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Late Cenozoic deformation of the Gavrovo and Ionian zones in NW Peloponnesos (Western Greece)

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Abstract
The structural deformation of Mesozoic-Tertiary sediments of the Ionian and Gavrovo zones in NW Peloponnesos is related to the propagation of a fold-thrust system during the Cenozoic. The sediments of the Gavrovo zone have been deformed by high angle reverse faulting generating an imbricate fan. Skolis mountain represents the Gavrovo thrust front. The detachment occurred in the underlying flysch of the Ionian zone. The Ionian zone has also been affected by shortening above a detachment horizon situated in the lower horizons of Triassic evaporites. The main compressional structure of the Ionian zone is a broad anticline revealed by a seismic survey west of Skolis mountain. The Gavrovo-sheet emplacement caused the downthrow and bending of the eastern part of the Ionian zone followed by halokinesis of Triassic evaporites to the west. Post-compressional normal faulting has predominated since the Pliocene, resulting in the formation of the Kato Achaia and Simopoulo basins in the peripheral area of Skolis mountain. Diapirs of Triassic evaporites occur in the mentioned basins that complicate the tectonic pattern in front of the Skolis thrust.

Key words *External Hellenides – Gavrovo thrust – NW Peloponnesos – seismic modeling*

1. Introduction

The work presented here was carried out during the recent investigation of hydrocarbon prospects in the NW Peloponnesos. The study area is part of the Western Hellenides thrust fault belt which runs parallel to the coast of Western Greece (fig. 1).

Skolis mountain represents the tectonic boundary between the Ionian and Gavrovo zones (Fleury, 1980) and offers an excellent case study of compressional tectonics in a thrust fault belt. It also offers the opportunity of studying the structure and relationship between the above mentioned zones.

The surrounding area of Skolis mountain is occupied by upper Eocene to Oligocene flysch, while two ESE-WNW trending grabens bound the flysch outcrop to the north and to the south (fig. 2).

Information obtained by aerial photographs, field observations and well data are used to better portray the structural style of these zones. A seismic survey followed the detailed geological fieldwork. Several seismic reflection pro-

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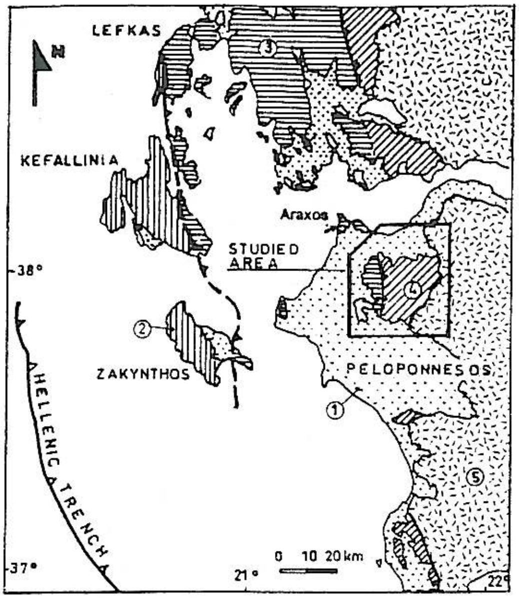

Fig. 1. Location map of the study area with isopic zones of the External Hellenides.

files have been done in the study area. Three of these profiles are presented in this work in order to support a model for the tectonic evolution of this sector of the External Hellenides.

2. Geological setting

Three northwest-southeast trending tectonostratigraphic zones are defined in the NW Peloponnesos based on their stratigraphy and paleogeography (figs. 1 and 2). From the east to the west: the Pindos, Gavrovo and Ionian zones (Aubouin, 1959; Dercourt, 1959; Aubouin and Dercourt, 1962; Jenkins, 1972; Izart, 1976; Sorel, 1976; Fleury, 1980; Thiebault, 1982; Bizon *et al.*, 1992). The External Hellenides are considered to have initially been part of a passive continental margin during the early Mesozoic Tethyan ocean opening (Aubouin, 1959; Auboin and Dercourt, 1962). Since the early Cretaceous, they have developed as a part of the foreland fold and thrust belt resulting from the collision of the Apulian microplate with the Eurasia plate after the closure of Tethys ocean (Dewey *et al.*, 1973; Smith and Moores, 1974).

Moreover, active subduction of the Ionian oceanic lithosphere beneath the Hellenic margin of the European plate has been taking place since middle Miocene times in the Eastern Mediterranean (Le Pichon and Angelier, 1979).

A more external zone, the Pre-Apulian zone, is developed further west, outcropping on the Ionian islands. This zone was previously regarded as the undeformed Hellenides foreland, but more recent work revealed that it was dominated by shortening during Tertiary-Quaternary times (Underhill, 1989).

The External Hellenides, except the Pindos zone, correspond to an external carbonate platform from the Lias to the middle Eocene that has been broken up by rifting since the late Lias era (Bosellini and Winterer, 1975; Thiebault, 1982). This rifting resulted in the formation of structural highs, such as the Pre-Apulian and Gavrovo shallow water platforms and depressions such as the Ionian basin.

The pelagic sediments of the Pindos zone reveal the existence of a deep water basin during the same period. The External Hellenides were progressively deformed by shortening due to the above mentioned collision between the Apulian and Eurasia plates. This shortening process first involved the Pindos zone from the late Eocene onward, while the Gavrovo and Ionian zones were progressively involved during the Neogene (Aubouin, 1973).

3. Compressional structures

3.1. *Pindos zone*

This zone is exposed in the eastern sector of the study area and consists of upper Triassic to upper Cretaceous pelagic sediments that underlie Paleocene to Eocene flysch. The western boundary of this zone is well defined by a major low angle thrust fault, the Pindos thrust, representing the most internal structure of the External Hellenides. The mountainous chain of the Erymanthos and Panachaiko mountains (fig. 2) reaches altitudes of 2200 m and 1900 m respectively and corresponds to the Pindos zone, while

