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MIGRATION AND TRAPPING OF THE IONIAN SERIES HYDROCARBONS (EPIRUS, NW GREECE)*

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ABSTRACT

Surface oil shows in the Ionian zone of NW Greece are mainly linked to the organic matter rich Lower Posidonia beds of Toarcian age and shale fragments within the Triassic breccias. The calcareous formations of the Ionian series are characterized by insignificant primary porosity-permeability. Only fractured carbonates might comprise potential reservoir rocks capped on top by the detrital series. Other prospective traps, with the evaporites playing the role of cap-rocks, are related to the degree of basement involvement in the structural evolution of the Ionian basin.

KEY WORDS: Source rocks, reservoir rocks, cap-rocks, expulsion, secondary migration, trapping, Ionian basin.

1. INTRODUCTION

The Ionian zone of western continental Greece has constituted a field of interest in hydrocarbon exploration during the last 50 years. The study has led to the discovery of numerous structural and stratigraphic trapping possibilities and good quality sources rocks, reservoirs, and seals (IGRS-IFP 1966, BP 1971, Chiotis, 1983, Palakas et al. 1986, Jenkyns 1988, Karakitsios 1995, Roussos & Marnelis 1995, Kamberis et al. 1996, Karakitsios & Rigakis 1996, Rigakis & Karakitsios 1998). This interest remains still active especially after the recent international licensing campaign for the offshore-onshore areas along western Greece fostered by the Hellenic Petroleum.

The objectives of this paper are the evaluation of the possible reservoir and cap-rock lithologies as well as the study of the migration pathways and the trapping mechanism of hydrocarbons expelled from the various source rocks of the Ionian series.

2. GEOLOGICAL FRAME

The Ionian zone of northwest Greece (Epirus region) constitutes part of the most external zones of the Hellenides (Paxos zone, Ionian zone, Gavrovo zone; Fig. 1A). The rocks of the Ionian zone range from Triassic evaporites and associated breccias through a varied series of Jurassic through Upper Eocene carbonates and lesser cherts and shales followed by the Oligocene flysch (Fig. 2).

The stratigraphy of the Ionian basin exhibits three distinct sequences (Karakitsios 1995) (Fig. 2):

a) A prerift sequence which is represented by the early Liassic Pantokrator Limestones (Aubouin 1959, IGRS-IFP 1966, Karakitsios 1990, 1992). These shallow water limestones overlie Early to Middle Triassic evaporites (more than 2000 m thick) through the Foustapidima Limestones of Ladinian-Rhetian age (Renz 1955, Pomoni-Papaioannou & Tsaila-Monopolis 1983, Dragastan et al. 1985, Karakitsios & Tsaila-Monopolis 1990). The "sub-evaporite beds" of the Ionian zone in Western Greece do not crop out, nor were they penetrated by deep wells (IGRS-IFP 1966, BP 1971).
b) A synrift sequence that began with the deposition of the Siniais stones and their lateral equivalent, the Louros Limestones (Karakitsios & Tsaila-Monopolis 1988). Foraminifera, brachiopods and ammonites in Louros Lime-stones indicate a Pliensbachian age (Karakitsios 1990, 1992, Dommergues et al. 2001). These formations correspond to the general subsidence of the Ionian area (formation of Ionian basin), which was followed by the internal synrift differentiation of the Ionian basin marked by smaller paleogeographic units. These paleogeographic units are recorded in the prismatic synsedimentary wedges of the synrift formations and include the Siniais or Louros Limestones, the Ammonitico Rosso or its lateral equivalent Lower Posidonia

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beds, the Limestones with Filaments, and the Upper Posidonia beds (Fig. 2). Stratigraphic sections throughout the study area reveal abruptly changing thickness in the syntectonic sequences within a few kilometers. The synrift differentiation is related to opening of the Tethys Ocean, which was accompanied by the formation of a series of north-northwest and east-southeast trending conjugate faults. The early Liassic shallow marine platform was affected by listric block-faulting, which was recorded in the differential subsidence within each small paleogeographic unit (Bernoulli & Renz 1970, Karakitsios 1992, Karakitsios 1995). The directions of synsedimentary tectonic features (e.g. slumps and synsedimentary faults) indicate that deposition was controlled by structures formed during the extensional tectonic phase. The sedimentation style corresponds, in general, to a half-graben geometry. Prismatic sedimentary wedges of the synrift formations in the small paleogeographic units (in most cases the units did not exceed 5 km across) vary in thickness east-west. Thus, unconformities are located on top of tilted blocks, while complete Toarcian to Tithonian successions with Ammonitico rosso or Lower Posidonia beds at their base are located in the deeper part of the half grabens. Theoretical and field data suggest that the extensional phase provoked halokinesis in the Ionian zone evaporitic substratum; the halokinesis influenced the synrift mechanism by increasing the extensional fault throws (Karakitsios 1988, 1990, 1992, 1995).

