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EVOLUTION AND PETROLEUM POTENTIAL OF WESTERN GREECE

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This paper reviews previous data on the geological evolution of Western Greece, with special emphasis on the petroleum potential of the Pre-Apulian zone (including new data) and the Ionian zone, the two most external portions of the Hellenide fold-and-thrust belt. From the Triassic to the Late Cretaceous, Western Greece constituted part of the southern passive margin of Tethys, and siliceous facies are widely associated with organic-carbon rich deposits. Pelagic Late Jurassic units rich in marine organic matter constitute important hydrocarbon source rocks in the pelagic–neritic Pre-Apulian zone succession. Oil–oil correlation with an Apulian zone oil sample (from Aquila, Italy) indicates similar geochemical characteristics. Thus, the significant volumes of oil generated by the rich and mature source rock intervals identified in the Pre-Apulian zone are likewise expected to be of good quality. In the Ionian zone, four organic-carbon rich intervals with hydrocarbon potential have been recorded.

The tectonic history of the Pre-Apulian zone, which is characterised by the presence of large anticlines, is favourable for the formation of structural traps. By contrast, locations suitable for the entrapment of hydrocarbons in the Ionian zone are restricted to small anticlines within larger-scale synclinal structures. Hydrocarbon traps may potentially be present at the tectonic contacts between the Ionian zone and both the Pre-Apulian and Gavrovo zones. Major traps may also have been formed between the pre-evaporitic basement and the evaporite-dominated units at the base of both the Pre-Apulian and the Ionian zone successions. The degree of participation of the sub-evaporitic basement in the deformation of the Pre-Apulian and Ionian sedimentary cover will determine the location and size of these traps.

Various scenarios regarding the deformation of the sub-evaporitic succession are examined in order to determine the hydrocarbon trapping possibilities of each model. The hypothesis of continental subduction (Early to Late Miocene) of the shared pre-evaporitic basement of the Pre-Apulian and Ionian zone eastwards of the Ionian zone is regarded favourably, as it appears to be compatible with the presence of a Phyllite – Quartzite – dominated (HP/LT) metamorphic unit beneath the Gavrovo-Tripolis zone carbonates in Peloponnesus and Crete.

INTRODUCTION

Exploration for hydrocarbons in Western Greece dates back to the 1860s. Early exploration focused on the abundant oil shows which are known to occur in this area (Monopolis, 1977), and exploration activities have recently been revived (Xenopoulos, 2000). So far, the results have been less than encouraging although both Albania and Italy host substantial oil- and gasfields (Mattavelli and Novelli, 1990; Van Greet *et al*., 2002; Mavromatidis *et al.*, 2004; Roure *et al*., 2004; Graham Wall *et al*., 2006).

In this paper, data on the geological evolution of Western Greece are presented and evaluated with particular reference to the area's petroleum potential. Potential reservoir units and traps are described in the most external zones of the Hellenide fold belt, namely the Pre-Apulian and Ionian zones. Finally, tentative conclusions are drawn regarding the oil potential of these formations according to various alternative geological scenarios.

Key Words: Western Greece, Pre-Apulian Zone, Ionian Zone.

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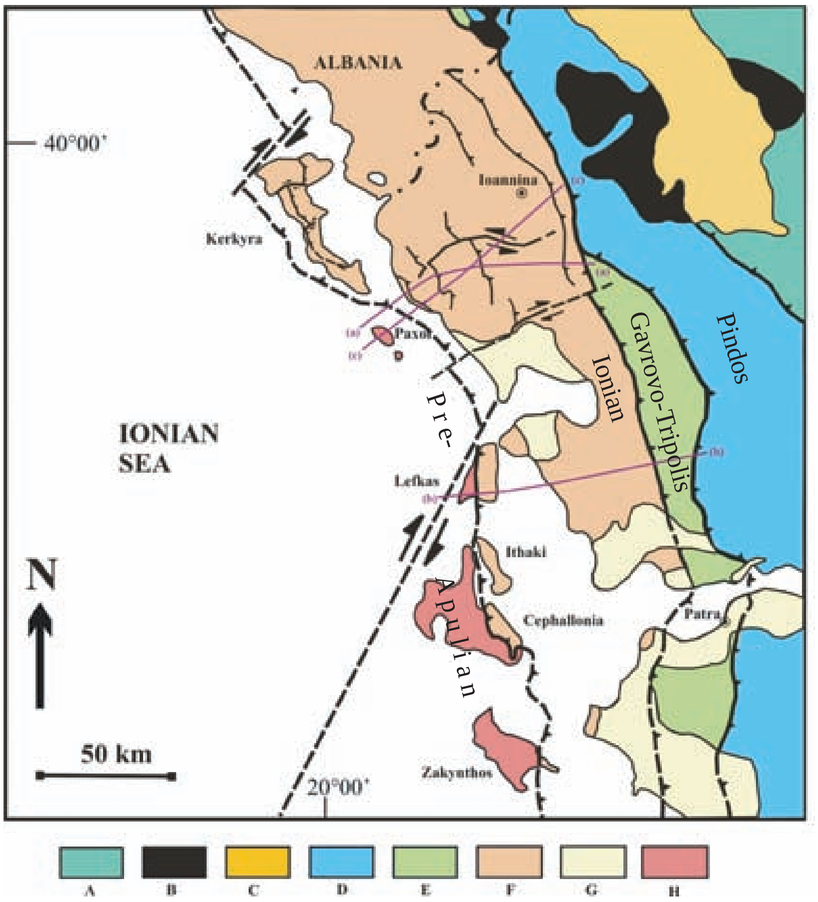


Fig. 1. Simplified geologic map of Western Greece (see Fig 8 insert for regional location). Profile lines (a), (b) and (c) refer to Fig. 17. Key: A. Pelagonian domain; B. ophiolites; C. Mesohellenic molasse; D. Pindos zone; E. Gavrovo-Tripolis zone; F. Ionian zone; G. Neogene – Quaternary (post-Alpine sediments);H. Pre-Apulian zone.

GEOLOGICAL SETTING

Western Greece is dominated by the external zones of the Hellenide fold-and-thrust belt, namely the Pre-Apulian (or Paxos), Ionian and Gavrovo - Tripolis zones (Fig. 1). From the Triassic to the Late Cretaceous, Western Greece was part of the Apulian continental block on the southern passive margin of Tethys. In this area, siliceous facies are widely associated with organic-carbon rich deposits. Rocks in the Pre-Apulian zone consist of Triassic to Miocene deposits, mainly neritic-pelagic carbonates. Hydrocarbon source rocks include pelagic deposits rich in marine organic material, although terrigenous organic matter is also found in siliciclastic sediments. The Ionian zone comprises sedimentary rocks ranging from Triassic evaporites to Jurassic - Upper Eocene carbonates and minor cherts and shales, which are overlain by Oligocene flysch. Organic-rich intervals occur within Triassic evaporites and Jurassic-Cretaceous pelagic argillaceous-siliceous sediments. The Gavrovo-Tripolis zone constituted a shallow-water platform from the Triassic to the Middle - Late Eocene in which no organic matter-rich intervals have so far been recorded.

At a regional scale (hundreds of kilometres), the Alpine belt can be considered to be the margin of the Tethys Ocean which has been inverted in response to the collision of Apulia with Europe (de Graciansky *et al.*, 1989). On a smaller scale (tens of kilometres), the sub-basins of the Hellenic Tethyan margin have been inverted to produce the main Hellenic thrust sheets or folded zones. This occurred progressively from the innermost (eastern) zones to the more external (western) zones (Karakitsios, 1995).

The thrust boundary between the Ionian and Pre-Apulian zones is marked by intrusive evaporites. This suggests that contractional deformation was the most important structural control on orogenesis in Western Greece. Although halokinesis was important along boundary faults during Mesozoic extension, thrusting has overprinted the Mesozoic extensional structures to such an extent that the latter are almost impossible to distinguish. Field observations of the relationship between the Pre-Apulian and Ionian zones emphasize the close association between Hellenide thrusts and folds and areas of evaporite exposure (evaporite dissolution-collapse breccias: Karakitsios and Pomoni-Papaioannou, 1998), even where the precise location of the thrust is unclear. Evaporites crop out along the leading edges of thrust sheets in both zones. This location, together with their occurrence in tectonic windows above tectonized flysch (observed in many places), suggests that the evaporites represent the lowest detachment level of individual overthrust sheets in the external Hellenides. Furthermore, the absence of pre-evaporite units from outcrops in Western Greece, the great thickness of the evaporites (more than 3km in boreholes in the Ionian Zone: IGRS-IFP, 1966; BP, 1971), and the probable incorporation of Permian basement into the thin-skinned orogenic wedge east of the Pindos thrust (Smith and Moores, 1974) all support the idea that the evaporites form a moderate to major *décollement* level throughout the external Hellenides, rather than widespread diapirism (Underhill, 1988; Karakitsios, 1992, 1995). Thus, the role of the evaporites is similar to that in thin-skinned thrust belts in Western Europe (Rigassi, 1977; Laubscher, 1978; Williams, 1985; Allen *et al.*, 1986; Ricci Lucchi, 1986).

The Pre-Apulian zone

The Pre-Apulian zone corresponds to the most external domain of the Hellenic fold-and-thrust belt. It has traditionally been considered as a relatively uniform, Mesozoic – Cenozoic carbonate domain, transitional between the Apulian Platform and the Ionian Basin. Its general setting is complex as a result of intense tectonic deformation, including phases of extension, collision and flexural subsidence, with undetermined amounts of shortening and block rotation (Accordi *et al.*, 1998). Outcropping successions differ in stratigraphic completeness, sedimentary development and faunal/floral content.

The depositional sequence in the Pre-Apulian zone (Fig. 2) begins with Triassic limestones containing intercalations of black shales and anhydrites. The oldest of these beds, according to borehole data (ESSO Hel., 1960), are dated as Toarcian to Bajocian. The stratigraphically lowest outcrops, located in Lefkas Island (Fig. 1), comprise Lower Jurassic dolomites and Middle Jurassic cherts and bituminous shales (Bornovas, 1964; BP, 1971). The Upper Jurassic succession consists of white chalky limestones with dolomite intercalations, accompanied by rare cherts and organic-carbon rich black shales, containing the planktonic species *Calpionella alpina, Calpionella elliptica* together with the benthic foraminifera *Valvulinella wellingsi*, *Phenderina* sp., *Pseudocyclammina* sp. and the algal species *Clypeina jurassica*. Borehole data from Zakynthos Island indicates the presence in the basal Cretaceous of conglomerates derived from carbonate and magmatic rocks. Lower Cretaceous limestones and dolomites crop out only on Cephallonia Island, and their facies is less pelagic than age-equivalent Ionian facies. The depositional environment throughout the Cenomanian-Turonian interval is indicated by the presence of rudist fragments, the benthic foraminifera *Cuneolina* sp., *Ticinella* sp., and the algal genus *Thaumatoporella* sp. Within the Campanian-Maastrichtian, however, the platy limestones gradually become chalky with thin argillaceous layers. They contain, especially towards the top of this formation, planktonic foraminifera such as *Globotruncana stuarti* and *Gl. elevate* in addition to rudist fragments. This co-existence indicates the presence of intra-platform basins characterizing the slope between the Apulian Platform and the Ionian Basin.

Paleocene micritic limestones with planktic foraminifera were described by BP (1971) in the Pre-Apulian zone. Mirkou (1974) noted that these Paleocene units sometimes rest on Santonian or Maastrichtian limestones, and that neritic-facies microbreccias and brecciated limestones occur at their base. This indicates intense tectonic activity which resulted in the differentiation of the Pre-Apulian zone into relatively deep-water and relatively shallow (sometimes emergent) areas, which provided the brecciated material. The Lower Eocene comprises pelagic limestones with marl intercalations. The Upper Eocene consists of massive limestones with algae, bryozoans, corals, echinoids and large foraminifera (*Nummulites* sp., *Alveolina* sp.). Oligocene sediments were deposited in small basins (tectonic grabens) between larger or smaller emergent areas, which were locally eroded, reflecting tectonic instability which continued throughout the Oligocene. During the Oligocene-Aquitanian, the diversification of foraminiferal assemblages suggests the presence of subsiding foreland basins. Finally, in the late Early Miocene, progressive deepening occurred, flooding the former carbonate slope (or carbonate ramp: Accordi *et al*., 1998).

