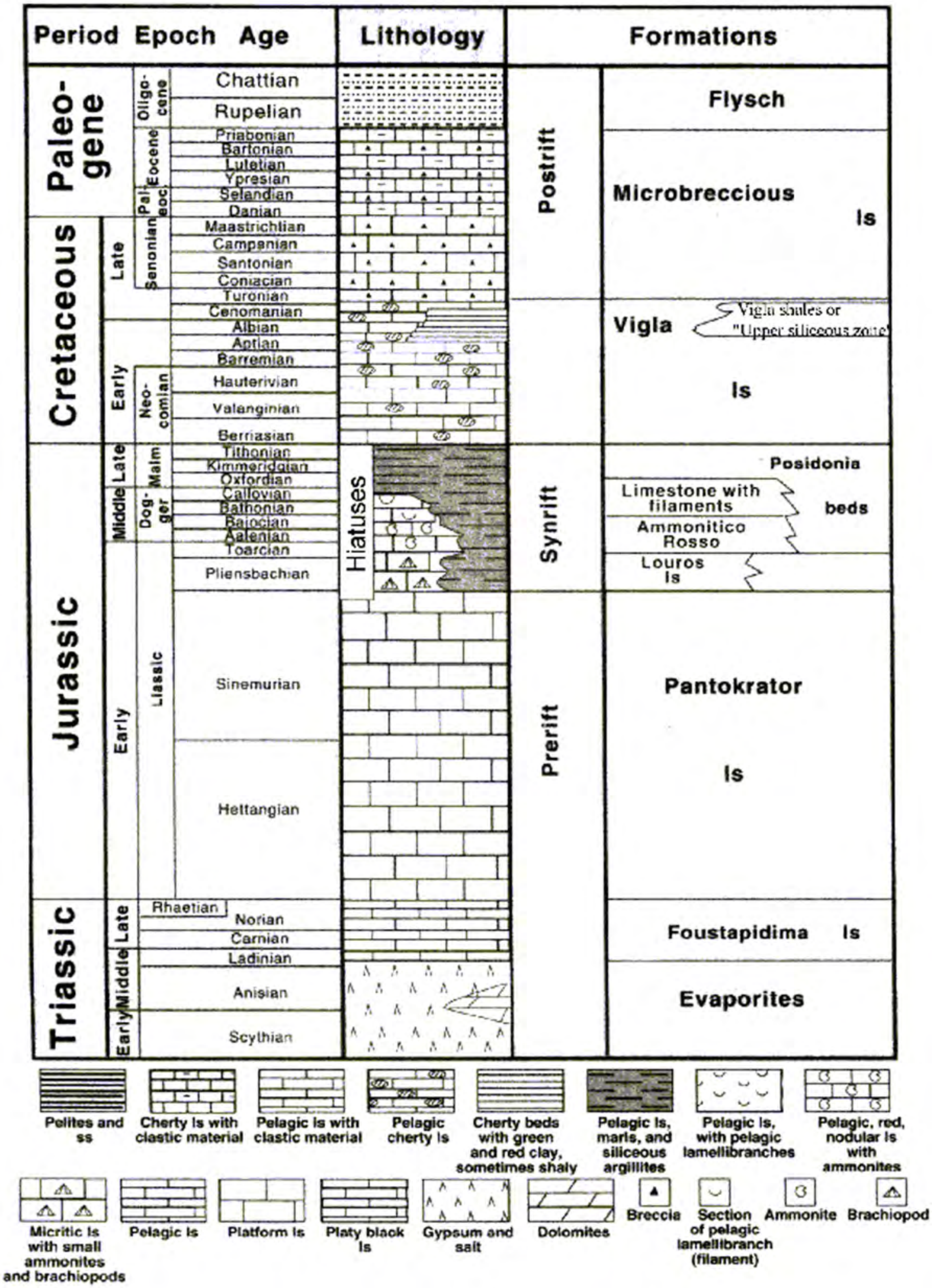
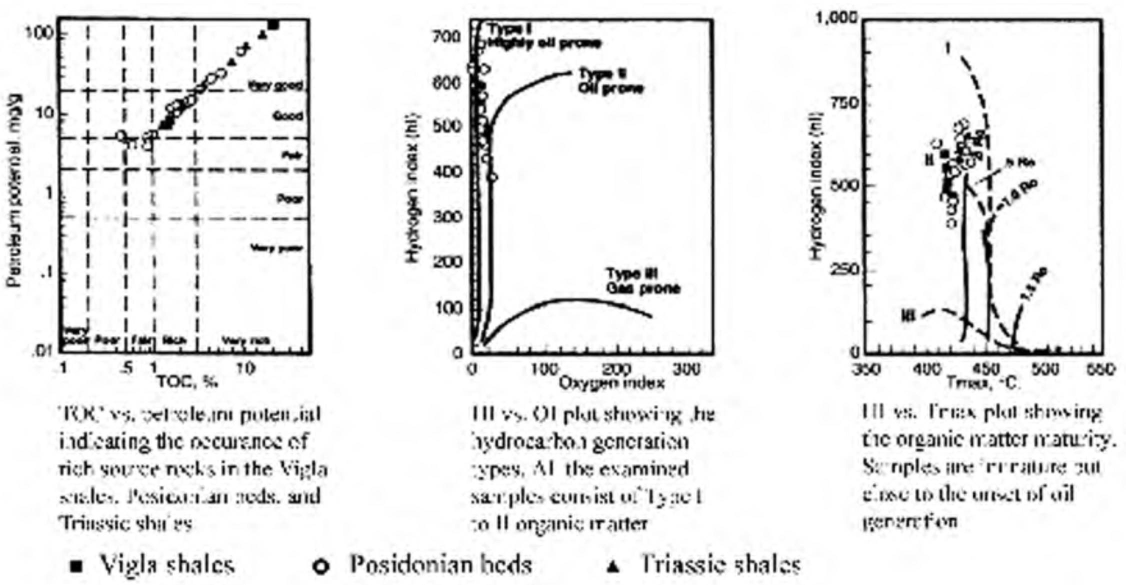