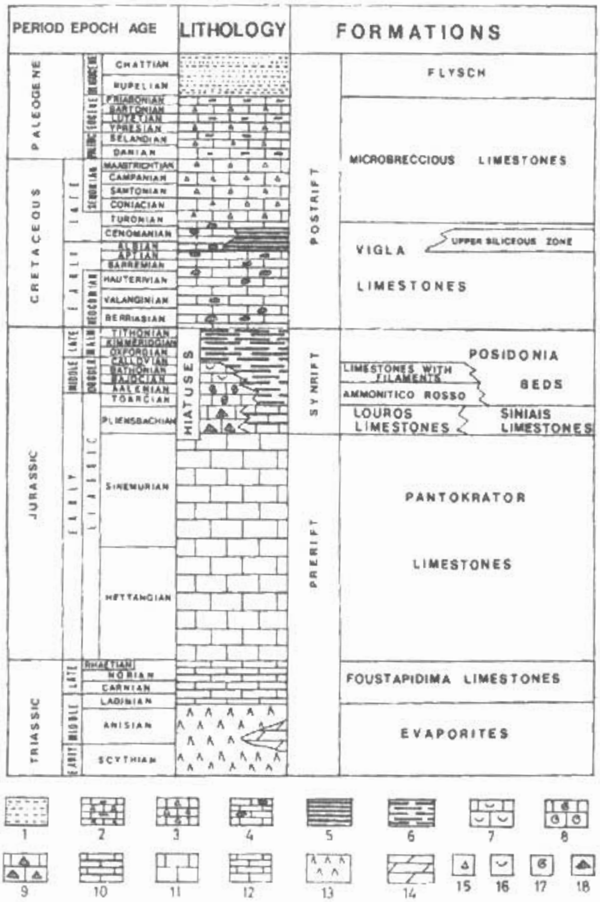

Fig. 2. Representative stratigraphic column of the Ionian zone (after Karakitsios 1995): 1= pelites and sandstones; 2= cherty limestones with clastic material; 3= pelagic limestones with clastic material; 4= pelagic cherty limestones; 5= cherty beds with green and red clay, sometimes shaly; 6= pelagic limestones, marls, and siliceous argillites; 7= pelagic limestones with pelagic lamellibranches; 8= pelagic, red, nodular limestones with ammonites; 9= micritic limestones with small ammonites and brachiopods; 10= pelagic limestones; 11= platform limestones; 12= platy black limestones; 13= gypsum and salt; 14= dolomites; 15= breccia; 16= section of pelagic lamellibranch (filament); 17= ammonite; 18= brachiopod.

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c) A postrift period that is defined by an early Berriasian breakup marked by an unconformity at the base of the Vigla Limestones. Sedimentation during the postrift period was synchronous in the whole Ionian basin (Karakitsios 1990, Karakitsios & Koletti 1992). 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 (Karakitsios 1992, 1995). The deposits of the Vigla Limestones do not correspond to an eustatic sea-level rise, but to a general sinking of the entire basin (Karakitsios & Koletti 1992). The persistence of differential subsidence during the deposition of the Vigla Limestones, shown by the strong variation in thickness of this formation, is probably due to the continuation of halokinetic movements of the Ionian zone evaporitic substratum (IGRS-IFP 1966, Karakitsios 1988, 1990, 1991, 1992). 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.