Accordi *et al.* (1998) investigated the structural control on carbonate deposition and distinguished six tectono-sedimentary sectors within the Pre-Apulian zone, which was studied in the Paliki peninsula of Cephallonia Island. The boundaries of these sectors were identified by lithologic and stratigraphic discontinuities. The relationship between the different sectors is somewhat hypothetical, although, according to the above authors, they probably correspond to a number of tectonically obliterated areas of unknown extent. A general trend can be hypothesized for the study area, passing from a Late Cretaceous rimmed platform to a Paleocene homoclinal carbonate ramp. In the Paleocene, local tectonic subsidence together with eustatic sea-level changes and biological controls on the carbonate “factory” resulted in the deposition of a range of shallow-water to slope deposits, punctuated by episodes of emergence. Furthermore,

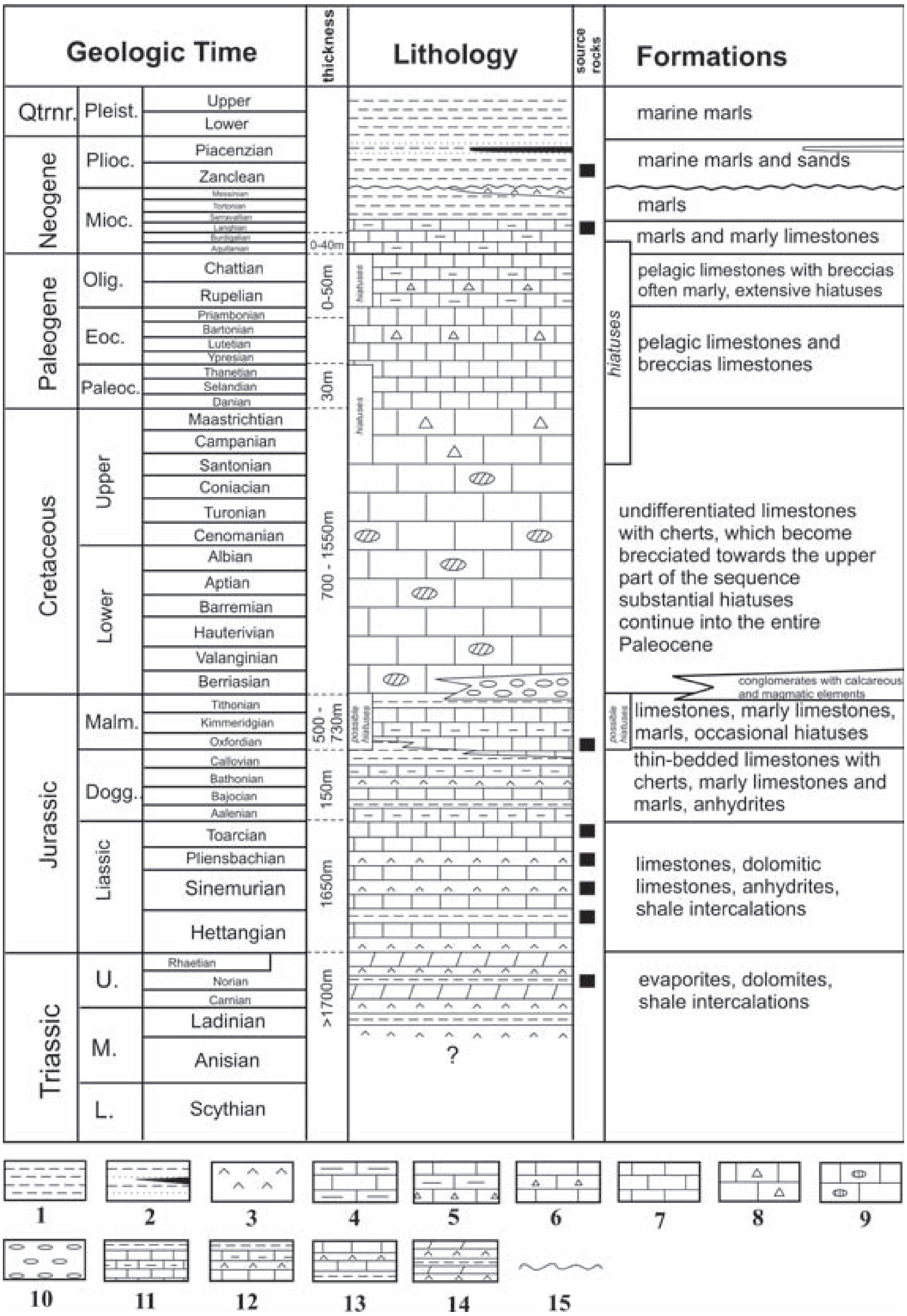


Fig. 2. Generalized lithostratigraphic column for the Paxos (Pre-Apulian) zone.
Key: 1. marine marls; 2: marine marls and sands (black: lignite intercalations); 3: evaporites; 4: limestones, often marly; 5: pelagic limestones or marly limestones with breccia intervals; 6: mixed pelagic-neritic limestones sometimes with breccias; 7: pelagic limestones; 8: mixed pelagic-neritic calcareous sediments with rudist fragments; 9: pelagic limestones with nodules and rare cherty intercalations; 10: conglomerates with calcareous and magmatic elements; 11: pelagic limestones, often marly; 12: limestones, shales and basal anhydrites; 13: limestones and dolomitic limestones, anhydrites and shale intercalations; 14: evaporites with shale intercalations; 15: unconformity.

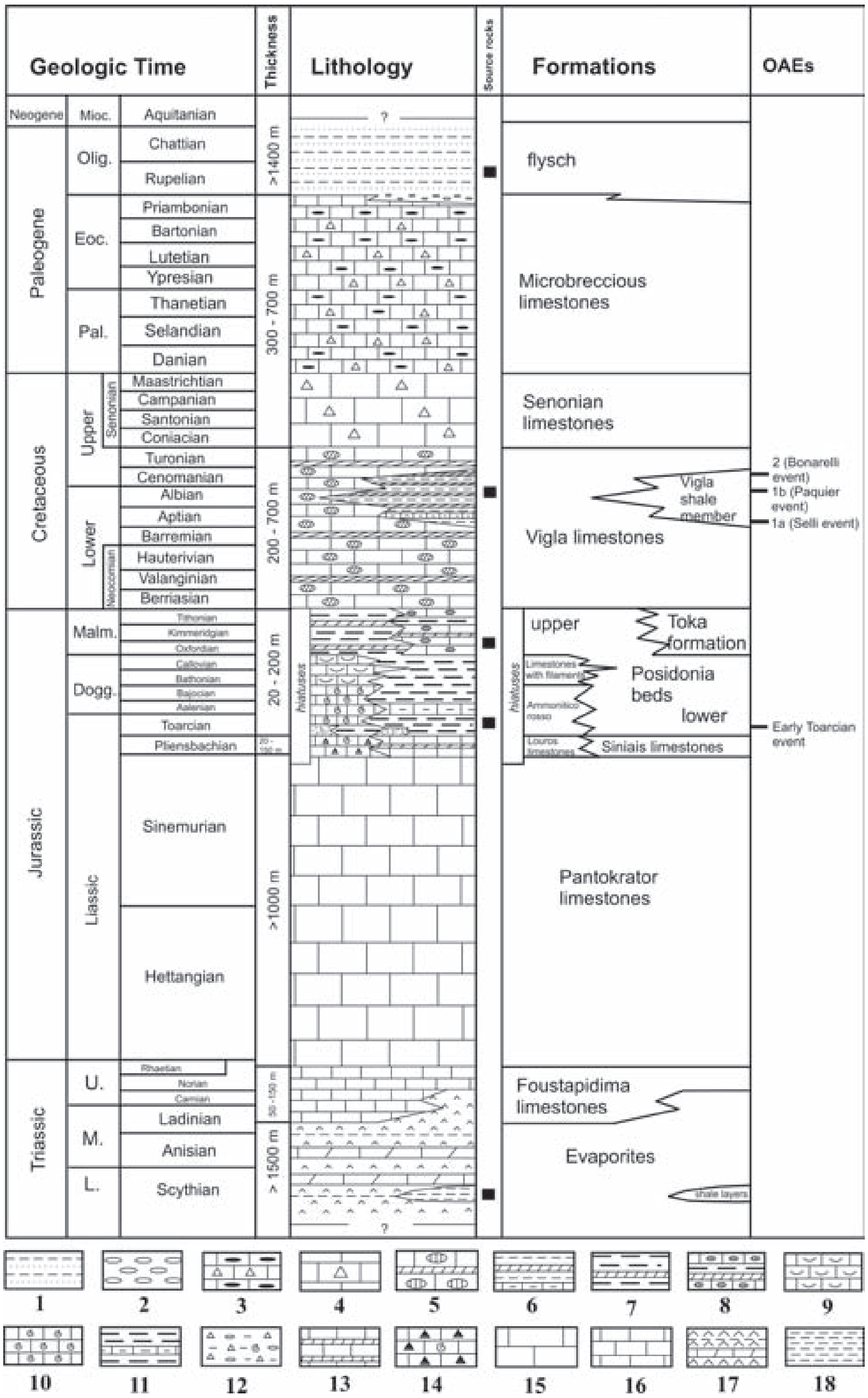


Fig. 3. Generalized lithostratigraphic column for the Ionian zone.
1: Shales and sandstones; 2: conglomerates; 3: limestones with rare cherty intercalations, occasionally microbreccious; 4: pelagic limestones with clastic platform elements; 5: pelagic limestones with cherts; 6: cherty beds with shale and marl intercalations; 7: alternating cherty and shale beds; 8: pelagic limestones with cherty nodules and marls; 9: pelagic limestones with bivalves; 10: pelagic, nodular red limestones with ammonites; 11: marly limestones and laminated marls; 12: conglomerates-breccias and marls with ammonites; 13: pelagic limestones with rare cherty intercalations; 14: external platform limestones with brachiopods, and small ammonites in upper part; 15: platform limestones; 16: thin-bedded black limestones; 17: evaporites; 18: shales.

the presence of a hiatus representing the greater part of the Eocene can be demonstrated in the same area.

It has so far generally been accepted that the Pre-Apulian zone lacks typical flysch sediments. However, the observed progressive transition from typical Ionian flysch to the more calcareous, age-equivalent facies in the Pre-Apulian zone (BP, 1971) indicates that post-Oligocene Pre-Apulian sediments correspond to an atypical distal flysch unit. The partial or complete absence of this unit from some areas is due to the fact that these areas corresponded to the most external part of the forebulge in the Hellenide foreland basin, which has possibly been eroded.

Structures developed in the Pre-Apulian zone (mainly on the islands of Cephallonia and Zakynthos) may be accommodated within a simple model of continued foreland-directed migration of Hellenide (Alpine) thrusting during the Late Neogene and Quaternary. Initial activity on the Ionian thrust can be dated as Early Pliocene, and the main thrusts (and some of the backthrusts) observed in the Pre-Apulian zone (e.g. on Cephallonia and Zakynthos Islands) are of late Pliocene and Pleistocene ages (Hug, 1969; Nikolaou, 1986; Underhill, 1989).

The Ionian zone

The Ionian zone is made up of three distinct stratigraphic sequences (Karakitsios, 1995; Fig. 3):

(i) A **pre-rift sequence**, represented by the early Liassic Pantokrator Limestones. These shallow-water limestones overlie Early to Middle Triassic evaporites (more than 2,000 m thick) and the Foustapidima Limestones of Ladinian - Rhaetian age. The sub-evaporitic basement of the Ionian zone is not exposed at the surface, and neither has it been penetrated by deep wells.