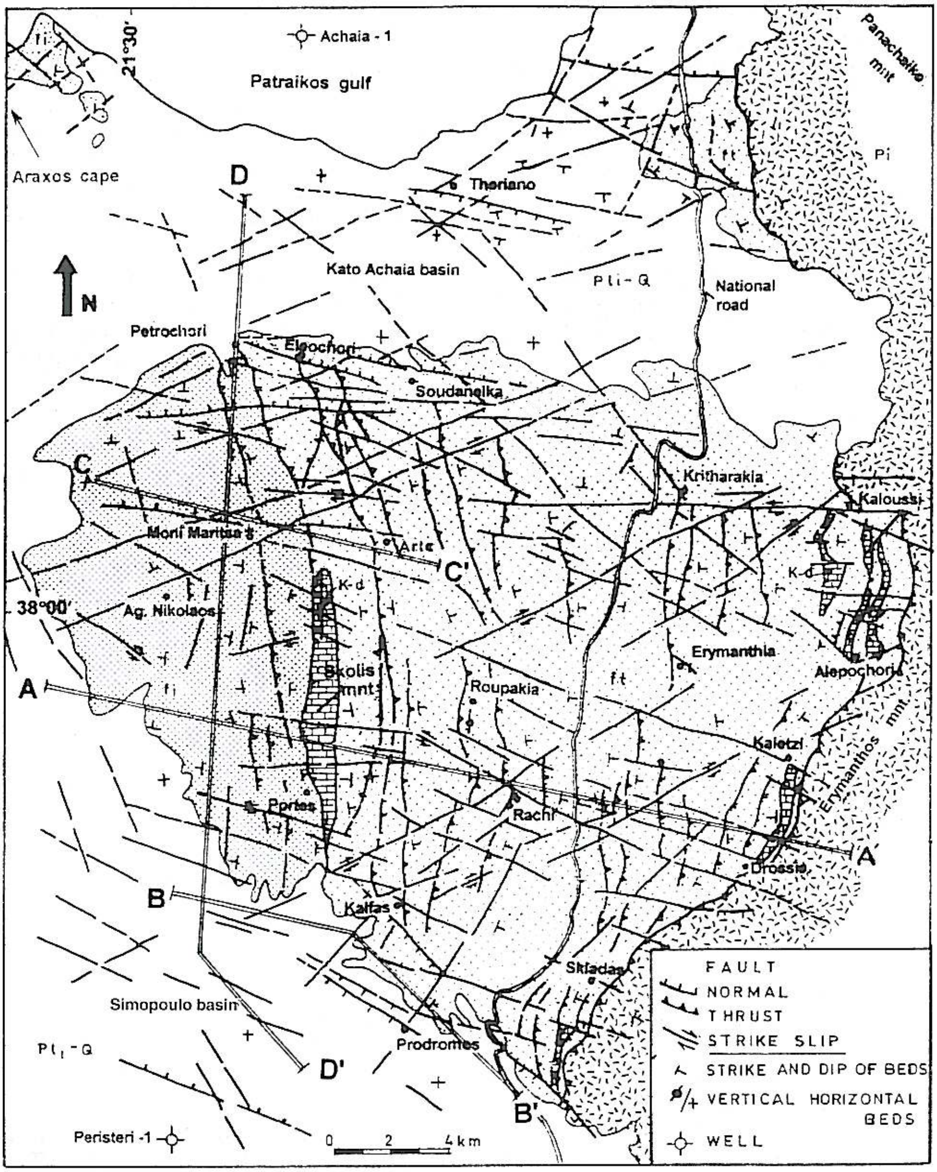

Fig. 2. Geological map of NW Peloponnesos.

the relatively lower relief is associated with the Gavrovo flysch. The late Eocene to early Oligocene Gavrovo flysch predates the Pindos thrust sheet emplacement. The frontal fault zone is characterized by the presence of several thrust slices representing an imbricate fan. These thrust slices dip to the northeast near Kaloussi village (fig. 2) and southeast on Erymanthos mountain, at angles between 30°-70°, rooting on the underlying detachment situated in the flysch of the Gavrovo zone.

3.2. *Gavrovo zone*

The Gavrovo zone consists of late Cretaceous-Eocene shallow marine carbonates which outcrop on Skolis mountain and late Eocene-Oligocene flysch that outcrops in the surrounding area (fig. 3).

Skolis mountain is the most impressive topographic feature in the study area, a N-S trending steep mountain, reaching 1000 m of altitude, rising above the lower flysch relief with a mean altitude of about 300 m (fig. 4a). It consists of Senonian to Eocene shallow marine carbonates of the Gavrovo zone. At the western flank, Senonian carbonates overthrust shaly flysch (Fleury, 1980). The presence of *Globigerina altiapertura* in the footwall flysch indicates lower Oligocene age. To the west, the uppermost conglomerates of flysch correspond to late Oligocene age (Izart, 1976). Hence, the thrust emplacement took place after the late Oligocene. On the northwestern slopes of Skolis mountain, small-scale compressional structures have been observed, resulting in a repetition of the carbonate series (Fleury, 1980). Excavation works in a quarry close to Portes village reveal a representative cross-section of the Skolis thrust. At this location, Senonian carbonates overthrust eastward dipping flysch of lower Oligocene age. The flysch strata close to the thrust surface are steeply dipping and overturned, while the cleaved shales clearly show the intense deformation of the footwall flysch (fig. 4b).

The main thrust-fault roots on a detachment horizon that is situated in the uppermost members of the underlying flysch of the Ionian zone as supported by seismic surveys (figs. 5 and 10). This is in agreement with previous works (Dercourt, 1959; Fleury, 1980). On the southeastern flanks of Skolis mountain, the carbonates are strongly broken up and dip steeply to the east. The carbonates are faulted against gently westward dipping flysch due to the existence of a subvertical fault. This fault acted as a normal fault in a later stage, due to tilting of the hanging wall carbonates of Skolis mountain (fig. 3). Intense deformation is locally recognized in these carbonates, combined with gravitational sliding. On the contrary, on the northern part of Skolis mountain the carbonates gently dip to the north, forming a periclinal structure.

The first seismic profile (BB′) strikes ESE-WNW and it is located 3.5 km south of Skolis mountain (fig. 5). In this profile the above-mentioned thrust is buried beneath the Quaternary sediments, south of Portes village. The Skolis thrust is well documented in the middle part of this profile. The seismic image reveals the existence of a subsurface hanging wall anticline affecting the flysch and the carbonates of the Gavrovo zone. The folding terminates against the thrust faults reflecting probably a downward ramp-flat thrust geometry. West of the Skolis thrust, a second eastward dipping thrust is easily detected in this seismic profile, rooting downwards on the same detachment surface as

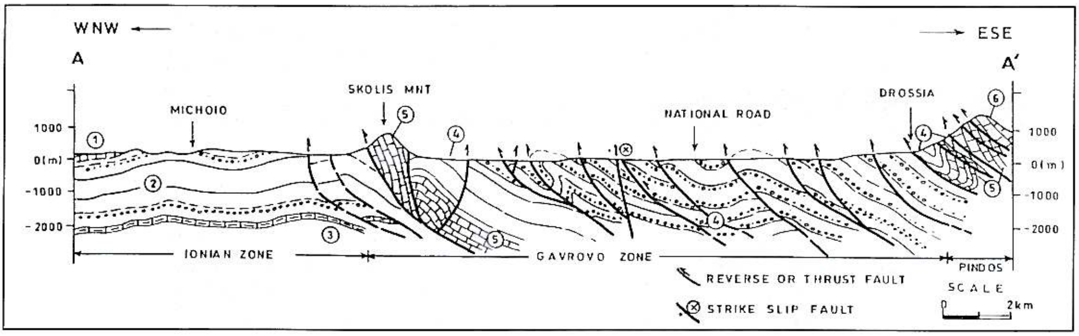

Fig. 3. Cross-section through the Skolis mountain and vicinity (AA′). Line of section is shown in fig. 2.