In the Gavrovo and Ionian zones the main orogenic movements took place at the end of the Burdigalian, whereas in the Paxos and Apulian zones they occurred during the Pliocene-Pleistocene (IGRS-IFP 1966, Bizon 1967). Observation of the Ionian zone tectonics shows that structures (folds and thrusts) in the central and western parts of the Ionian zone are displaced westwards, whereas in its eastern part they are displaced eastwards (Fig. 1B). The Ionian zone constitutes a good example of inversion tectonics in a basin with evaporitic substratum (Karakitsios 1995). Balanced cross-sections constructed through the intermediate and more external part of the basin show that several times 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 substratum halokinesis, the most elevated footwalls have been thrusted over the preexisting hanging walls (Karakitsios 1995). The amount of shortening involves a westward growth of horizontal displacement of the Ionian zone. Since the estimation of the shortening was only based on surface geological data, it should be regarded as conservative (Karakitsios 1995). However, in all cases the localization of reverse faults and thrusts took place in the location of Jurassic paleofaults (Karakitsios 1995). The double divergence of the Ionian zone structures (westwards in the western and central part and eastwards in the eastern part) is attributed to structures inherited from the Jurassic extensional phase (Karakitsios 1995). The extensional Jurassic faults of the external Ionian zone (Apulian side), dipping eastwards, were reactivated during the compressional phase as compressional westwards displacements, whereas those of the internal Ionian zone (Gavrovo side), dipping westwards, were reactivated as compressional eastwards displacements. Listric faults were entirely transformed into either transcurrent or reverse faults and/or thrusts, which is consistent with the classical inversion tectonics scheme. In the cases where halokinesis played an important role in the development of the structures, the reverse fault movement occurred only in the upper part of the faults. This phenomenon was facilitated by diapiric movements promoted by the salt layer at the base of the evaporites. Field and available seismic data point out that a moderate decollement took place along the sub-surface evaporites, especially in the external domain of the Ionian zone (Karakitsios 1995).

3. THE IONIAN ZONE SOURCE ROCKS AND THEIR DEPOSITIONAL MODEL

Five possible source rock horizons have been identified in the Ionian zone of northwest Greece (Rigakis & Karakitsios 1998): the Vigla shales Albian-Turonian), the Upper Posidonia beds (Callovian-Tithonian), the Lower Posidonia beds (Toarcian-Aalenian), the marls at the base of the Ammonitico Rosso (Lower Toarcian) and some shale fragments within the Triassic breccias. All the above source-rock horizons have good hydrocarbon potential and their organic matter is of type I to II (Karakitsios & Rigakis 1996, Rigakis & Karakitsios 1998).

The burial history curves have shown that the oil window, located in the central Ionian zone in the interval between 3750-5800m (as in the case of the Botsara sub-basin), is decreasing from west to east (Rigakis & 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 as well as 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 the early maturation stage, while in the eastern areas Vigla shales are mature. 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.

The preservation of the organic matter in the Lower and Upper Posidonia beds through Toarcian to Tithonian and in the marls at the base of the Ammonitico Rosso during early Toarcian times, is directly related to the geometry of the synrift period of the Ionian basin (Karakitsios 1995, Rigakis & Karakitsios 1998). Organic matter preservation in the Vigla shales is related to the subbasins that were preserved due to the continuation of

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halokinetic movements during the postrift period (karakitsios 1995). Thus, anoxic conditions were selectively created during the whole synrift and sometimes during the postrift period. The geometry of the formed restricted subbasins favored water stagnation and, consequently, the development of locally euxinic conditions of the bottom waters. This particular geometry of the synrift and postrift period of the Ionian zone promoted also the anoxic events otherwise recorded in the entire Tethys realm during Early Toarcian times (Jenkyns 1988, Farrimond et al. 1989) and Cenomanian (Farrimond et al. 1990). 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 establishment of evaporitic conditions in the entire basin favored the preservation of the organic matter. The processes accounting for the formation of the evaporite solution collapse breccias caused also the fragmentation of the initial organic rich layers which presently occur as organic rich shale fragments incorparated within the Triassic breccias (Karakitsios & Pomoni-Papaioannou 1998).

Surface oil shows in the Ionian zone are mainly attributed to the Toarcian Lower Posidonia beds and lesser to the late Callovian-Tithonian Upper Posidonia beds, the Albian-Turonian Upper Siliceous zone or "Vigla shales" of the Vigla limestones (IGRS-IFP 1966, Nikolaou 1986, Baudin & Lachkar 1990, Roussos & Marnelis 1995, Karakitsios 1995, Karakitsios & Rigakis 1996, Rigakis & Karakitsios, 1998, Rigakis, 1999), the marly beds at the base of Ammonitico Rosso and some horizons containing organic matter rich shale fragments in the Triassic breccias (Karakitsios & Rigakis 1996, Rigakis & Karakitsios 1998).

4. POROSITY AND PERMEABILITY-RESERVOIR ROCKS AND CAP ROCKS

Porosity measurements were effected on surface samples of various formations of the Ionian series through the combination of the pycnometer GeoPyc 1360 and the helium pycnometer Micrometrics' AccuPyc 1330. The results are shown on Table I.