(ii) The overlying s**ynrift sequence** begins with the pelagic Siniais Limestones and the laterally equivalent semipelagic Louros Limestones of Pliensbachian age. These formations correspond to general deepening of the Ionian domain with the formation of the Ionian Basin. The structural differentiation that followed separated the initial basin into smaller palaeogeographic units with a half-graben geometry; in most cases, these units do not exceed 5 km across. This is recorded in the abruptly changing thickness of the synrift formations which take the form of synsedimentary wedges. In the deeper parts of the half-grabens, these include complete Toarcian - Tithonian successions comprising, from base to top: *Ammonitico rosso* or lower Posidonia beds, Filamentous Limestones, and upper Posidonia beds. In the elevated parts of the half grabens, the succession is interupted by hiatuses and unconformities. The directions of synsedimentary structures (e.g. slumps and synsedimentary faults) indicate that deposition was controlled both by structures formed during extension related to the opening of the Neotethys Ocean, and halokinesis of evaporites at the base of the Ionian zone succession (Karakitsios, 1995).

(iii) The **post-rift sequence** begins with the pelagic Vigla Limestones, whose deposition was synchronous throughout the Ionian Basin beginning in the early Berriasian (Karakitsios, 1992; Karakitsios and Koletti, 1992). The Vigla Limestones blanket the syn-rift structures (Karakitsios, 1992), and in some cases, directly overlie pre-rift units (e.g. the Pantokrator Limestones). As a consequence, the base of the Vigla Limestones represents the break-up unconformity of the post-rift sequence in the Ionian Basin. Longstanding differential subsidence during the deposition of the Vigla Limestones, as shown by the marked variations in the thickness of this formation, was probably due to continued halokinesis of the basal-Ionian zone evaporites.

The Senonian limestones, which rest on the Vigla Limestones, comprise two facies: (a) limestones with fragments of Globotruncanidae and rudists, and (b) microbrecciated intervals with limestones and rudist fragments within a calcareous cement containing pelagic fauna. Thus, the Senonian is interpreted to correspond to a period of basinal sedimentation, and its facies distribution reflects the separation of the Ionian Basin into a central topographically-higher area characterised by reduced sedimentation, and two surrounding talus slopes with increased sedimentation (IGRS-IFP, 1966). Adjacent to this area, separate carbonate platforms (the Gavrovo Platform to the east, and the Apulia Platform to the west) provided clastic carbonate material to the Ionian Basin.

Homogenous Paleocene and Eocene sediments were deposited after the Cretaceous without significant facies changes. During the Paleocene, the erosion of Cretaceous carbonates on the Gavrovo and Apulian Platforms provided the Ionian Basin with microbreccia or brecciated materials. However, the supply of clastic material diminished significantly during the Eocene, especially in the central Ionian Basin. The main depositional facies during this period consisted of platy wackestone/mudstones with Globigerinidae and siliceous nodules, analogous to those in the Vigla Limestones, but lacking continuous cherty intervals. The greatest thicknesses of the Eocene units can be found in marginal parts of the Ionian zone, where the microbreccias are more frequent.

Flysch sedimentation began in most of the Ionian zone at the Eocene – Oligocene boundary, and deposits including marly limestone transitional beds conformable overlie the Upper Eocene limestones.

Major orogenic movements took place at the end of the Burdigalian (IGRS-IFP, 1966), with the

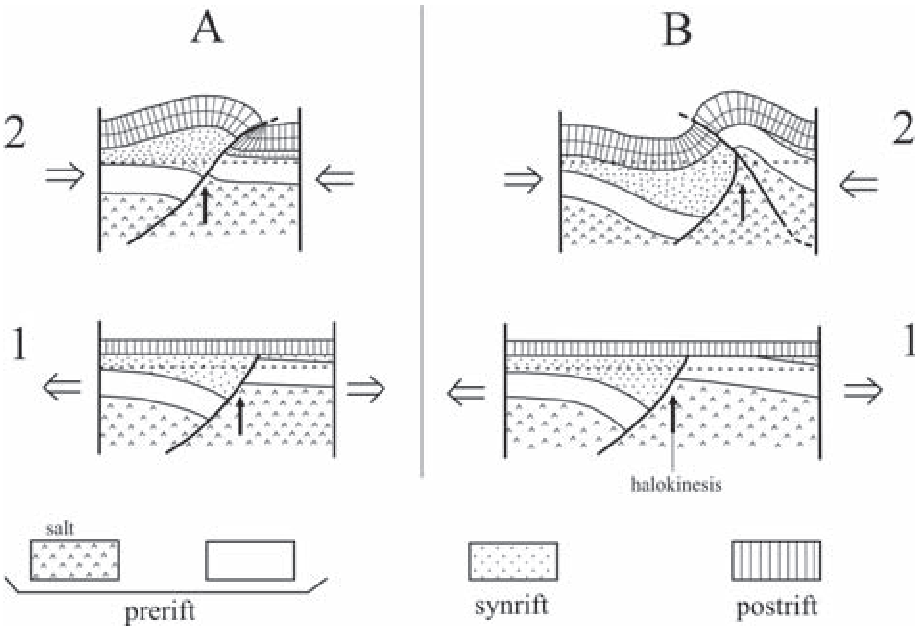


Fig. 4. Cartoons of inversion tectonics affecting a half-graben system with evaporitic basement (Ionian zone, NW Greece): (A) classical inversion tectonics (B) specific style of inversion tectonics observed at locations where halokinesis of the evaporitic substratum occurs; elevated extensional footwall is thrust over the pre-existing hanging wall during later compression. A1 and B1 correspond to the beginning of the post-rift period; A2 and B2 correspond to the end of post-rift deposition and show the subsequent inversion geometries (modified after Karakitsios, 1995).

inversion of the Ionian Basin succession (Karakitsios, 1995). The double divergence of the basin (westwards in the central and western parts, and eastwards in the eastern part) is attributed to structures inherited from the Jurassic extensional phase which were reactivated during compression with westward and eastward displacement, respectively. In general, extensional faults were reactivated with either reverse or transcurrent displacement, consistent with classical inversion tectonics (Fig. 4A). In some cases during the compressional phase, extensional faults were not reactivated as simple thrusts, but the elevated extensional footwalls were thrust over pre-existing hanging walls due to movement of the basal evaporitic units (Karakitsios, 1995, Fig. 4B). This was facilitated by diapiric movements involving the basal evaporitic intervals. Field and available seismic data suggest that at least moderate *décollement* took place along the evaporites (Karakitsios, 1995). However, the degree of this *décollement* is unknown and remains speculative.

Considering the existing data on the external Hellenides, the hypothesis of a major *décollement* along the evaporites is more favourable. In fact, as the Ionian and Gavrovo-Tripolis crust corresponds to thinned continental crust (Makris, 1977; Finetti, 1982; Bonneau, 1982; Bassoullet *et al.*, 1993), the pre-evaporitic basement of the Ionian zone is probably underthrust and incorporated into the thin-skinned orogenic wedge east of the Pindos thrust (Smith and Moores, 1974), or it has been subducted beneath the more internal zones. Thus, it has been subject either to basement deformation east of the Ionian zone, or to continental subduction.

Continental subduction of the pre-evaporitic basement eastwards of the Ionian zone is consistent with the presence of the Phyllite - Quartzite Unit beneath the Gavrovo-Tripolis calcareous zone in the south Hellenides (e.g. Peloponnesus and Crete). The Phyllite - Quartzite Unit is characterized by HP-LT metamorphism (Seidel and Okrusch, 1977; Bassias and Triboulet, 1985), and its palaeogeographic attribution continues to be debated (Karakitsios, 1979; Bonneau, 1984; Hall *et al.*, 1984; Fassoulas, 1999). If the Phyllite – Quartzite Unit is considered to be the subducted pre-evaporitic continental basement of the Pre-Apulian and Ionian zones, HP-LT metamorphism can readily be explained. This continental subduction took place earlier in the southern part of the Hellenic arc. Consequently, by Miocene times, in the south, the Apulian block had been completely subducted and subduction of the Eastern Mediterranean Ocean had begun. At the same time, Apulian thinned continental crust in Western Greece continued to be subducted. Syn-compressional uplift and vertical buoyancy of the subducted crustal slice has caused the rapid exhumation of the metamorphic Phyllite - Quartzite unit in the south Hellenides.

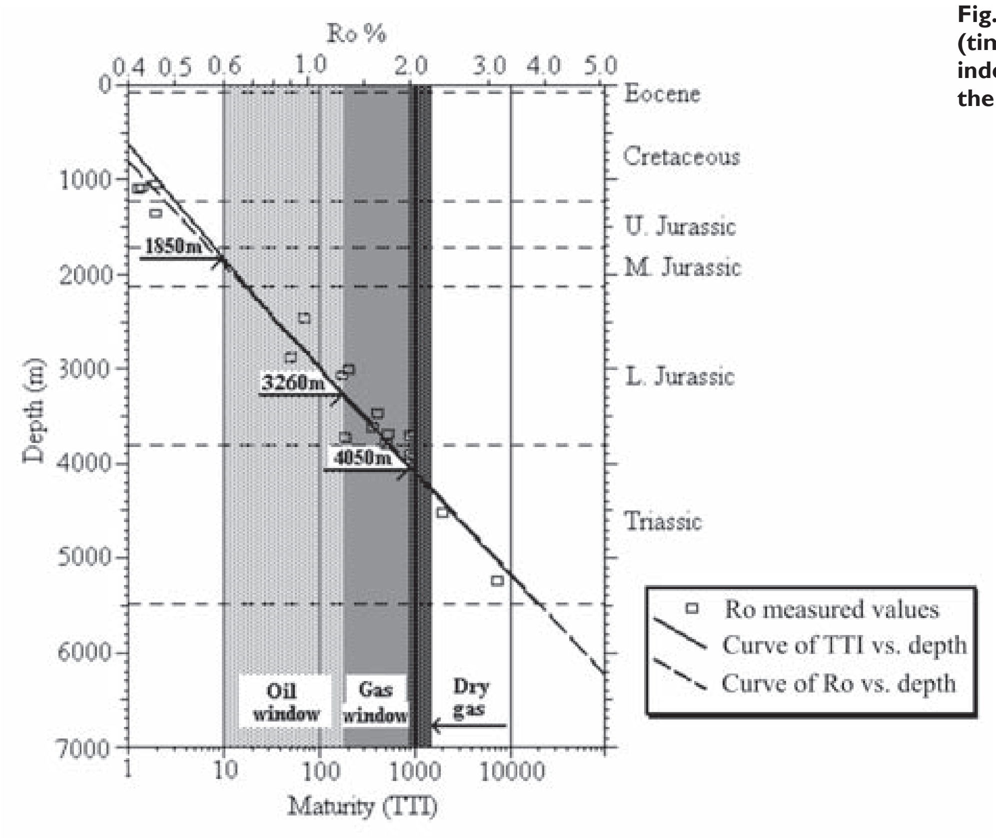


Fig. 5. Plot of maturity (time temperature index) versus depth for the Pre-Apulian zone.

OIL POTENTIAL

Hydrocarbon exploration activities in Western Greece have led in the past to the study of potential source rocks, mainly in the Ionian zone, while structural and stratigraphic trapping possibilities have also been discussed (IGRS-IFP, 1966; BP, 1971; Chiotis, 1983; Palakas *et al.*, 1986; Jenkyns, 1988; Karakitsios, 1995; Roussos and Marnelis, 1995; Kamberis *et al.*, 1996; Karakitsios and Rigakis, 1996; Rigakis and Karakitsios, 1998, Rigakis, 1999; Karakitsios *et al.*, 2001; Zelilidis *et al.*, 2003; Karakitsios, 2003; Rigakis *et al.*, 2004). Data from these studies are reviewed in the following sections and is integrated with new data on potential source rocks in the Pre-Apulian zone.