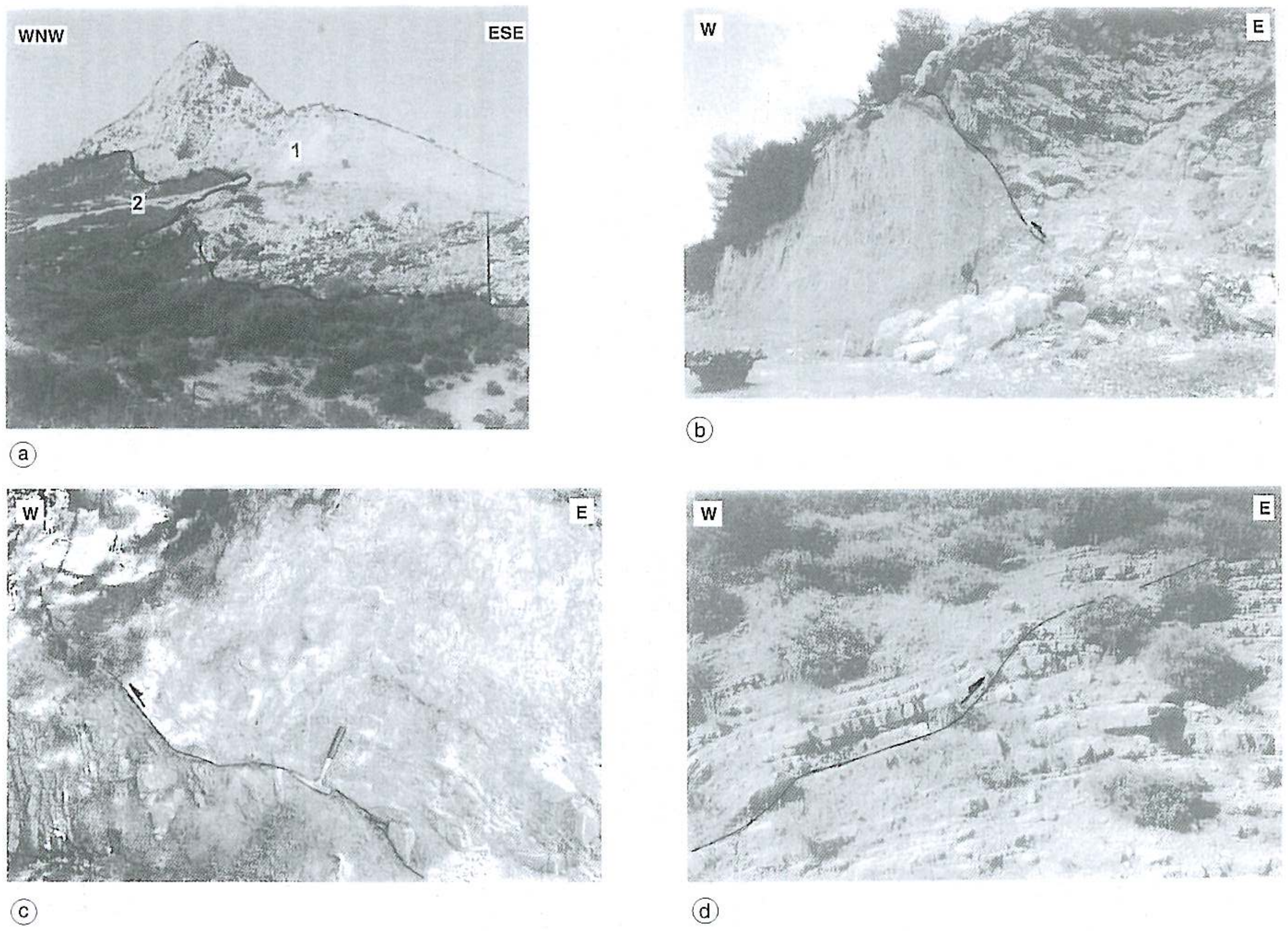

Fig. 4a-d. Photographs illustrating compressional structures of Gavrovo zone, NW Peloponnesos. a) Skolis mountain, with steeply dipping upper Cretaceous carbonates (1) thrust Oligocene flysch sediments (2); b) Skolis thrust, steeply dipping overturned flysch underlying the Gavrovo carbonates (site: quarry near Portes village); c) thrust fault on flysch, south of Eleochori village; d) backthrust on flysch, west of Drossia village.