Formation	Average Total Porosity (%)
Post-Alpine Formations	Negligible, except for some sandstone horizons of fair porosity
Flysch	Negligible, except for some sandstone horizons of fair porosity
Paleocene-Eocene Limestones	3
Senonian Limestones	3
Vigla Limestones	1.5
Vigla Upper Siliceous Zone	3
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

Except for the above direct porosity measurements, porosity dedicated electrical logging suites performed in the Ioannina-1 well (density-newtron-sonic compensation electrical logs) were used for indirect porosity calculations of the Siniais and Pantokrator limestones and the Triassic breccias. 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 sharing reservoir rock characteristics are those of the Eocene limestones and the Triassic, Liassic and Lower Cretaceous dolomites. Additionally, the flysch (Oligocene), the post [illegible] evaporites appear to constitute the most potential cap-rocks. The geometric configuration of the above formations (reservoir and

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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. It can thus be inferred that the opening and the tectonic inversion of the Ionian basin have exerted a major influence on the deposition of source rocks as well as the formation of potential hydrocarbon traps.

5. MIGRATION AND TRAPPING

The data collected so far allows for an approximate estimation of the amount of hydrocarbons which has been expelled from the source rock during the first migration phase. It has been calculated that in the Botsara syncline this migration accounts for almost the 75-80% of the hydrocarbons that have been produced (Rigakis 1999). 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. There, the shows are in close contact with the Posidonia beds, so it becomes obvious that secondary migration, following the expulsion of the oil from the source rock, is only limited. That could be very encouraging, as far as the entire proccess of expulsion-migration is concerned, since it indicates that those phenomena might take place at relatively low maturation levels before the onset of the oil window (Rigakis 1999).

Surface oil shows in the Ionian zone are inextricably linked to hydrocarbon migration. Such shows have been observed in the central and external Ionian zone with most of them located along the edges of the Botsara syncline (fig. 1B). 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. The following are related to the oil shows encountered in the wells drilled in the Epirus area:

- In the Lavdani-1 and Lavdani-2 wells oil shows appeared along the overthrust fault that juxtaposes the flysch with the Bourdigalian beds. In addition to that, shows were reported within the flysch and the underlying limestones in the Lavdani-1 well.
- In the Delvinaki-1 well hydrocarbon indications are manifested as oil shows along the Delvinaki overthrust fault which brings the Triassic breccias on top of the flysch.
- Oil shows that were observed in the Filiates-1 well are related to specific horizons within the Triassic evaporites.
- Dead oil shows in the calcareous series and the Radovizi formation of Acquitanian age were reported in the Dragopsa-1 and Lippa-1 wells.

The low porosities and permeabilities of the formations that make up the Ionian zone would either imply high fluid pressures, which seems 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.

The above considerations along with the fact that fieldwork data is the only information source would imply that the approach of the migration-entrapment aspects is feasible not on the basis of a basin-wide study but only at the scale of specific structures. In that respect some aspects of general interest concerning the Ionian zone will be discussed first.

In the entire Ionian Series there are two main formations that could play the role of the cap-rock: the flysch and the subsurface evaporites. Structures related to those formations will be considered separately.

5.1. Flysch-related traps

From the structural map of the Epirus area (Fig.) it becomes obvious that most of the anticlines, comprising high relief topographic zones, have been subjected to intense erosion. Consequently, formations sharing cap-rock characteristics, such as the flysch, the Bourdigalian and in general the clastic post-Alpine formations, have been diminished in thickness 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 accummulated 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 potential cap-rocks are largely preserved. In those areas locales suitable for the entrapment of

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hydrocarbons are restricted in the larger synclinal structures and so surface oil shows have been observed along the peripheral edges of the synclines. These shows are the result of migration 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.

5.2. Evaporite-related traps

The evaporates have played a critical role in the tectonic evolution of the Ionian basin (Karakitsios 1995, Karakitsios & Pomoni-Papaioannou 1988): a) during the Middle Lias the evaporitic substratum halokinesis influenced the intense block-faulting which affected the early Liassic shallow platform (Pantokrator limestones) resulting in the formation of several small, structurally controlled subbasins, b) during the compressional tectonic phase of the Alpine orogeny, the preexisting extensional structures (from Pliensbachian through Tithonian) were reactivated (inversion tectonics of Ionian basin), c) the geometric characteristics of the inverted basin depend on the differential evaporitic halokinesis, the lithological properties and transformations of the evaporites, the diapiric movements caused by the salt layer and the detachment along the subsurface evaporites.