The Pre-Apulian zone

Potential hydrocarbon source rocks in the Pre-Apulian zone are mostly pelagic deposits rich in marine organic material, although terrigenous organic matter is found in siliciclastic deposits of Miocene to Recent age. Thus, source rock intervals occur (Fig. 2) within: (a) the Miocene and Pliocene succession; (b) the Upper Jurassic (equivalent to the Aptici Formation of Italy); (c) the Lower Jurassic (equivalent to the Complesso Anidritico Formation of Italy); and (d) the Upper Triassic (equivalent to the Burano Formation, Italy).

Lignite-rich intervals with gas-prone Type III organic matter have been identified in Pliocene siliciclastics. Intervals rich in Type III organic matter also occur in Miocene marls. However the most promising source rocks occur in the Upper Jurassic, where a succession more than 200m thick has a Total Organic Carbon (TOC) content of between 0.6 and 11.2 wt% (average 2.2 wt%). Average Petroleum Potential (PP) values are 11mg/g (maximum: 43.5 mg/g). The organic matter is Type I to II (i.e. highly oil prone). Based on these characteristics, it is possible that Upper Jurassic source rocks have produced significant volumes of oil. In the Lower Jurassic, four separate horizons have fair organic matter contents (TOC: average 0.6 wt%, PP: average 1 mg/g) of Type II-III material. In the Triassic, one interval contains residual highly mature organic matter, with average values of TOC and PP of 0.5% and 0.25 mg/g, respectively.

Source rock maturity is generally low due to the low geothermal gradients in the area; 1.69°C/100m for siliciclastic sediments as determined at the *Parga-1* well (location in Fig. 8) and 1.30-1.55°C/100m for carbonates (*Paxi-Gaios-1x* well: Fig. 8). According to Flores *et al*. (1991), the palaeogeothermal gradient was much higher in the geological past, ranging from 2.5°C/100m in the Triassic to 3.5°C/100m in the Late Cretaceous, decreasing to 2.5 °C/100m in the Oligocene. From that time, there has been a gradual decrease to the present-day values.

Bearing the above values in mind, the thermal maturity of the source rocks was modelled in different parts of the basin, and the results are consistent with values measured at the *Paxi-Gaios-1x* well (Fig. 5), where the oil window occurs at 1850-3260m. Upper

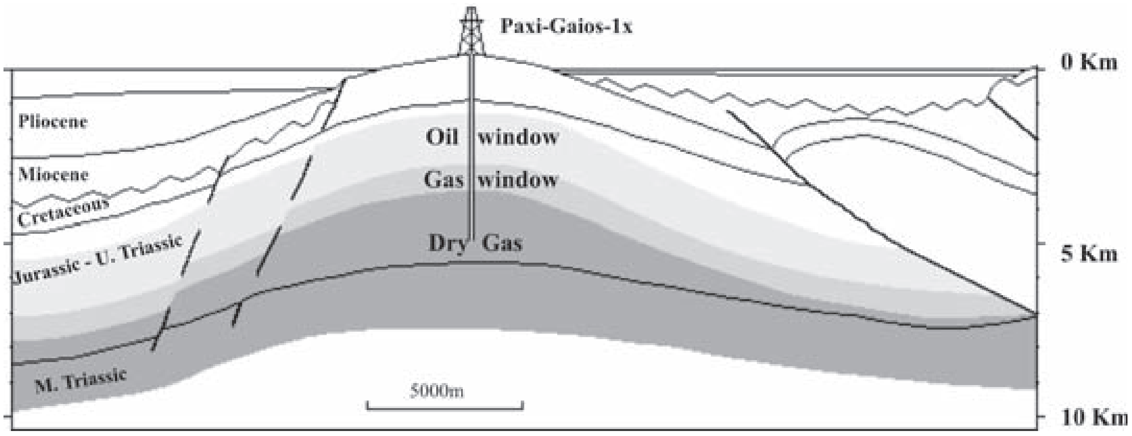
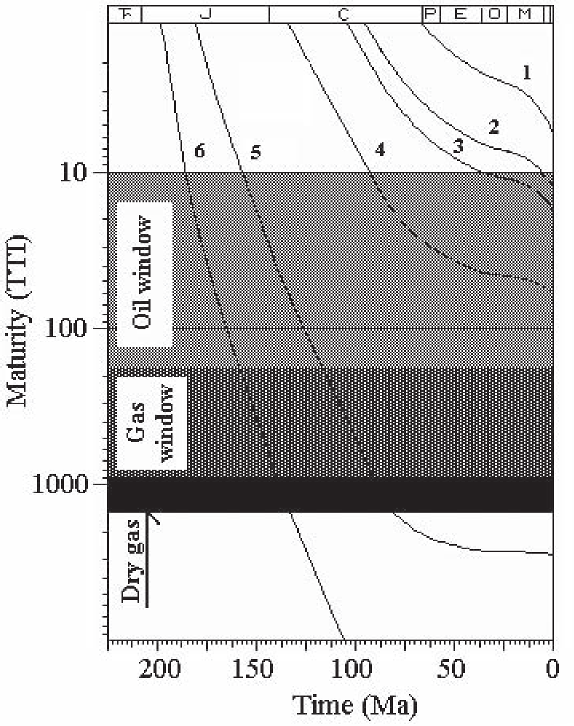


Fig. 6. The extent of the oil window in the Pre-Apulian zone.



a/a	Interval	Onset of petroleum generation
1	Cretaceous	immature
2,3	Upper Jurassic	Lower Oligocene
4	Middle Jurassic	Upper Cretaceous
5	Lower Jurassic	Upper Jurassic
6	Triassic	Middle Jurassic

Fig. 7. Graph of maturity (TTI) versus time for the Pre-Apulian zone, indicating times when possible source rocks are modelled to have entered the oil generation window.

Jurassic potential source rocks in this well appear to be immature; Lower Jurassic units are mature, while Triassic source rocks are overmature. In the central parts of the Pre-Apulian zone, the oil window, due to the greater thickness of the overlying recent sediments, is located at depths between 5600 m and 7250 m, and Upper Jurassic source rocks are therefore mature in deeper parts of the basin (Fig. 6). The generally low maturity of the deposits favours generation and preservation of oil in deep areas. In the *Paxi-Gaios-1x* well, the bottom of the oil window is located at 3880 m, and in deeper parts of the basin it is located at 7800 m.

The timing of oil generation for the principal source rock interval has been modelled (Fig. 7). Triassic source rocks became mature in the Middle Jurassic. Lower Jurassic source rocks became mature in the Late Jurassic, while maturation of Upper Jurassic source rocks took place in the Early Oligocene. Finally, Miocene source rocks are immature for oil generation at the present day. Oil generation from Triassic and Lower Jurassic intervals in the Pre-Apulian basin took place before major orogenesis. For Upper Jurassic source rocks, oil generation took place before the main Alpine orogenic phase in the Hellenides (i.e. 34Ma) as far as the deeper parts of this formation are concerned and much later the shallower ones (6Ma). However, rates of oil generation are generally low, and more oil could have been generated from these source rocks after orogenesis and trap formation.

In the Pre-Apulian zone, a number of oil shows have been identified both at the surface and in boreholes in different parts of the basin (e.g. on

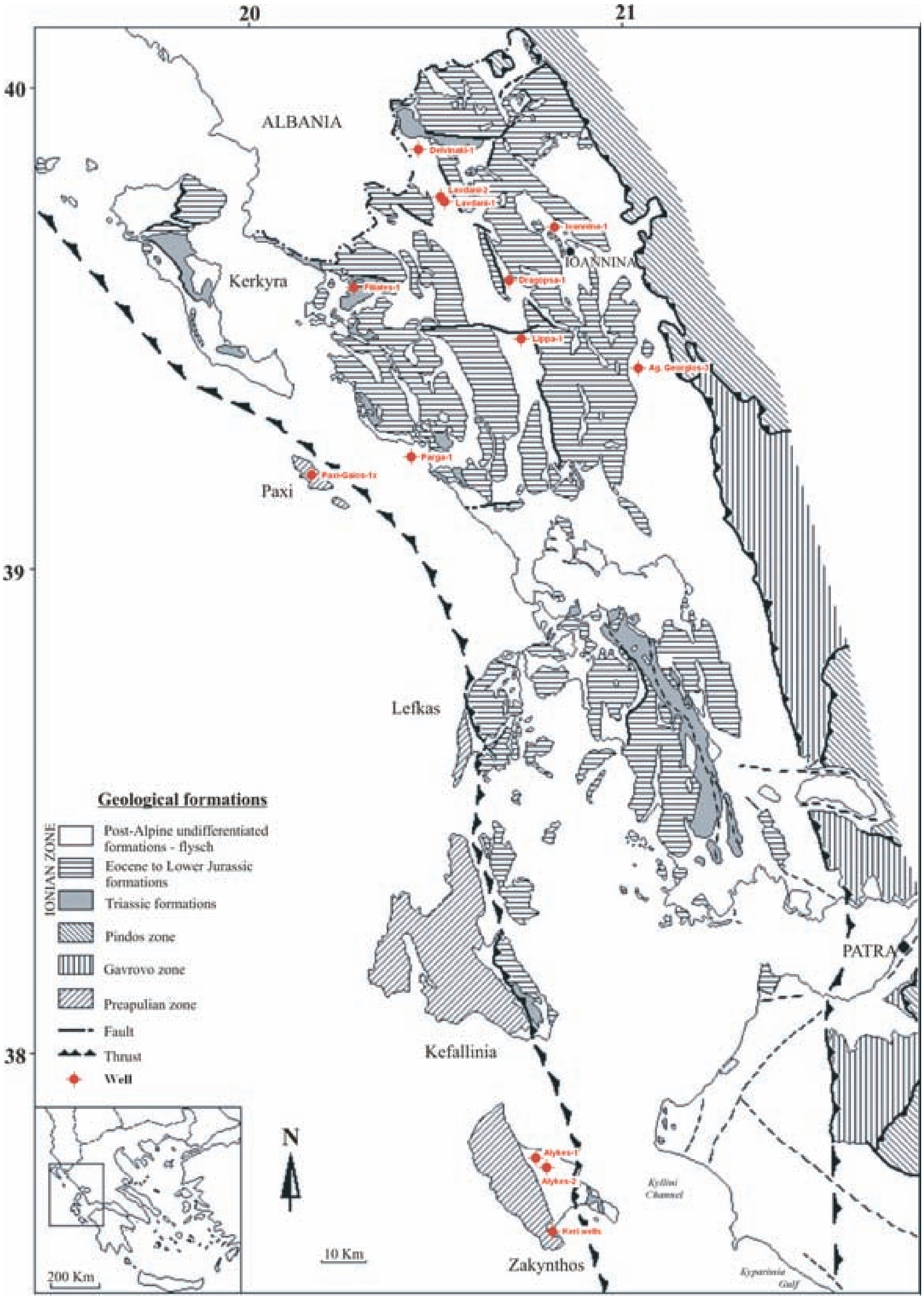


Fig. 8. Simplified geological map of Western Greece indicating well locations referred to in the text.

Zakynthos and Paxi Islands: Fig. 8). The *Keri* oil seep on Zakynthos, was first mentioned by Herodotus (484-430 BC) and oil has also been identified in shallow wells drilled nearby where a non-economic accumulation has been identified. A small yet important oilfield has also been found in the Alykes area in NE Zakynthos. On Paxi Island, there are numerous surface oil seepages and carbonate impregnations, and oil shows have also been identified in two deep wells drilled on the island (Fig. 8).