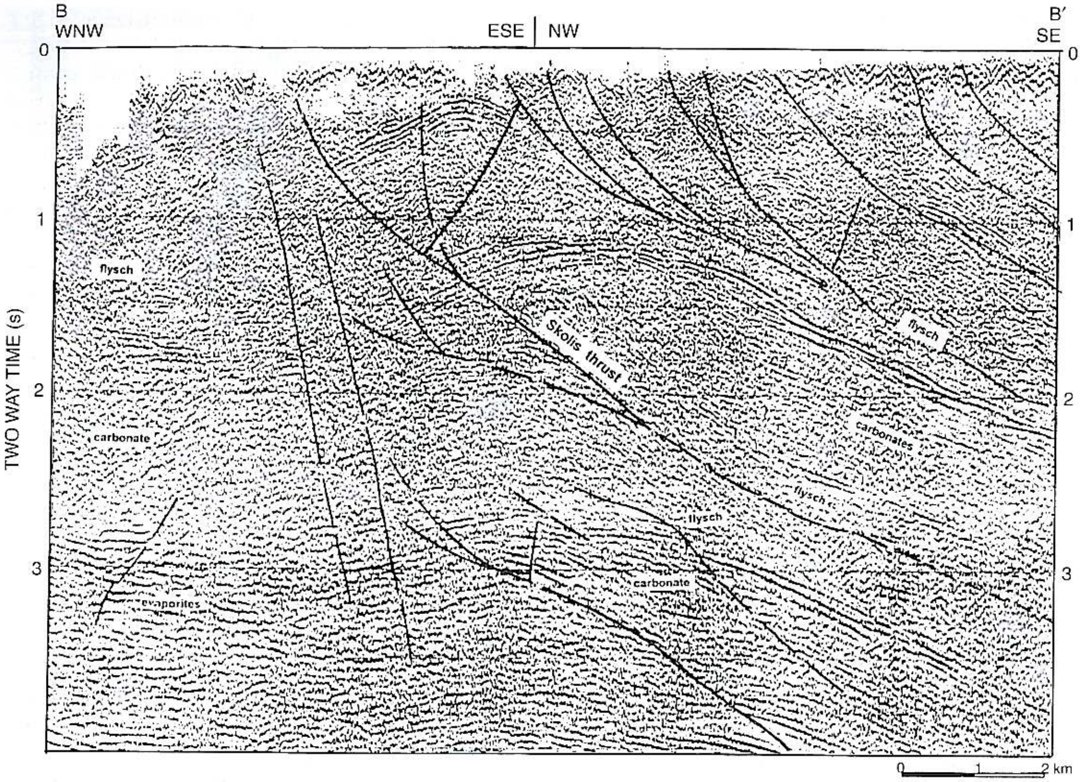

Fig. 5. Seismic line (uninterpreted and interpreted) south of Skolis mountain, showing the Skolis thrust fault and hanging wall anticline (BB′). Note the imbricate faults in Gavrovo zone, in the right part of section. Line of section is shown in fig. 2.

the main thrust. The existence of this thrust is confirmed on the field close to Portes village (fig. 2). A NNE-SSW trending back thrust exists southeast of Skolis mountain (fig. 3). This thrust fault dips to the west, rooting downwards on the Skolis thrust.

East of the Skolis thrust, a few contractional features have previously been described in geological maps (Tsoflias, 1980, 1981). However, a detailed analysis of aerial photographs and fieldwork reveals that the Gavrovo zone has been strongly affected by compressional tectonics, as indicated by the existence of several N-S to NNW-SSE oriented thrust-faults and asymmetrical folds plunging to the east. We mention some of these, from west to east as: Eleochori-Kalfas fault, Soudaneika-Rachi fault, Kritharakia-Skiadas fault and Kaloussi-Drossia fault (figs. 2 and 4c). In fact, these are fault zones, which consist of several individual eastward dipping thrust-faults which are characterized by small displacements. A change in orientation is also observed along their strike due to the existence of W-E trending strike-slip faults. The more eastern thrust-fault zones are aligned in parallel to the adjacent Pindos thrust. Also, minor back-thrust faults have been recognized east of Skolis mountain, which are located behind the main thrust-faults, as near Erymanthia, Eleochori and Alepochori villages (figs. 2 and 4d).

The reverse faulting generates the thickening of the flysch sequence to the east, towards the Pindos thrust (fig. 5). Close to the Pindos thrust, the deformation of the Gavrovo zone is more intense and closely spaced thrust faults have been formed (fig. 3). Thus, although Oligocene flysch outcrops in the surrounding area, several imbricates close to Pindos thrust expose upper Eocene carbonates and flysch, near Alepochori and Drossia villages. Narrow, thrust-fault related anticlines and synclines have been observed between Skolis mountain and the Pindos thrust. The axial planes of these folds strike north-south and plunge to the east, supporting a thrust movement to the west.

Due to intensive erosion, the upper members of flysch sediments are absent in the region east of Skolis mountain representing an uplift area in comparison to the Ionian zone. However, the existence of upper members of flysch (upper Oligocene age) beneath the Pindos thrust cannot be excluded.

A thin sedimentary cover, less than 20 m thick, is locally preserved in the study area; it consists of two horizons of continental deposits. The upper one is composed of Diluvian reddish deposits, while the lower one of brownish fluviatile deposits. It is characterized by low-relief erosion surfaces. This cover resulted from a peneplanation process that is well marked in the flysch domain, east of Skolis mountain (*e.g.*, Erymanthia village). Marine terraces of Pre-Tyrrhenian interglacial age have been recognized west of Skolis mountain. These terraces have been formed at a maximum altitude of 115 m above sea level. The estimated rates of net uplift in the mentioned area are 0.6 mm/year (Stamatopoulos *et al.*, 1998).

3.3. *Ionian zone*

The carbonate sequence of this zone is exposed northwest of the study area near Cape Araxos. The lower part of this outcrop consists of bedded pelagic limestone with cherts of Tithonian-early Cretaceous age («Vigla» limestone) while the upper part comprises micritic limestone with bedded turbidites and breccia of upper Cretaceous to Eocene age (Tsoflias, 1977). Late Eocene to early Oligocene flysch overlies the previous carbonate sequence. The lower members of Jurassic age (Posidonia beds, Sinies and Pantokrator limestone) as well as the Triassic members (Foustapidima limestone) do not outcrop in the study area. These lower members of the Ionian zone have been drilled through in the Sosti-1 well located 23 km southwest of Skolis mountain.

The Triassic evaporites are observed west of the study area, near Kyllini peninsula. However, their presence in the subsurface is confirmed in the exploratory oil wells Achaia-1 and Peristeri-1 (fig. 2). The seismic survey reveals the existence of evaporites in the subsurface of the study area. This sequence is also characterized by significant thickness variations (500-4000 m) as supported by seismic data (Voulgaris *et al.*, 1993).

Flysch of middle-upper Oligocene age has also been encountered in the Peristeri-1 well (Kamberis, 1987). The upper members of the flysch sequence, of lower to upper Oligocene age, outcrop west of Skolis mountain. This flysch has not undergone intense imbrication similar to that of the Gavrovo zone. Thus, the flysch and the underlying carbonates almost preserve their initial deposition thickness, 2500 m and 3500 m, respectively.

Most of the flysch west of Skolis mountain participates in a broad anticline which is the most prominent structure of the Ionian zone in the study area. The axis of this open symmetric anticline strikes north-south and is located 5 km west of Skolis mountain. It is traced between the extensional basins of Kato Achaia to the north, and Simopoulo to the south, predominating most of the outcropping flysch west of Skolis mountain. The anticline axis plunges both to the north and to the south forming a pericline.