Oil exploraton wells in the Ionian zone have penetrated in some cases more than 3000m of evaporites (IGRS-IFP 1966, BP 1971). However, the initial thickness of the evaporitic series should be much less since all the wells have been drilled in anticlinal zones where diapiric phenomena are very pronounced (Karakitsios 1992).

In conclusion it can be said that the deformation mechanism of the Triassic evaporites involves four main stages: a) halokinetic stage, b) detachment stage, c) diapiric stage and d) brecciation stage. The first three stages are sequential in time while the fourth stage was first initiated after the deposition of the evaporites and continued persisting during the time dominated by the first three stages. However, it becomes more pronounced after the third stage up to present times. So 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).

For the purpose of this study the Triassic breccias will not 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 proccesses 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 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 possible participation of the pre-evaporitic basement in the deformation of the sedimentary cover:

- In the first case (participation of the basement in the deformaton) suitable structures for hydrocarbon accummulations 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 substratum or even no detachment at all. All the known source rocks of the Ionian series might possibly contribute to hydrocarbon accumulations in some of those traps ("per descensum" migration) but more importantly all of the above prospective traps are prone to hydrocarbon supply by potential source rocks of the unknown pre-evaporitic basement.
- The second case (non participation of the basement in the deformation of the sedimentary cover) implies a relatively high degree of detachment of the sedimentary cover at the evaporitic level. This in turn would mean absence of basement structures and hence absence of traps at the Ionian zone level. In this case the pre-evaporitic basement is underthrust under the more internal zones thus being subject either to basement deformation east of the Ionian zone or to continental subduction. The second case appears to be compatible with the presence of the Phyllites-Quartzites Unit beneath the Tripolis calcareous series in Peloponnese and Crete. The Phyllites-Quartzites Unit is characterized by HP-LT metamorphism and it could thus be considered initially as the pre-evaporitic basement of the Ionian zone.

Other worth considering potential traps are those related to structures present in the tectonic contact zone between the Ionian and the Gavrovo zones. As far as the Epirus area is concerned field data shows that the tectonic relationships between the above zones do not fall in the typical rule governing the Hellenic Belt overthrusts (i.e. overthrusts with westwards vergence). It is inversely more likely that the Ionian zone is thrust over the

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Gavrovo zone than the opposite which should be normally expected. This is exemplified in the case of the internal Ionian zone where the folds are characterized by eastwards vergence. The latter could also be accounted for by the involvement of inversion tectonics in the evolution of the Ionian basin or even by east-oriented back-thrusts. However, only seismic reflection data, which is still missing, could give important information about the above mentioned structures. Considering the case that the Ionian zone is thrusted over the Gavrovo zone anticlinal structures at the base of the Ionian and the underlying Gavrovo zone flysch could form part of potential traps. As opposed to the Epirus area, in the Aitoloakarnania area field observations favor for the typical Hellenic Belt deformation style (i.e. structures with westwards vergence) and so it seems more likely that the Gavrovo zone is thrust over the Ionian zone although as in above case seismic reflection data and deep wells which could provide valuable information do not exist. If the evolution of the overthrusts follows the established deformation style potential traps might be located in the vicinity of anticlinal structures at the base of both the Gavrovo flysch and the underlying Ionian flysch.

6. CONCLUSIONS

- Surface oil shows in the Ionian zone are mainly attributed to the Toarcian Lower Posidonia beds and lesser to the late Callovian-Tithonian Upper Posidonia beds, the Albian-Turonian Upper Siliceous zone or "Vigla shales" of the Vigla limestones, the marly beds at the base of the Ammonitico Rosso and some horizons containing organic matter rich shale fragments in the Triassic breccias. These five horizons have good hydrocarbon potential and their organic matter is of type I to II. The timing of the principal source rock horizons maturation is the Upper Jurassic for the Triassic shale fragments and the Serravalian for the Lower Posidonia beds.
- Direct porosity measurements and electrical logging suites 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. So it seems that fracture porosity-permeability plays the dominant role in determining hydrocarbon migration and trapping.
- Studies concerned with the hydrocarbon trapping mechanism and 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 (base of the flysch). Updip migration is taking place at the base of the flysch according to the mechanism of "along cap-rock migration". If the basement is involved in the deformation of the overlying sedimentary cover it is likely that the base of the evaporitic sequence could be involved in the localization of potential traps. However, the latter could only be clarified through the use of deep seismic reflection data.

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