Oil-oil correlation studies (Fig. 9) indicate that the Zakynthos oils (“Group D1” of Rigakis, 1999) can be differentiated from the *Paxi* oils due to their high carbon isotope values (greater than -23.3‰). *Paxi* oils

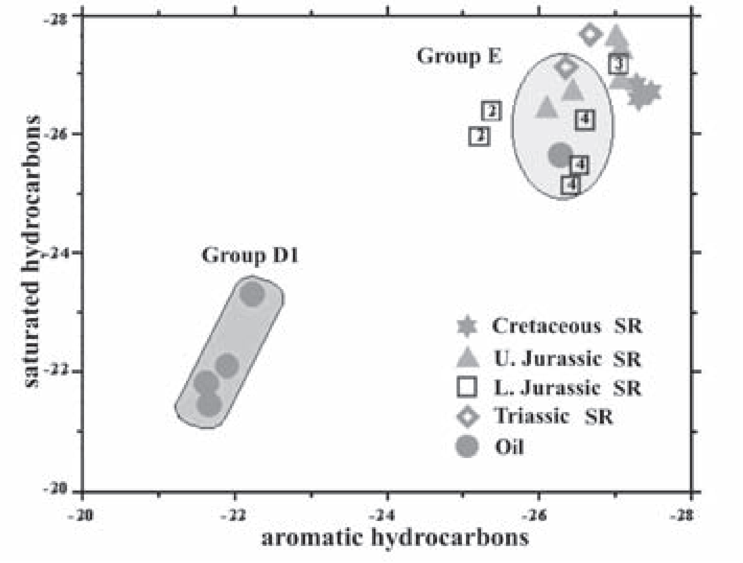


Fig. 9. Graph of carbon isotope ratios ($\delta^{13}C$) in saturated versus aromatic hydrocarbons for Zakynthos oils (Group D1) and Paxi (Group E) oils and source rocks. SR: source rock; 1 2, 3 and 4: different levels (from top to bottom) of source rocks in the Liassic interval in the Pre-Apulian zone succession (see Fig. 2 for stratigraphic position).

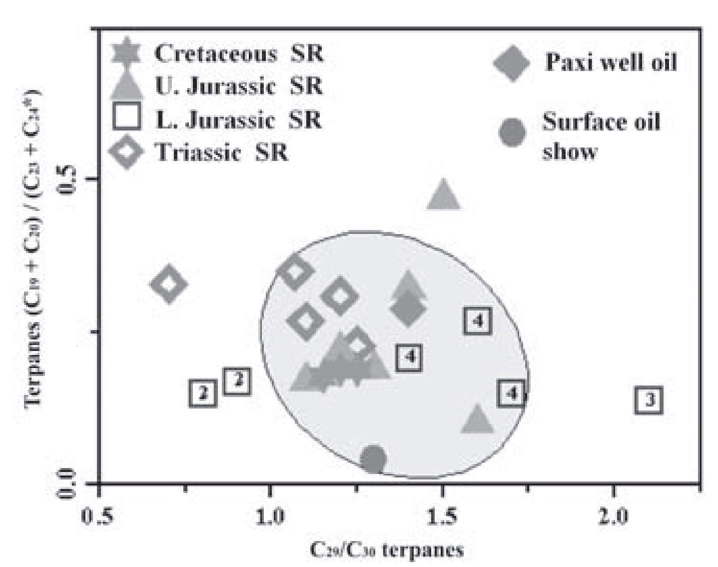


Fig. 10. Oil-source rock correlation in the Paxi area based on characteristic terpane ratios. SR: source rock; 1, 2, 3 and 4: see Fig. 9 caption.

have characteristic biomarker ratios that differentiate them from other oils in Western Greece and are therefore classified as a separate "Group E" (Fig. 9). Oil-source correlations suggest that oil from well *Paxi-Gaios-1x* was generated by Lower Jurassic and Triassic source rocks (Figs. 9 and 10). The Zakynthos oils, by contrast, appear to be related to a Miocene source, possibly siliciclastic, as is indicated by the oils' high carbon isotope values and low maturation level (lower than 0.6% Ro, as indicated by homohopane ratios: C_{31} 22S/(22S+22R) = 0.53). This low maturity oil may have been generated by Miocene source rocks located in the Zakynthos - Kyllini Channel and in the Kyparissia Gulf (Fig. 8).

The *Paxi* oils (Rigakis, 1999) can be correlated with oils from the Southern Adriatic, for example at *Aquila (*data in Mattavelli and Novelli, 1990). Thus the difference in their carbon isotope values for aromatic hydrocarbons is less than 2‰, and the pristane/phytane ratio is less than one in both oils. Oleanane is absent, while diasternes and gammacerane are barely present in both oils. Also, the C_{29}/C_{30} hopane ratio is greater than one in both oils (Fig. 11), while the C_{27}/C_{30} ratio steranes is less than one. Accordingly, these two oils probably have a similar origin. The *Aquila* oil is thought to have originated from the Burano Evaporite Formation (Mattavelli and Novelli, 1990) and similar source rocks probably generated the *Paxi* oil. The Apulia and Pre-Apulia zone oils appear to have similar geochemical characteristics. Furthermore, structures identified in the Pre-Apulian zone west of Corfu may be filled with light oil, similar to the *Aquila* oil. In conclusion, significant quantities of light oil generated by organic-rich and mature source rock intervals may be expected in the Pre-Apulian zone (Fig. 12 a, and b).

Porosity measurements carried out on surface samples of various formations in the Pre-Apulian succession, and porosity deduced from electrical logs at well locations, indicate that porosities in neritic and mixed facies rocks range from 4-13% but are

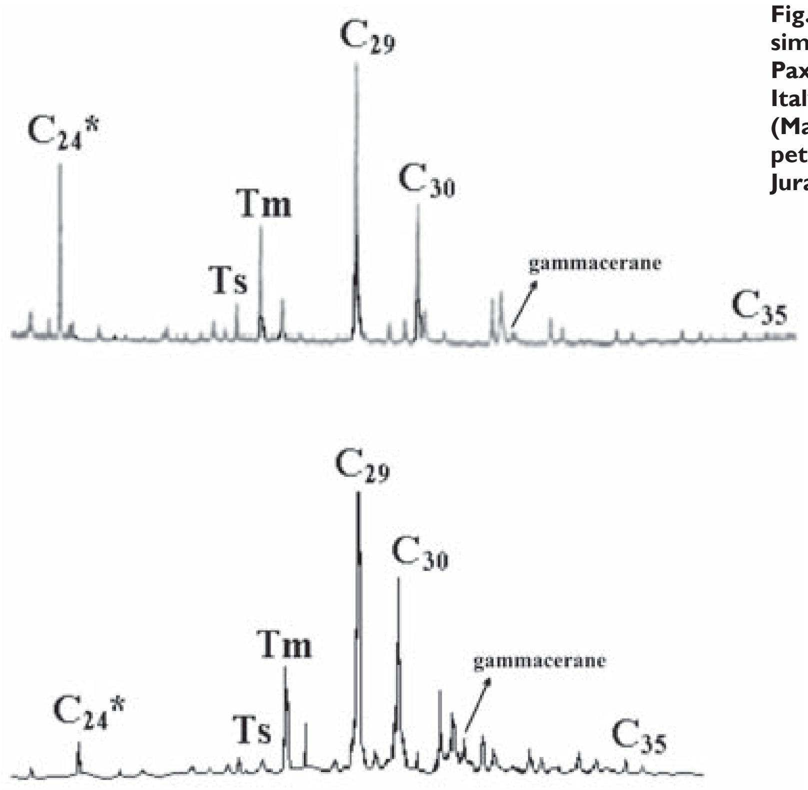


Fig. 11. Chromatograms illustrating the similarity of the Aquila oil (above) and the Paxi oil (below). (i) Aquila petroleum, Italy, 3866 m, Eocene carbonates (Mattavelli and Novelli, 1990). (ii) Paxi petroleum (Greece), 1986 m, Middle Jurassic carbonates (present work).

accompanied by low permeabilities. In pelagic facies rocks, porosity and permeability are even lower. The Upper Miocene is thought to be an effective cap rock.

The accumulation and preservation of organic matter in the Mesozoic-Palaeogene succession in the Pre-Apulian zone appears to be related to the presence of structurally-controlled sub-basins, similar to those resulting from Ionian Basin differentiation. Post-Palaeogene organic-rich intervals are related to depozones in the migrating external forebulge of the Hellenide foreland basin, following the westward migration of the front of the thrust belt.

The Ionian zone

Organic carbon-rich units (TOC = 1.00-28.87 wt%; Fig. 3) with source-rock potential have been recorded in the Ionian zone. These include the Vigla shales or “Upper Siliceous zone” of IGRS-IFP (1966) (Albian - Turonian); the Upper Posidonia Beds (Callovian - Tithonian); the Lower Posidonia Beds and the coeval marls at the base of the Ammonitico Rosso (Toarcian); and the shales incorporated within the Triassic breccias (Karakitsios, 1995; Karakitsios and Rigakis, 1996; Rigakis and Karakitsios, 1998; Karakitsios *et al*., 2001; Karakitsios *et al*., 2002). All these potential source rocks have good hydrocarbon potential and contain Type I to II OM (Karakitsios and Rigakis, 1996; Rigakis and Karakitsios, 1998). Burial history curves (Fig. 13) show that the oil window, which in the central Ionian Basin (Botsara sub-basin; see location in Fig. 14) occurs between 3700 m and 5800 m, deepens eastwards (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 Vigla shales are at an early mature stage, while the Vigla shales are mature further east (Rigakis and Karakitsios, 1998; Rigakis, 1999; Karakitsios *et al*., 2002). Studies of potential source rocks in the Ionian flysch have indicated differences in levels of maturity and origin. Organic matter, of mixed terrestrial plant and planktonic origin, is predominately gas prone (Fig. 12 c–e). Its thermal maturity, as assessed from pyrolysis Tmax, ranges from immature to peak mature.

The Triassic Shales entered the oil window in the Late Jurassic, and the Lower Posidonia beds in the Serravallian (Karakitsios and Rigakis, 1996; Rigakis and Karakitsios, 1998).

The accumulation and preservation of organic matter in the Vigla shales (Albian - Cenomanian) is generally attributed to preserved sub-basins, due to the continuation of halokinetic movements during the post-rift period (Karakitsios, 1995). In the Gotzikas area of NW Epirus (south of Tsamantas; Fig. 14), this unit includes at least 20 dm of organic-rich calcareous mudstones and shales. Laboratory analyses (bulk carbonate / organic carbon stable-isotope (C, O) ratios, and detailed organic geochemical studies on bulk and solvent-extractable organic matter: Karakitsios *et al.*, 2002) showed that: (a) TOC contents (1 to 6 wt%), Hydrogen Index (HI, mean: 321 mg/g) and the $\delta^{13}C_{TOC}$ (-26.5±1.0‰) values varied little within the lower part of the Gotzikas section; and (b) a sharp positive shift in $\delta^{13}C_{TOC}$, of approximately 4.5 per mil, is observed in the uppermost black shale unit (-22.14‰), which also has the highest TOC content (28.87 wt%) and HI (529 mg/g) and is the most enriched in amorphous organic matter.

This TOC-enriched and isotopically heavy black shale shows important similarities, both compositionally and isotopically, with early Albian black shales from ODP site 10°49’C (North Atlantic) and from the Vocontian Basin of SE France (“Niveau Paquier”; Herrle, 2002). Consequently, it is suggested that the uppermost part of the Vigla shale records Oceanic Anoxic Event (OAE) 1b, which has been recorded throughout the Tethys-Atlantic region.

Organic matter accumulation and preservation in the lower and upper Posidonia beds (Toarcian to Tithonian), and in the marls at the base of the Ammonitico Rosso during the Early Toarcian, are directly related to the structural geometry during the synrift phase in the Ionian Basin. The geometry of the restricted sub-basins resulted in stagnation, and consequently in the development of locally euxinic conditions (Karakitsios, 1995).

The geometry of the sub-basins during both synrift and postrift phases favoured Oceanic Anoxic Events (Toarcian) OAE, OAE1a, OAE1b and OAE2 (Jenkyns, 1988; Farrimond *et al.*, 1989). This is indicated by the high proportion of organic matter within some intervals in the Lower Posidonia beds, the marls at the base of the Ammonitico Rosso, the Upper Posidonia beds, and the Vigla shales (up to 28.9 wt%), together with abrupt excursions of carbon and oxygen isotope ratios (Karakitsios, 1995; Tsikos *et al.*, 2004; Karakitsios *et al.*, 2004; Karakitsios *et al.*, 2007a).