The second seismic profile (CC') which passes near the northern end of Skolis mountain, images the Ionian zone (fig. 6). Two strong reflectors are easily recognized. The first one corresponds to the base of the Ionian flysch (or the top of the Ionian carbonates) at 1.4 s, while the second one to the base of Ionian carbonates (or the top of the evaporites) at 2.7 s respectively. The observed reflectors have been correlated with the Ionian sequence encountered in the oil exploration wells located close to the study area (Achaia-1 and Sosti-1 well). The previously

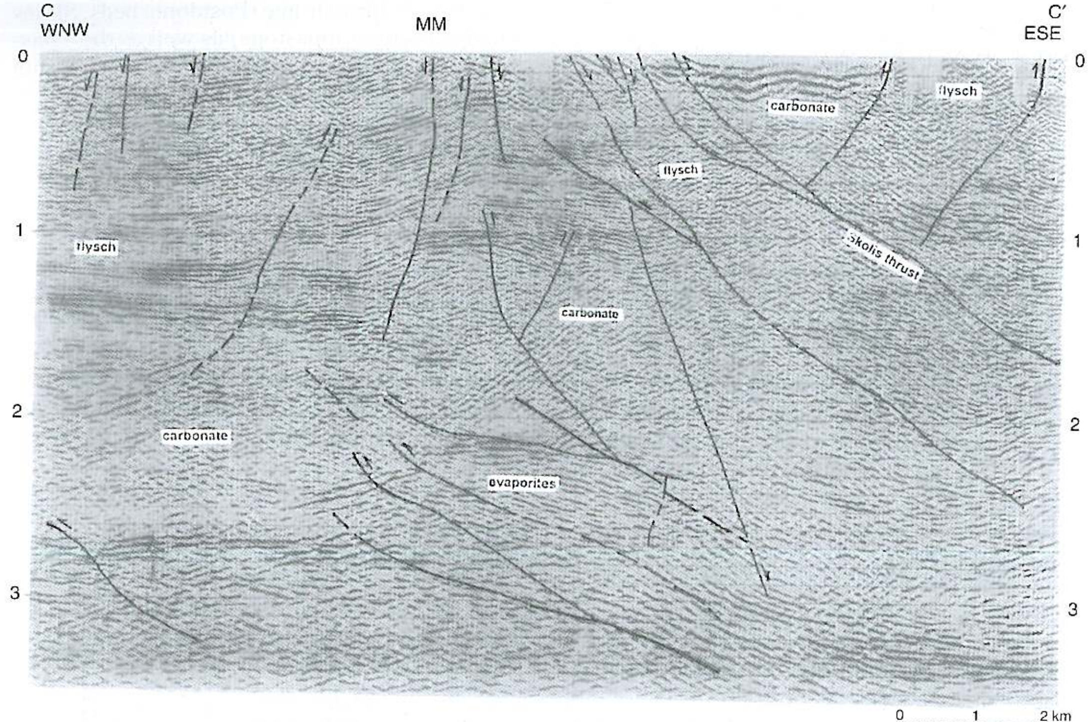

Fig. 6. Seismic line (uninterpreted and interpreted) north of Skolis mountain showing the deformation of the Ionian zone (CC′). Note the basement (Triassic sequence) involved in the shortening process. Line of section is shown in fig. 2.

mentioned anticline is partly associated with a blind east dipping thrust-fault which affects both the carbonates and the lower-most members of flysch of the Ionian zone. The displacement is small, approximately 0.3 s at the upper segment of the thrust. It is remarkable that the western part of this profile presents a better seismic image with easily detected reflectors. This difference is partly due to the relatively thick overlying sequence of flysch reaching 1.3 s in this sector.

The top of the Triassic sequence is clearly deformed by blind thrust faults, forming a buried imbricate fan. These faults root downwards into the basal part of this sequence (fig. 6). Several similar thrust faults have also been recognized west of the study area, associated with N-S trending folding (Kamberis *et al.*, 1996). As mentioned above, evaporites mark the detachment horizon during the shortening process of the External Hellenides. The emplacement of the Ionian thrust on the Pre-Apulian zone took place during the early Pliocene and occurs further west on Zakynthos and Kefallinia islands (Sorel, 1976; Fleury, 1980; Underhill, 1989).

Furthermore, field observations on both the Gavrovo and the Ionian zones reveal the existence of several minor strike-slip faults that cut the thrust fault zones and strike at high angle to the main compressive structures. They are considered secondary features that arose during the thrust propagation to the west during Miocene times. Most of these faults correspond to ENE-WSW dextral and ESE-WNW sinistral strike-slip faults. We mention some of them, such as the Eleochori and Prodromos strike-slip

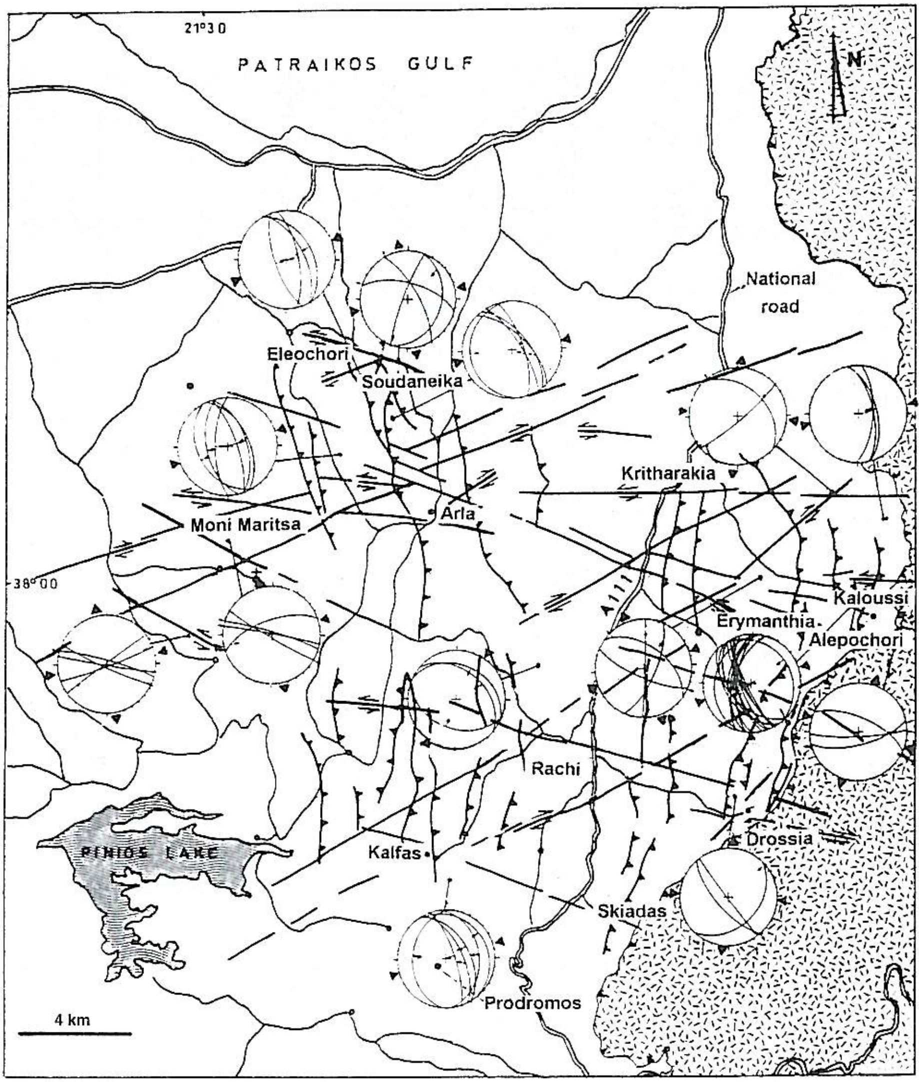

Fig. 7. Tectonic map of the area studied, including the equal area projection of reverse and strike slip faults and the resulting directions of compression indicated by arrows.