Fig. 2. Representative column of the Ionian series (after Karakitsios, 1995)



TOC vs. petroleum potential indicating the occurance of rich source rocks in the Vigla shales, Posidonian beds, and Triassic shales

HI vs. OI plot showing the hydrocarbon generation types. All the examined samples consist of Type I to II organic matter

HI vs. Tmax plot showing the organic matter maturity. Samples are immature but close to the onset of oil generation

Fig. 3. A: TOC vs petroleum potential. B: HI vs OI plot showing the hydrocarbon generation types. C: HI vs Tmax plot showing the organic matter maturity.

3. DEPOSITIONAL MODEL

The organic rich shale fragments within the Triassic breccias were initially deposited as stratigraphic layers in relatively shallow restricted sub-basins inside the evaporitic basin. The lack of detailed stratigraphy of subsurface evaporites in the Ionian zone does not allow any suggestion about the exact stratigraphic position of the shale layers; consequently, it is not possible to correlate the deposition of these layers with any geological event of Triassic age (e.g., sea level changes, local subsidence, anoxic events etc.). However, the establishment of the evaporitic sedimentation in the entire basin favored the preservation of organic matter. Consequently, the processes that formed the evaporite dissolution collapse breccias caused also the fragmentation of the initially organic rich shale layers, which are present actually as organic rich shale fragments in the Triassic breccias (Karakitsios and Pomoni-Papaioannou, 1998).

The accumulation and preservation of the organic matter in the Lower and Upper Possidonia beds through Toarcian to Tithonian and in the marls at the base of the Ammonitico Rosso dur-ing Early Toarcian, are directly related to the geometry of the synrift period of the Ionian basin. The geometry of the restricted sub-basins favored water stagnation and consequently the development of locally euxinic conditions in the bottom waters (Karakitsios, 1995). As far as the well documented Toarcian Oceanic Anoxic Event of Tethys (Jenkyns, 1988; Farrimond et al., 1989) is concerned, the particular geometry of the sub-basins, during the synrift period of the Ionian basin, favored the record of the anoxic event as it is evidenced by the high amount of organic mater included in the Lower Posidonia beds and the marls at the base of the Am-monitico Rosso.

The accumulation and preservation of the organic matter in the Vigla shales (Albian-Cenomanian) is generally attributed to sub-basins that were preserved due to the continuation of halokinetic movements during the post-rift period (Karakitsios, 1995). Although, in the Gotzikas area of NW Epirus, this member contains at least 20 dm-thick, organic-rich calcareous mudstones and shales. Analysis for bulk carbonate/organic carbon stable-isotope (C,O) ra-tios, and detailed organic geochemical study on bulk and solvent-extractable organic matter, showed that (Karakitsios et al., 2002): a) TOC contents (1 to 6 wt%), Hydrogen Index (HI, mean: 321 mg/g) and d13CTOC (-26.5±1.0‰) values show little variation across the lower part of the Gotzikas section, and b) a sharp positive shift in d13CTOC by approximately 4.5 per mil is observed, in the uppermost black-shale unit (-22.14‰), which also has the highest TOC con-tent (28.87 wt%) and HI (529 mg/g) and is most enriched in amorphous organic matter This TOC-enriched and