Organic-matter rich shales within the Triassic breccias were initially deposited as distinct stratigraphic intervals in relatively shallow restricted sub-basins within the Triassic Ionian evaporitic basin. The lack of a detailed stratigraphic scheme for the subsurface evaporites in the Ionian zone does not permit the precise position of the shale horizons to be reconstructed. Consequently, it is not possible to correlate the deposition of these intervals with, for example, sea-level changes, local subsidence or anoxia during the Triassic. However, the establishment of evaporitic conditions throughout the basin favoured the preservation of organic matter. As a result, the processes that resulted in the evaporite-dissolution collapse breccias also caused the fragmentation of the organic-rich shale layers, which now form fragments and intraclasts within the Triassic breccias (Karakitsios and Pomoni-Papaioannou, 1998).

For any particular basin, it is important to note that the TOC content alone does not determine the volume of oil present; the most important factor is the thickness of the source rock unit. This means that relatively thin OAE intervals, although very rich in organic material, cannot by themselves be considered as source rocks although they can contribute to oils derived from thicker source rocks. The formation of thick source rock intervals is controlled mainly by regional palaeogeographic factors, while thin OAE intervals generally reflect global-scale palaeo-oceanographic conditions. For example, the Pindos zone (to the east of the Ionian zone) is characterized by very poor overall oil potential, although three oceanic anoxic events (Toarcian, Aptian – Albian and Santonian) have been recorded there (Karakitsios *et al.*, 2007b). Their limited thickness prevents them from generating substantial volumes of oil.

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 1. Average total porosity of units in the Ionian zone succession (for formation names see Fig. 3).

Porosity and permeability

Porosity measurements carried out on surface samples from various formations in the Ionian zone series are presented in Table 1. Electric logs suites from the *Ioannina*-1 well were used for indirect porosity calculations. Average porosity values are similar in both cases. However, permeability is variable. The Triassic breccias and Pantokrator Limestones show fairly good permeability, as do sandstone intervals within the flysch and the post-Alpine siliciclastic succession. The other formations are characterized by very low to negligible permeability.

Studies of the primary matrix porosity and the secondary fracture porosity in the formations comprising the Ionian series indicates that the best reservoir rock characteristics are to be found in the Triassic breccias, the Liassic and Lower Cretaceous dolomites, and the Eocene limestones. In addition,

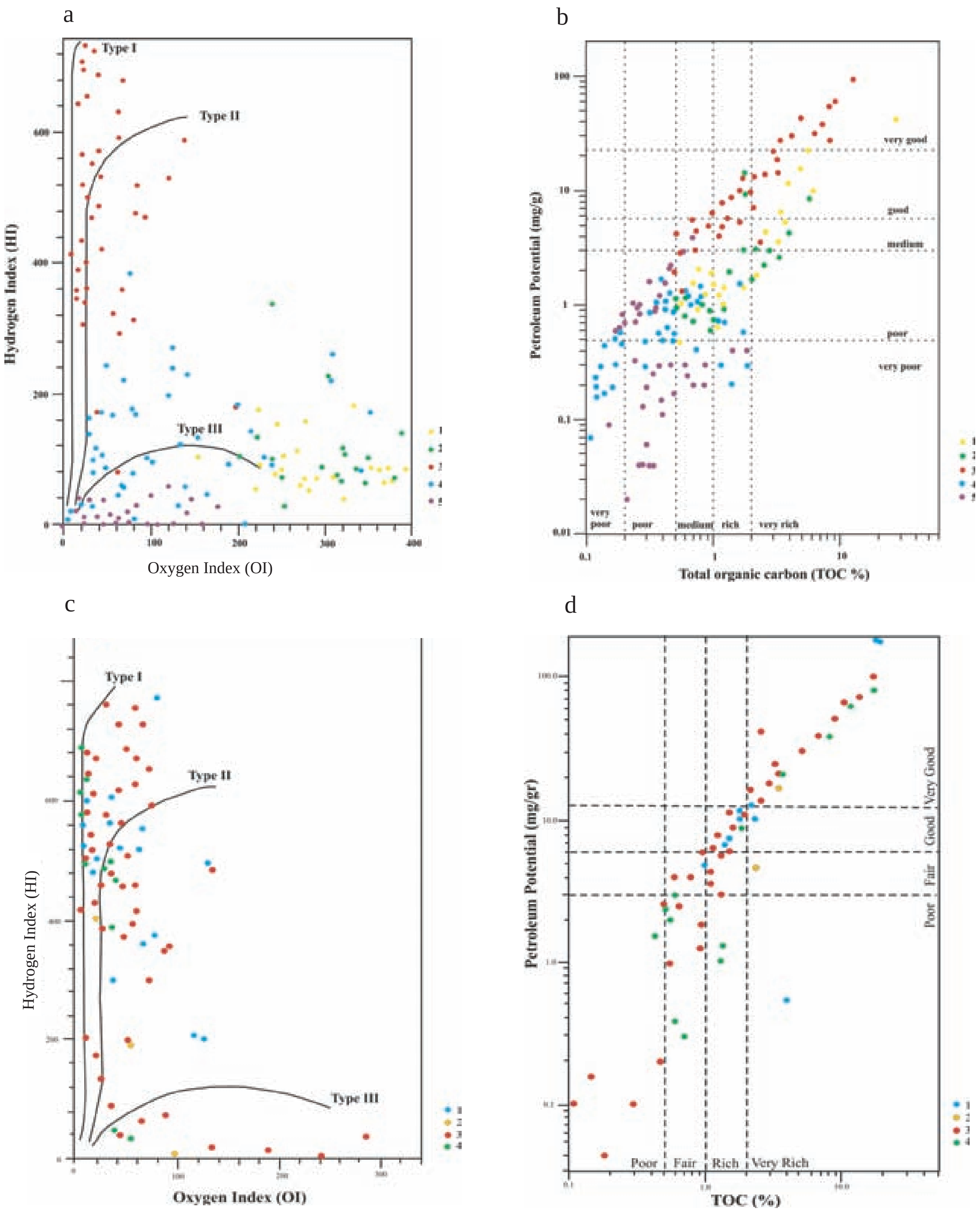


Fig. 12. (a) Paxos zone: plot of OI versus HI; (b) Paxos zone: plot of TOC versus petroleum potential, indicating the occurrence of source rocks. Key: 1: Pliocene, 2: Miocene, 3: Upper Jurassic, 4: Lower Jurassic, 5: Triassic. (c) Ionian zone: plot of OI versus HI; (d) Ionian zone: plot of total organic carbon versus petroleum potential indicating the occurrence of source rocks; (e) Ionian zone: plot of HI vs. T_{max} showing that samples are immature but close to the onset of oil generation. 1: Vigla shales, 2: Upper Posidonia beds, 3: Lower Posidonia beds and marls at the base of Ammonitico Rosso, 4: Triassic shales within the evaporites.

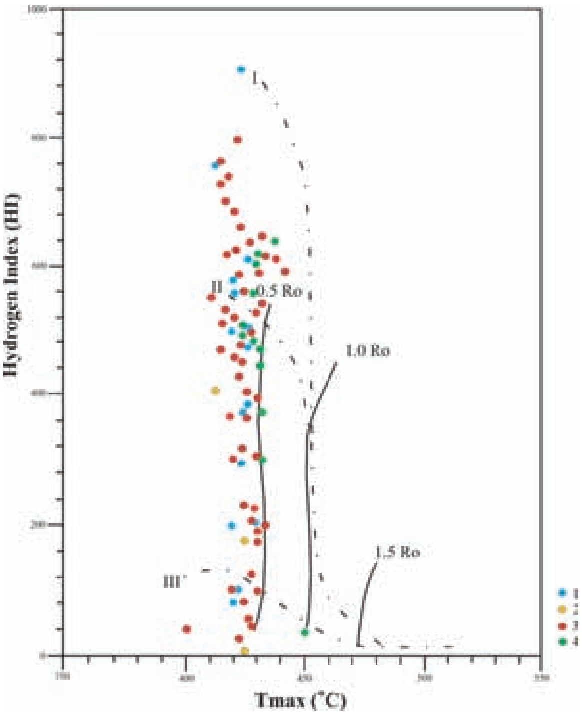


Fig. 12e. See caption, page 210.

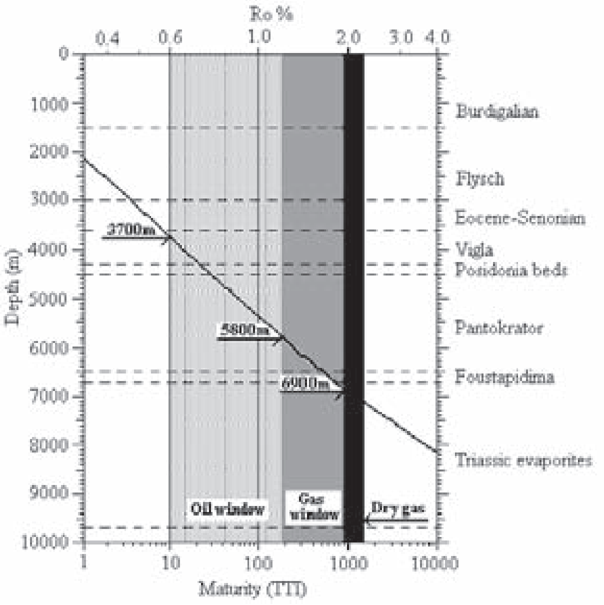


Fig. 13. Plot of maturity (TTI) versus depth, Botsara sub-basin, central Ionian Zone (location in Fig. 14).

the (Oligocene) flysch, the post-Alpine clastic succession (Neogene) and the Triassic evaporites appear to constitute seals and cap-rocks. The geometric configuration of the reservoir and cap-rock units is a function of the basin's tectonic evolution, which in turn controls the location of prospective traps.

Dolomitization plays an important role in controlling porosity and permeability. In general, dolomitization increases secondary fracture porosity. This is important in the Ionian zone, because the dolomitization front changed through time. In the internal and external parts of the Ionian zone, dolomitization continued well into the Cretaceous, whilst in the central part, it did not continue after the Middle Jurassic. As a result, the precise location of a rock unit within the Ionian zone will have an important influence on dolomite related porosity and permeability.

Hydrocarbon volumes

The volume of hydrocarbons which has been expelled from Ionian zone source rocks can be estimated. In the Botsara syncline (Fig. 14), migration is estimated to account for 75-80% of the hydrocarbons that have been produced (Rigakis, 1999). This is consistent with the fact that the source rocks are very rich in organic matter (TOC between 1.10 and 19.12%; Rigakis and Karakitsios, 1998). Oil shows in this area occur mainly as a result of secondary migration from reservoir rocks, but, in some cases the shows can best be explained by primary migration, as in the case of the *Petousi* oil shows (Fig. 14). These shows are in close contact with the Posidonia beds, so secondary migration, i.e. migration after the expulsion of oil from the source rock, is clearly limited. This may be encouraging for future exploration because it indicates that expulsion and migration may have taken place at relatively low maturation levels, before the onset of the oil window (Rigakis, 1999).

Surface oil shows have been observed in the central and external Ionian zone, mostly along the margins of the Botsara syncline (Fig.14). The shows in general take the form of hydrocarbon impregnations in porous rocks, joints and faults, together with liquid oil seeps and asphalt (dead oil) residues. Oil seeps are probably derived from formations ranging in age from Triassic to Burdigalian. They have mainly been observed in faults, or in the contacts between the limestones and the overlying units (flysch, Burdigalian). Most exploration wells which have been drilled in the Ionian zone in the Epirus region have also provided some evidence for oil at depth (Karakitsios *et al.*, 2001). Thus (Fig. 8):

- In wells *Lavdani-1* and *Lavdani-2*, oil shows occur along a thrust fault that juxtaposes the flysch with the Burdigalian. Shows were also reported within the flysch and the underlying limestones in *Lavdani-1*.
- In nearby well *Delvinaki-1*, hydrocarbon indications include oil shows along the Delvinaki thrust fault, which brings Triassic breccia on top of the flysch.
- Oil shows in the *Filiates-1* well occur in distinct intervals within the Triassic evaporites.
- Dead oil shows in the Radovici Formation (Aquitanian) were reported in well *Lippa-1*.