faults, which coincide with the northern and southern boundary of the flysch outcrop (fig. 2). Moreover, the existence of analogous faults in flysch sequence like Moni Maritsas fault, Kalfas-Kaletzi fault and Drossia-Rachi fault should be noted. The displacement on the above mentioned faults is less than 2 km.

An ENE-WSW compression is determined after the computation of the field measurements concerning the folds, thrust and reverse faults, using the computer program FAULT (Caputo, 1988). This orientation coincides with the direction of the acceptable main Alpine orogenic phase in Western Greece (fig. 7).

4. Extensional structures

In the study area, many normal mesoscale faults have been measured in Tertiary to Quaternary sediments. The WNW-ESE normal faulting affects both the flysch and the Pliocene-Quaternary sediments, reflecting a younger age. This faulting has also been reported for the area adjacent to the southern coastline of the Gulf of Patras (Kamberis, 1987; Doutsos *et al.*, 1987). In many cases, the WNW-ESE faults coexist with W-E and ENE-WSW trending normal faults

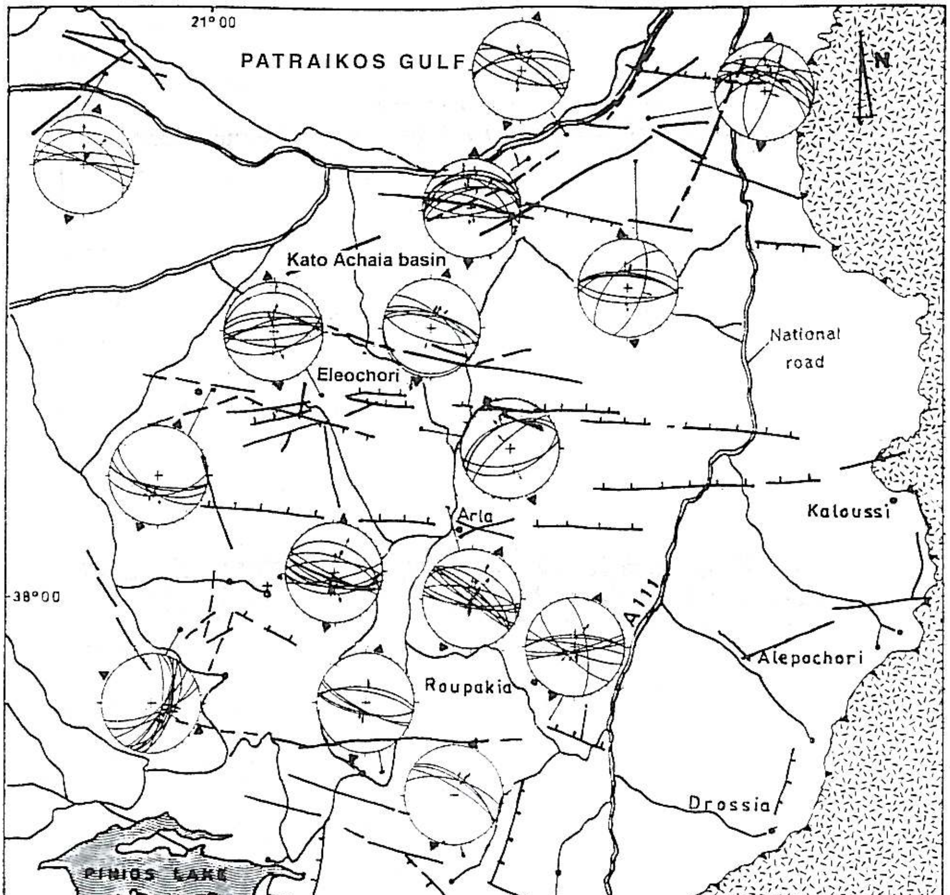

Fig. 8. Tectonic map of the area studied, including the equal area projections of normal faults and the resulting directions of extension indicated by arrows.

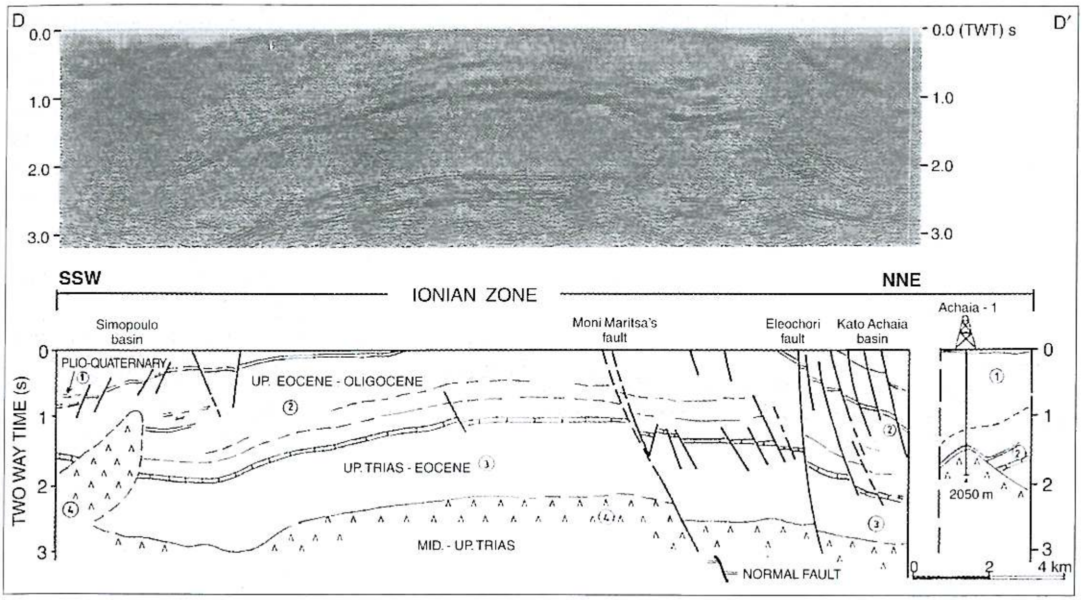

Fig. 9. Seismic line (uninterpreted and interpreted) parallel to the axis of Ionian zone (DD′). Note the Kato Achaia and Simopoulo extensional basins and the neighbour diapirs of the Triassic evaporites. Line of section is shown in fig. 2.