Formation	Average Total Porosity (%)
Post-Alpine Formations and Flysch	Negligible, except for some sandstone horizons of fair porosity
Paleocene, Eocene and Senonian Limestones	3
Vigla Limestones	1.7
Upper Posidonia Beds	5
Limestones with Filaments	3
Lower Posidonia Beds	5
Ammonitico Rosso	3
Siniais Limestones	2
Louros Limestones	3
Pantokrator Limestones	10
Foustapidima Limestones	3
Triassic Breccias	13

Table I: Average Total Porosity of the Ionian zone formations

isotopically heaviest black-shale unit shares important similarities, both compositionally and isotopically, with early Albian black shales from site ODP 1049C (N. Atlantic) and the Vocontian basin of SE France ("Niveau Paquier"). Consequently, at least the uppermost part of the Vigla shale member constitutes a new manifestation of the Oceanic An-oxic Event (OAE) 1b, whose sedimentary record is best developed in the Tethys-Atlantic re-gion.

4. POROSITY AND PERMEABILITY, RESERVOIR ROCKS AND CAP ROCKS

Porosity measurements carried out on surface samples of various formations of the Ionian se-ries gave the results figured in Table I. Porosity dedicated electrical logging suites performed in the Ioannina-1 well were used for indirect porosity calculations. Average porosity values are almost coincident in both cases. As far as permeability is concerned, apart from the Triassic breccias (fair permeability) and some sandstone interbeds within the flysch and the post-Alpine clastic formations (fair to average permeability) all the other formations are characterized by negligible permeability.

The study of the primary matrix porosity along with the secondary fracture porosity of the various formations comprising the Ionian series reveals that the most suitable lithologies shar-ing reservoir rock characteristics are those of the Eocene limestones and the Triassic breccias, Liassic and Lower Cretaceous dolomites. Additionally, the flysch (Oligocene), the post-Alpine formations (Neogene) and the sub-surface Triassic evaporites appear to constitute the most po-tential cap-rocks. The geometric configuration of the above formations (reservoir and cap-rocks) is a function of the tectonic evolution of the basin. The latter is of crucial importance in determining the location of prospective hydrocarbon traps in the entire Ionian basin.

5. MIGRATION AND TRAPPING

The amount of hydrocarbons that has been expelled from the source rock during the first mi-gration phase that has been calculated in the Botsara syncline accounts for almost the 75-80% of the hydrocarbons that have been produced (Karakitsios et al., 2001). This could probably be explained by the fact that the source rocks are very rich in organic matter. Oil shows in the area occur mainly as a result of secondary migration along the reservoir rock. However, in some cases these shows can be ascribed directly to primary migration as in the case of the Petousi oil shows. That could be very encouraging, as far as the entire process of expulsion-migration is concerned, since it indicates that those phenomena might take place at relatively low matura-tion levels before the onset of the oil window (Karakitsios et al., 2001).

Surface oil shows in the Ionian zone have been observed in the central and external Ionian zone with most of them located along the edges of the Botsara syncline. These involve mainly hydrocarbon impregnations of porous formations, joints, faults etc. Other shows reported include oil seeps as well as asphaltic (dead oil) residues. Oil seeps are likely to be linked to all the formations ranging in stratigraphic age from Triassic to Bourdigalian. They have mainly been reported either along fault surfaces or at the contact between the limestones and the overlying detrital formations (flysch, Bourdigalian). Most of the oil exploration wells that have been drilled in the Ionian zone have also provided some evidence of oil presence at depth (e.g. Lavdani-1 and 2, Delvinaki-1, Filiates-1, Dragopsa-1, and Lippa-1 wells; Karakitsios et al., 2001).

The low porosities and permeabilities of the formations that make up the Ionian zone would either imply high fluid pressures, which seem to be unlikely in the case of the Ionian basin, or fluid migration through "fracture macro-permeability conduits" in the vicinity of faulted and highly deformed zones. Thus, only a general approach of the migration-entrapment aspects is possible. It can be mentioned that in the entire Ionian Series there are two main formations that could play the role of the cap-rock: a) the flysch together with the clastic post Alpine formations, and b) the subsurface evaporites. Structures related to those formations will be consid-ered separately:

- In the anticline zones, formations sharing cap-rock characteristics, such as the flysch, the Bourdigalian and in general the clastic post-Alpine formations have been diminished in thick-ness or in some cases are completely missing. So, any oil that could have been trapped in structures incorporating those cap-rocks would have finally been destroyed due to its exposure to the surface. Thus, even in the case of active supply from a source rock it seems reasonable that hydrocarbons would have been spread throughout the entire reservoir exposure rather than accumulated in specific areas. The latter could probably explain the fact that apart from some special cases no surface oil shows are generally observed along the crestal parts of anticlines. On the other hand, synclines, as low relief topographic zones, have escaped erosion and so po-tential cap-rocks are largely preserved. In those areas localities suitable for the entrapment of hydrocarbons are restricted in the largest synclinal structures and so surface oil shows have been observed along the peripheral edges of the synclines. These shows are the result of migra-tion that takes place along the lower surface of the cap-rock ("along cap-rock" migration type). In this way oil during its migration course could be deflected upwards close to the erosional limit of the detrital cap-rocks thus resulting in the formation of surface oil shows. According to this migration scheme, intervening anticlines should be flushed and infilled with oil prior to the surface expulsion of any migrating hydrocarbons.
- Surface evaporitic exposures rarely reflect their initial depositional facies and configuration. This can be ascribed to a) the combination of their role as a detachment level during the compressional tectonic phase and their inherent physical property to flow (diapirism) and b) the solution-collapse mechanism involved in their generation resulting in surface exposures dominated by solution-collapse breccias (Karakitsios & Pomoni-Papaioannou, 1998). So, in terms of porosity-permeability, Triassic breccias cannot be treated as part of the Triassic evaporites although they constitute the form in which the latter appear in the surface. The reason behind this is that the breccias are not effective seals any more due to their high porosity-permeability values as a result of the processes involved in their generation (evaporite solution and post-evaporite strata collapse). Considering however the exploration attractiveness of potential structures at the lower level of the subsurface evaporites in their contact with the pre-evaporitic basement it becomes evident that fieldwork data is of minor importance unless supplemented by seismic data. Only deep seismic reflection techniques could provide with evidence about the crucial issue concerning the participation degree of the pre-evaporitic basement in the deformation of the sedimentary cover. Since, the luck of credible deep seismic data only some considerations can be done. Thus, if the pre-evaporitic basement is strongly involved in the deformation of the sedimentary cover, suitable structures for hydrocarbon accumulations could probably be located in the contact between the evaporites and the underlying basement. This case also implies very limited detachment of the sedimentary cover along the evaporitic basement that is less probable. In the contrary, if the pre-evaporitic basement is moderately or at all involved in the sedimentary cover deformation, it implies a relatively moderate to high degree detachment of the sedimentary cover at the evaporitic level. This in turn would mean absence of pre-evapotic basement structures and hence absence of traps in the between their contact level.

6. CONCLUSIONS

- Five organic-rich formations of source-rock potential have been observed in the Ionian basin: the Vigla shales (Albian-Turonian), the Upper Posidonia beds (Callovian-Tithonian), the Lower Posidonia beds (Toarcian), the marly beds at the base of the Ammonitico Rosso (Early Toarcian), and shale fragments in the Triassic breccias. These five horizons have good hydrocarbon potential and their organic matter is of type I to II. In the central Ionian basin (oil win-dow = 3700-5800m), the Triassic shales have already entered the gas window; the Lower and Upper Posidonia beds and the marls at the base of the Ammonitico Rosso are mature in terms of oil generation; the Vigla shales correspond to an early maturation stage.

- The preservation of the organic matter in the Lower and Upper Posidonia beds, and the marls at the base of the Ammonitico Rosso, is mainly due to the geometry of the synrift period, whereas in the Vigla shales it is also related to the Cretaceous Anoxic Events. The organic rich shale fragments within the Triassic breccias were initially organic rich stratigraphic layers de-posited in restricted sub-basins inside the evaporitic basin. The processes accounting for the formation of the evaporite dissolution collapse breccias are responsible for the present organic rich shale fragments incorporated within the Triassic breccias.

- Direct porosity measurements and electrical logging have shown that apart from the Triassic breccias and Pantokrator limestones, characterized by good porosity, the rest of the strata comprising the Ionian series have low porosity and negligible permeability values. Thus, it seems that fracture porosity-permeability plays the dominant role in determining hydrocarbon migration.

- Studies concerned with the hydrocarbon trapping mechanism (based entirely on surface data) have revealed that potential traps are mainly connected with small anticlines, incorporated in larger synclines, at the contact zone between the calcareous and the clastic series of the Ionian zone. Additionally, the base of the evaporitic sequence could include potential traps if the pre-evaporitic basement is involved in the deformation of the overlying sedimentary cover.

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