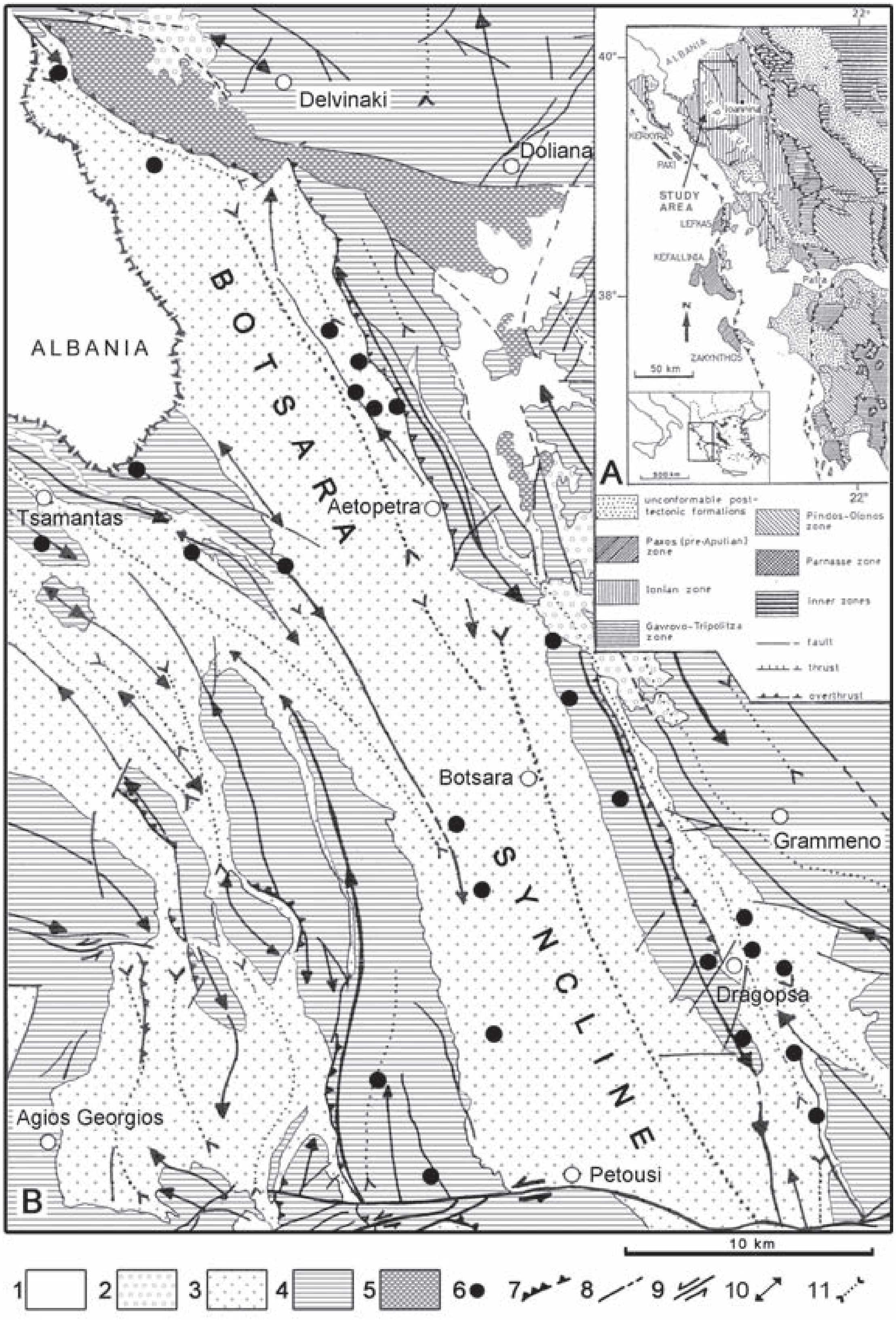


Fig. 14. Main map shows structures and surface oil shows in the NW Epirus region (see regional location in inset map: Karakitsios, 1995). 1: Quaternary, 2: continental Neogene, 3: flysch (Oligocene-Burdigalian), 4: limestone series (Late Triassic-Eocene), 5: evaporite dissolution-collapse breccias (Triassic), 6: surface oil show, 7: thrust, 8: normal fault, 9: transcurrent fault, 10: anticlinal axis, 11: synclinal axis. Modified after Karakitsios *et al.* (2001).

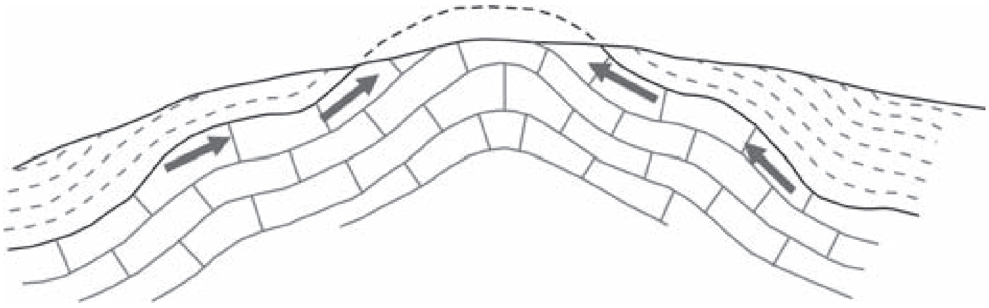


Fig. 15. Model of petroleum migration in large-scale anticlines. The petroleum migrates along the contact between the flysch (cap rock) and the underlying carbonate (reservoir) rock, generally without being trapped.

- Oil shows were also reported in Vigla limestones in well *Dragopsa-1*, and in well *Ag. Georgios-3* (in carbonates ranging from Jurassic to Eocene).

The low porosity and permeability of the formations that make up the Ionian zone could either imply high fluid pressures, which seem to be unlikely here, or fluid migration through permeable "fracture conduits" in the vicinity of fault zones.

MIGRATION AND TRAPPING

A major problem in the study of petroleum trapping and migration in the Pre-Apulian and Ionian zones is associated with the construction of cross-sections across the transport direction as defined by present-day structural geometries. Palaeomagnetic studies indicate considerable (~26°) clockwise rotation of Western Greece during the last 5 Ma which has altered original structural geometries significantly (Laj *et al.*, 1982; Horner and Freeman, 1983; Kissel and Laj, 1988). In addition, deep seismic reflection data cannot be acquired, because the evaporite basement is not a clearly discernible reflector. Nevertheless, present-day structures are still approximately perpendicular to the direction of thrust transport. As a result, surface structural and stratigraphic data have been incorporated to construct cross-sections, although the absence of subsurface data means that these remain speculative. Notwithstanding possible violations of the requirement for bed-length and area preservation between the undeformed and deformed states (Cooper and Trayner, 1986; Woodward *et al.*, 1986; Ford, 1987), published sections indicate minimum estimates of shortening, which range from 15-25% in the Pre-Apulian zone (Underhill, 1989), to 20-30% in the Ionian zone (Karakitsios, 1992). These variations in the amount of shortening probably reflect the highly irregular nature of the boundary between the Pre-Apulian and Ionian zones, with promontories and embayments along its length. The existence of one such promontory may have led to additional contraction in Cephallonia, with the local development here of additional thrust sheets relative to adjacent areas such as Zakynthos (Fig. 8) where little evidence of contraction is reported onshore (Underhill, 1989).

The Pre-Apulian Zone

The Pre-Apulian zone is characterized by major anticlines which provide promising structural traps. However, these structures are not exposed onshore, and deep drilling offshore will be required to elucidate their location and reservoir potential. Miocene–Pleistocene marly limestones and marls may constitute potential cap-rocks in the Pre-Apulian zone, while reservoir rocks may be present in Jurassic and Cretaceous (often brecciated) limestones. For traps related to the pre-evaporitic basement of the Pre-Apulian succession, the same conditions apply as in the Ionian zone; the degree of participation of the sub-evaporitic basement in the deformation of the Pre-Apulian sedimentary series will therefore determine trap location and size.

The Ionian Zone

Two units in the Ionian series may serve as cap-rocks: the flysch (Table 1), and the Triassic evaporites. Structures related to those formations will be considered separately.

Most anticlines in the Epirus area (Western Continental Greece), comprising zones of high topographic relief, have been subjected to intense post-orogenic erosion. Consequently, units with cap-rock characteristics, such as the flysch and the Burdigalian succession, and other clastic post-Alpine units, have been reduced in thickness or are in some cases missing (due to the intense erosion). So any oil which may have been trapped in structures incorporating those cap-rocks would have escaped to the surface. Thus, even where there is active supply from a source rock, it seems reasonable that hydrocarbons would have spread laterally throughout an entire reservoir rock unit, rather than having accumulated in specific areas (Fig. 15). This probably explains why, apart from some special cases, no surface oil shows have in general been observed along the crests of the anticlines.

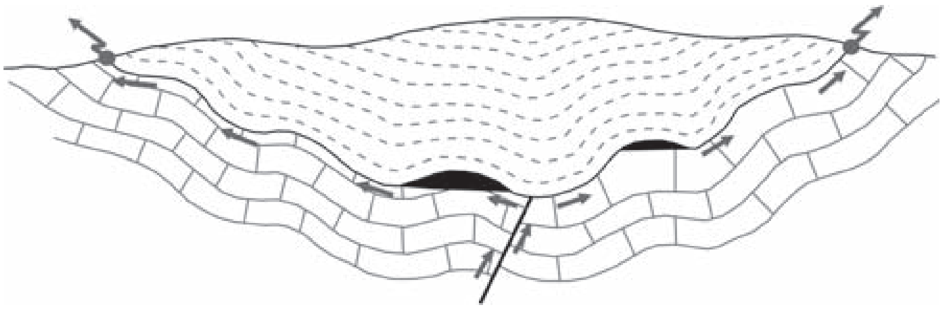


Fig. 16. Model of petroleum migration and accumulation in large-scale synclines. Petroleum migrates along the contact between the flysch (cap rock) and the underlying carbonate rocks (reservoir), filling small-scale anticlines within the larger-scale synclines before surface discharge (oil shows).

On the other hand, synclines which form zones of low topographic relief have escaped intense post-orogenic erosion and so potential cap-rocks are preserved. In these areas, localities suitable for the entrapment of hydrocarbons are restricted to minor anticlines within larger-scale synclinal structures; surface oil shows have been observed along the margins of these synclines (Fig 14 and 16). These shows are the result of migration that takes place along the lower surface of the cap-rock. According to this migration scheme, intervening anticlines should have filled with oil prior to the surface expulsion of migrating hydrocarbons (Fig. 16).

Subsurface evaporites have played a critical role in the tectonic evolution of the Ionian Basin (Karakitsios, 1995; Karakitsios and Pomoni-Papaioannou, 1988). The Jurassic extensional phase triggered halokinesis of the basement evaporites. This affected the synrift mechanism by enhancing the extensional fault throws, resulting in the formation of a number of small, structurally controlled sub-basins. During Alpine compression, pre-existing extensional structures (Pliensbachian through Tithonian) were reactivated. The precise geometric characteristics of inverted basins depend on the amount of evaporitic halokinesis and on the lithological properties of the evaporites, as well as on diapiric movements caused by the salt and on the detachment along the subsurface evaporites.