in the areas mentioned previously (fig. 8). The presence of these faults is related to the latest north-south extensional stage since the late Pliocene. In some cases, faults formed earlier have been reactivated due to this latest extension. Thus, two different kinematic indicators have been recognized on the fault-planes of some strike-slip faults in the flysch sediments where the tectonic striations are usually well preserved. The dip-slip movement is the younger one (Eleochori and Moni Maritsas fault). Also, obliquely NNE to NNW trending normal faults have been recognized in the flysch with tectonic striations dipping to the north or to the south. This oblique movement is also associated with the latest extensional stage.

The third seismic profile that is situated on the Ionian zone, 4.5 km west of Skolis mountain, portrays the main ESE-WNW trending extensional basins (fig. 9).

The first one, Kato Achaia basin, lies in the northern part of the study area, south of the Gulf of Patras. It is filled with a thick Pliocene-Quaternary clastic sequence that unconformably overlies the pre-Neogene folded rocks (Ferentinos *et al.*, 1985; Kamberis, 1987). This basin is bounded by two WNW-ESE trending fault zones, the Theriano fault zone to the north and the Eleochori fault zone to the south (figs. 2 and 9). The latter fault consists of several subvertical en echelon normal faults dipping to the north. Small populations of NNE-SSW trending faults are also encountered near the south coast of the Gulf of Patras (fig. 2).

NW to WNW trending normal faults control the Southern Simopoulo basin. Although the uppermost sediments are of upper Pliocene - Quaternary age, seismic and well data suggest that the lowermost sediments are relatively earlier formations of middle Miocene to lower Pliocene age (Kamberis *et al.*, 1992). For this reason, we consider that the deposition started earlier than in the Kato Achaia basin.

Within the borders of the above basins, the ESE-WNW trending normal faults clearly cut the previous N-S to NNW-SSE trending compressional structures, indicating that these faults postdate the compression and controlled the clastic sedimentation. In other sites, the ESE-WNW faulting cuts the recent sediments, like terra rossa and fluvial-torrential deposits of middle Pleistocene age, as near Portes village reflects the more recent faulting. Unless the above-mentioned latest faulting, the existence of small-scale synsedimentary faults affecting the flysch and carbonate sediments is also noted. The majority of these faults strike NNW-SSE, almost parallel to the Alpine axis (Agios Nikolaos monastery).

It is interesting that the latest diapiric movements of the Triassic evaporites usually occur in the neighboring basins, as in the Gulf of Patras and the Simopoulo basin. Therefore, the diapirs of evaporites are clearly related to great thicknesses of Plio-Quaternary accumulations (fig. 9). The northern diapir in the Gulf of Patras is confirmed by the Achaia-1 well, and the southern diapir, in the Simopoulo basin, by the Peristeri-1 well (Kamberis, 1987). In several seismic profiles, the upper Pliocene to Quaternary sediments are clearly affected by these diapirs, suggesting that these structures have been active up to the present (Kamberis *et al.*, 1996). Moreover, the local existence of some recent faults that strike NNW-SSE to NNE-SSW, is associated with the above mentioned diapirs. Such faults are observed in the western part of the Simopoulo basin (fig. 2).

A diapir has also been recognized by seismic surveys, in front of the Skolis thrust. This occurrence is associated with the existence of a significant normal fault west of the Skolis thrust that affects the flysch and carbonate sequence of the Ionian zone (fig. 10). It strikes N-S, is aligned in parallel to Skolis mountain and dips to the east. It is characterized by an important throw (0.5 s, Two Way Time, in seismic profile). The existence of this important fault in front of the Skolis thrust can be the result of the overloading due to the thrust emplacement.

Thinning of the Ionian carbonate sequence towards the north is observed in several N-S trending seismic profiles (fig. 9). This can be related to the initial paleography of the Ionian

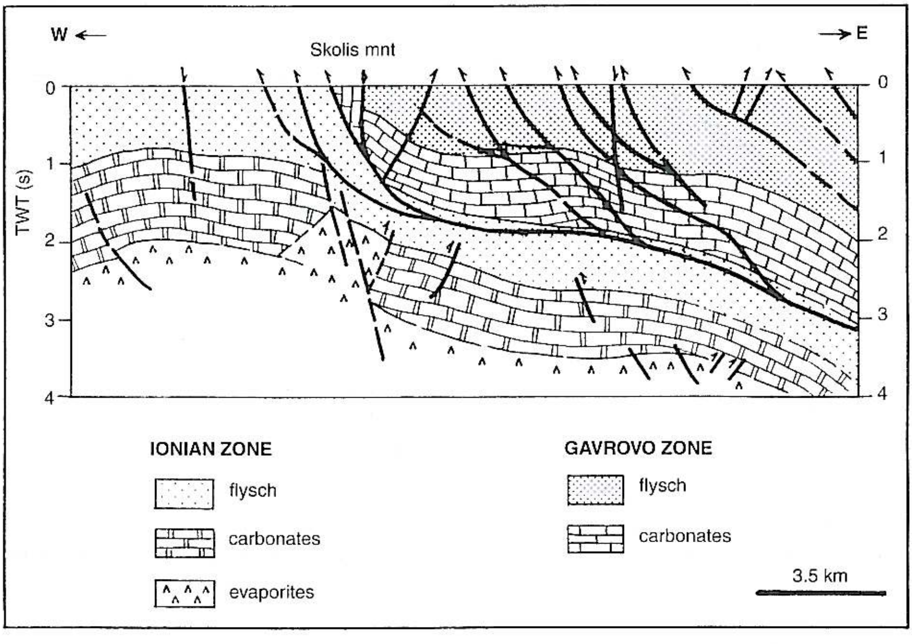

Fig. 10. Geological model on a seismic line which traces on the cross-section AA′.