Oil exploration wells in the Ionian zone have in some cases penetrated more than 3000m of evaporites (IGRS-IFP, 1966; BP, 1971). However, the initial thickness of the evaporitic series was probably much less, since all the wells have been drilled in anticlinal zones associated with diapiric structures (Karakitsios, 1992; 1995). Deformation of the Triassic evaporites involved four stages: (a) halokinesis; (b) décollement, (c) diapirism, and (d) brecciation. The first three stages were sequential in time. The final stage consisted of the development of dissolution-collapse breccias (Karakitsios and Pomoni-Papanioannou, 1998), and this took place in the meteoric zone after Ionian zone orogenesis and is still continuing at the present day. As a result of the above processes, surface exposures of evaporites rarely reflect their initial depositional facies and configuration.

The almost complete absence of data regarding the lower levels of the evaporites, near their contact with the sub-evaporitic basement, combined with their attractiveness for exploration, emphasises the importance of deep seismic reflection data. The Triassic breccias are not effective seals due to their high porosity and permeability which result from dissolution-brecciation processes. Deep seismic data may provide evidence concerning the possible participation of the pre-evaporitic basement in the deformation of the sedimentary cover.

There are two ways of interpreting surface and borehole data in the Ionian zone, regarding the importance of evaporites to the accumulation of petroleum. In the first scenario, the pre-evaporitic basement participates in the deformation of the Ionian sedimentary cover (IGRS-IFP, 1966; Fig. 17a). Suitable structures for hydrocarbon accumulation may be located at the contact between the evaporites and the underlying basement, and trapping is dependent upon the degree of the sedimentary cover *décollement* along the basal evaporites. All the known source rocks in the Ionian series may contribute to hydrocarbon accumulations in these traps, which are also available to hydrocarbons supplied by potential source rocks in the pre-evaporitic basement.

The second scenario (BP, 1971; Fig. 17b) involves moderate *décollement* of the Ionian sedimentary cover. The third scenario, in which the pre-evaporitic basement does not participate in the deformation of the sedimentary cover, is considered to be more likely in this paper (Fig. 17c). According to this scenario, there should be a major *décollement* at the evaporitic level. This would imply the absence of basement structures which would act as traps, but it would favour the possibility of subthrust plays, in places where the Ionian series is repeated (compressional duplex structures).

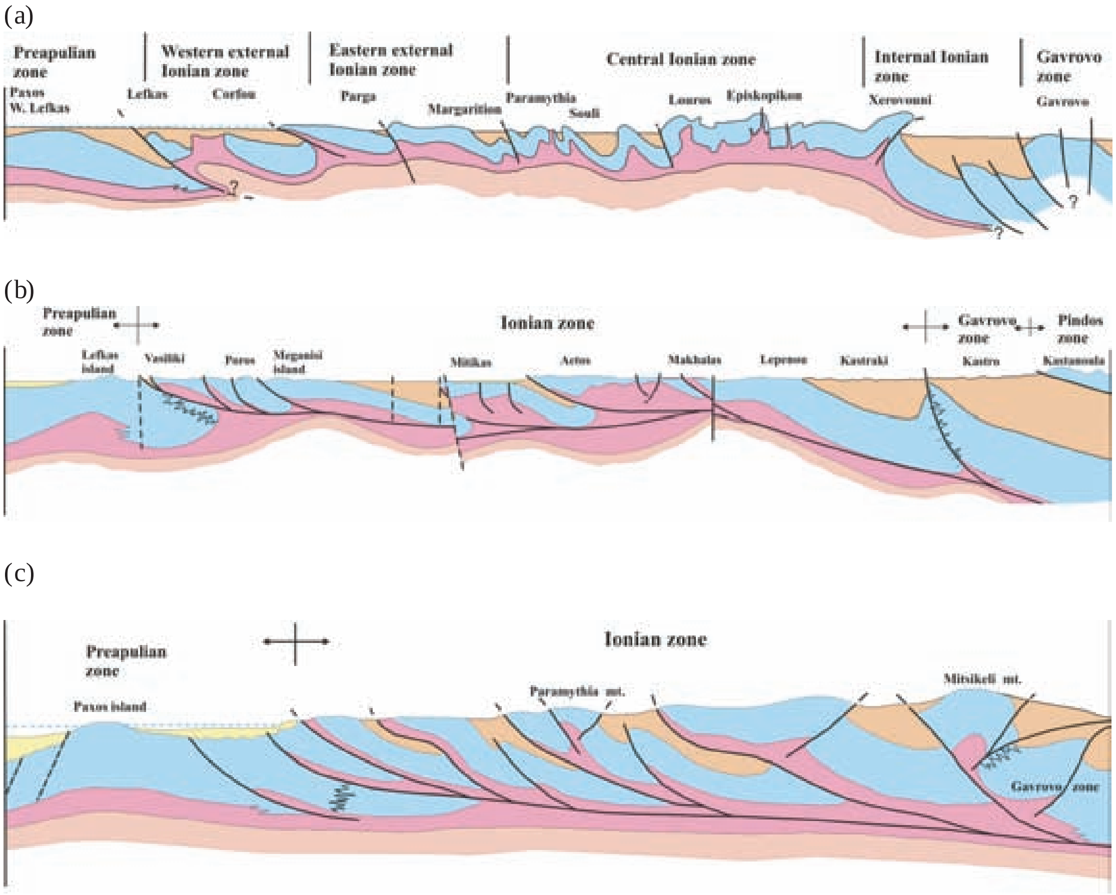


Fig. 17. Structural sections across western Greece showing evaporite-related structures. For profile locations, see Fig. 1.
(a) Section from the Pre-Apulian to the Gavrovo zone (after IGRS-IFP, 1966). The pre-evaporitic basement participates in deformation of the sedimentary cover, without *décollement* of the sedimentary cover along the evaporitic base. Hydrocarbon accumulations could be located below the contact between the evaporites and the underlying basement in anticlinal zones.
(b) Section from the Pre-Apulian to the Pindos Zone (after BP, 1971). The participation of the pre-evaporitic basement in the deformation of the sedimentary cover is accompanied by minor *décollement* of the sedimentary cover at the evaporites' level. Hydrocarbon accumulations can occur as in (a) above.
(c) Section across the Ionian Zone according to the present study. The pre-evaporitic basement does not participate in the deformation of the sedimentary cover. A major *décollement* at the evaporitic level is present. The pre-evaporitic basement underthrusts the more internal zones, thus being subject to basement deformation related to continental subduction east of the Ionian zone. This structure does not allow the formation of hydrocarbon traps between the evaporites and the pre-evaporitic basement, but favours the presence of subthrust plays in deep compressional duplex structures.
Zig-zag lines in Figs (b) and (c) indicate lateral facies transitions.

The structures which appear along the tectonic contact between the Ionian and Gavrovo zones may also be considered as potential traps. Field observations in Epirus show that the tectonic relationships between these zones differ from those between other Hellenic belt thrust sheets. It is more likely that the Ionian zone is thrust over the Gavrovo zone. This is exemplified in the internal part of the Ionian zone, where the folds verge eastwards. This may also be due to inversion tectonics during the evolution of the Ionian Basin, or even due to east-oriented back-thrusts. In this case, the anticlinal structures at the base of the Ionian zone and the underlying Gavrovo zone flysch could form potential traps.

In contrast to the Epirus region, field observations in the Akarnania region to the south favour a more typical style of Hellenic deformation (i.e. structures with a westward divergence). Consequently, it is more likely that the Gavrovo zone is thrust over the Ionian zone and borehole data appear to verify this hypothesis. As a result, potential traps could be located in the vicinity of anticlinal structures at the base of both the Gavrovo flysch and the underlying Ionian flysch.

The boundary between the two Ionian structural domains, with eastward vergence to the north, and westward vergence to the south, may coincide with the Ziros dextral transcurrent fault (Fig. 1).

CONCLUSIONS

The most promising areas for petroleum exploration in Western Greece are the Pre-Apulian and Ionian zones in the external Hellenides. Hydrocarbon source rocks in the Pre-Apulian zone are present within: (a) the Miocene and Pliocene succession, (b) Upper Jurassic units (equivalent to the Aptici Formation, Italy), (c) Lower Jurassic units (equivalent to the Complesso Anidritico Formation, Italy), and (d) the Upper Triassic (equivalent to the Burano Formation, Italy). Source rock maturity is generally low, due to the low regional geothermal gradient.

The results of maturity modelling are consistent with measured values from the *Paxi-Gaios-1x* well, where the oil window is located at depths of 1850-3260m. The Upper Jurassic source rocks in this well are immature. Lower Jurassic units are mature, while Triassic source rocks are overmature. In the central part of the Pre-Apulian Basin, the oil window is located between 5600 and 7250m. Consequently, Upper Jurassic source rocks are mature in the deeper areas of the Pre-Apulian Basin. Oil generation in Triassic source rocks occurred in the Middle Jurassic; for Early Jurassic source rocks, it occurred in Late Jurassic; and for Late Jurassic source rocks, it occurred in the Early Oligocene. Miocene source rocks are still immature for oil generation.

Paxi oil has lower carbon isotope values compared to Zakynthos oil, and has different biomarker ratios to other oils from Western Greece. Oil-source correlations show that oil from the *Paxi-Gaios-1x* well has been generated from the lowermost Lower Jurassic and Triassic source rocks. The Zakynthos oil is probably generated from Miocene source rocks. Oil-oil correlation show that the Aquila (Italy) and *Paxi* oil (in the Apulia and Pre-Apulia zones, respectively), have similar geochemical characteristics. Porosity in the Pre-Apulian series in the neritic and mixed pelagic-neritic facies, ranges from 4 to 13 %, but is accompanied by low permeability. In pelagic facies the porosity and the permeability are even lower. The main cap rock units occur in Upper Miocene marls.

The accumulation and preservation of the organic matter in Mesozoic-Palaeogene stratigraphic successions in the Pre-Apulian zone mostly took place in small, structurally-controlled sub-basins, analogous to those formed by Ionian basin differentiation, while post-Palaeogene organic-rich horizons are related to the migrating external forebulge depozones of the Hellenides' foreland basin.

In the Ionian Zone, hydrocarbon source-rocks have been observed within the Vigla shales (Albian-Turonian), the upper Posidonia beds (Callovian-Tithonian), the lower Posidonia beds (Toarcian) and the coeval marls at the base of the Ammonitico Rosso (Early Toarcian), and the shale fragments incorporated within the Triassic breccias. Apart from the flysch, the other formations have good hydrocarbon potential and the contained organic matter belongs to Types I to II. In the central Ionian basin (oil window = 3700 m – 5800 m), 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, while the Vigla shales are still in 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 controlled by the synrift geometry, whereas in the Vigla shales it may be related to the Cretaceous Anoxic Events. The organic-rich shale fragments within the Triassic evaporite dissolution-collapse breccias were initially deposited as organic-rich shale layers in restricted sub-basins within 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.

Porosity measurements have shown that, apart from the Triassic breccias and Pantokrator limestones which are characterized by good porosities, the rest of the Ionian zone formations have low porosity values and negligible permeability values. Thus, fracture porosity-permeability plays a dominant role in determining hydrocarbon migration.

Promising trap structures in the Pre-Apulian zone include large anticlinal structures identified by field and seismic reflection data. Localities suitable for the entrapment of hydrocarbons in the Ionian zone are restricted to small anticlines within larger-scale synclinal structures, at the contact zone between the calcareous and the clastic series of the Ionian zone. Potential hydrocarbon traps may also be present at the tectonic contacts between the Ionian zone and the Pre-Apulian and Gavrovo zones.

Major traps may also have formed between the pre-evaporitic substratum and the evaporitic formations at the base of both the Pre-Apulian and the Ionian zone successions.The degree of participation of the sub-evaporitic basement in the deformation of the Pre-Apulian and Ionian sedimentary cover determines the location and size of these traps. Various scenarios regarding the deformation of the sub-evaporitic formation are possible. The hypothesis of continental subduction of the common Pre-Apulian and Ionian zone pre-evaporitic basement eastwards of the Ionian zone, is regarded most favourably, as it appears to be compatible with the presence of the Phyllite – Quartzite metamorphic (HP-LT) unit beneath the Gavrovo - Tripolis Zone in Peloponnesus and Crete.

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