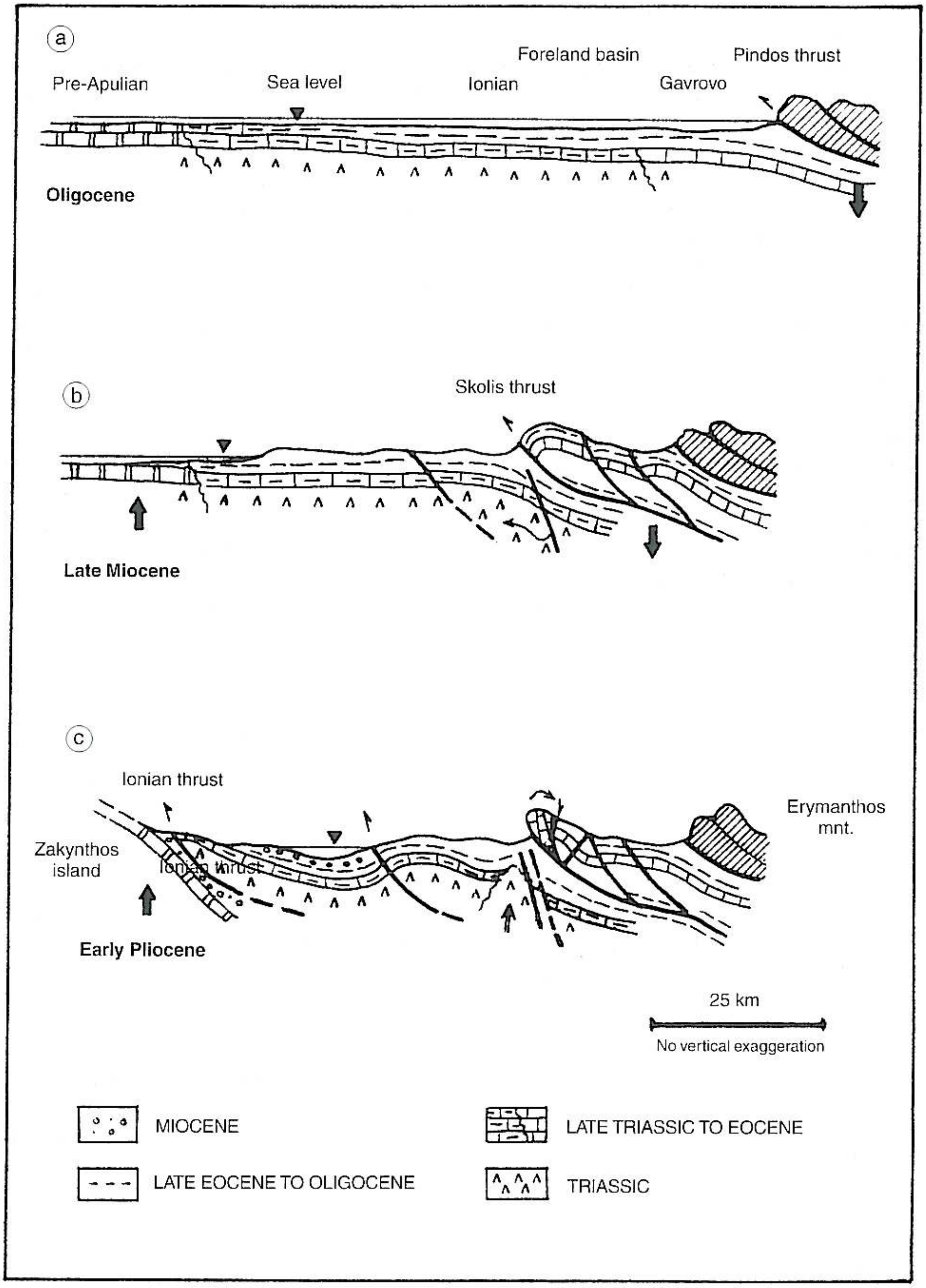

Fig. 11a-c. Schematic sections that illustrate the tectonic evolution of the External Hellenides during Neogene. See text for explanations.

basin during the carbonate deposition. Thus, the neighboring area of the Gulf of Patras represents an area of relative uplift in relation to the southern area, near the Simopoulo basin.

5. Discussion and conclusions

The mountain front areas of Erymanthos and Skolis mountain reflect the underlying ramps of the Pindos and Skolis thrusts supported by field observations and onshore seismic profiles.

Skolis mountain consists of shallow marine carbonates of the Gavrovo zone, which overthrust the Ionian flysch sequence. The detachment horizon of the Gavrovo zone lies in this flysch sequence at a depth of 4.5 km (1.7 s TWT) east of Skolis mountain and 8 km (3.1 s TWT) beneath the Pindos thrust front (fig. 10).

The Gavrovo and the Ionian zones have been deformed by an array of thrusts that propagate towards the foreland. In this situation, each newly formed thrust develops in the footwall of the older thrust. This procedure is termed piggyback thrust propagation (Dahlstrom, 1970), where the higher thrust represents the earlier displacement (Pindos thrust), and the lower ones the later displacements (Gavrovo and Ionian thrusts). East of Skolis mountain, the Gavrovo zone is an eastward dipping monocline bounded to the east by the Pindos thrust. The Gavrovo flysch is affected by intense thrust faulting showing an imbricate geometry (Dahlstrom, 1970; Butler, 1982). The existence of blind thrusts, fault propagation folds, as well as back thrust east of Skolis mountain completes the structural pattern of this zone.

The proposed model suggests a great deal of shortening of at least 20 km.

In contrast to the Gavrovo zone, the Ionian flysch located west of Skolis mountain presents weak internal deformation, expressed by the presence of an open anticline in front of the Gavrovo thrust front (fig. 10).

The Triassic evaporites are the principal level along which there has been the detachment of the overlying sedimentary succession (B.P., 1971).

The progressive progradation of the accretionary prism (Pindos zone) to the west caused the overloading and a lithosphere down-flexure towards the orogen. As a result, the Ionian-Gavrovo foreland basin has been formed in front of the orogenic belt, in which synorogenic sediments (flysch) accumulated (fig. 11a).

The superposition of the Gavrovo zone on the Ionian zone gave rise to halokinetic movements of the Triassic evaporites from east to west, resulting in the further folding of the Ionian formations (fig. 11b). The emplacement of the Skolis thrust caused later diapiric movements that are expressed mainly in the surrounding area of Skolis mountain. In these areas, post-orogenic extensional basins have been formed since the Pliocene. These basins are controlled by the ESE-WNW normal faulting.

The high angle Skolis thrust as well as the subvertical hanging wall carbonates in the southern part of Skolis mountain can be related with this diapir as well as with the existence of a significant normal fault zone. Thus, a back tilting of the Skolis thrust after its emplacement, due to later diapiric movement, can not be excluded (fig. 11c).

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