CRUSTAL INVESTIGATIONS IN ZAKYNTHOS-NW PELOPONNESUS AREA (W. GREECE)

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A B S T R A C T

The structure of the earth's crust in the western part of the Hellenic margin was investigated using seismic refraction and wide angle reflection techniques. Data acquisition was carried out along an E-W trending 120 km long profile in the area of Zakinthos - North-western Peloponnesus, during September 1987. Field operations involved 15 shots combined with 4 profile segments in order to ensure maximum coverage of the offshore area without the use of OBS recorders. Interpretation of the recorded seismic sections was accomplished by travel time iterative 2D computer modelling, based on the Gaussian beam theory. Synthetic seismograms were also generated in order to assist the interpretation procedure. Application of this method allowed the determination of 9 seismic units from the surface down to a maximum depth of 36 km, with P-wave velocities ranging from 2.7 to 8.0 km/sec. The deepest reflector distinguished was the Mohorovicic discontinuity, located at depths ranging from 29 to 36 km. Furthermore, the obtained two dimensional models indicate that the area is characterised by strong lateral inhomogeneities resulting from the Alpine and Post-alpine tectonic activity in this part of the Hellenic margin and salt tectonics associated with the existence of Triassic evaporites in the area.

ΔΙΕΡΕΥΝΗΣΗ ΤΗΣ ΔΟΜΗΣ ΤΟΥ ΦΛΟΙΟΥ ΣΤΗΝ ΠΕΡΙΟΧΗ ΖΑΚΥΝΘΟΥ-ΒΔ ΠΕΛΟΠΟΝΝΗΣΟΥ

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Π Ε Ρ Ι Λ Η Ψ Η

Στην παρούσα εργασία παρουσιάζονται τα αποτέλεσματα της διερεύνησης της δομής του φλοιού στο δυτικό τμήμα του Ελληνικού τόξου με την εφαρμογή της μεθόδου της σεισμικής διάθλασης. Η συλλογή δεδομένων έγινε κατά μήκος μιας σεισμικής τομής με γενική διεύθυνση Α-Δ και συνολικό μήκος 120 χιλιομέτρων, στην περιοχή Ζακύνθου-Βορειοδυτικής Πελοποννήσου. Κατά τη διάρκεια των εργασιών υπαίθρου πραγματοποιήθηκαν 15 συνολικά εκρήξεις σε συσχετισμό με 4 επιμέρους τμήματα της σεισμικής τομής με σκοπό την καλύτερη δυνατή κάλυψη του υποθαλασσίου χώρου χωρίς τη χρήση καταγραφικών τύπου OBS. Η ερμηνεία της σεισμικής τομής έγινε με

τη βοήθεια τεχνικών προσέγγισης των παρατηρηθέντων χρόνων διαδρομής με δισδιάστατα προσομοιώματα, βάσει της μεθοδολογίας των δεσμών ακτίνων Gauss. Ο υπολογισμός συνθετικών σεισμογραμμάτων αποτέλεσε ένα επιπλέον βοήθημα για την καλύτερη αξιοποίηση και ερμηνεία των δεδομένων. Η εφαρμογή της μεθόδου επέτρεψε την αναγνώριση 9 επιμέρους σεισμικών στρωμάτων, από την επιφάνεια μέχρι μέγιστο βάθος 36 χιλιομέτρων. Οι σεισμικές ταχύτητες των στρωμάτων αυτών καλύπτουν εύρος από 2.7 έως 8.0 km/sec. Ο βαθύτερος ανακλαστήρας που εντοπίστηκε ήταν η ασυνέχεια Mohorovicic, σε βάθος που κυμαίνεται από 29 έως 36 χιλιόμετρα. Τέλος, θα πρέπει να σημειωθεί ότι, σύμφωνα με τα δισδιάστατα προσομοιώματα που προέκυψαν από την ερμηνεία η περιοχή χαρακτηρίζεται από έντονες πλευρικές μεταβολές. Οι μεταβολές αυτές οφείλονται πιθανά στην Αλπική και Μεταλπική τεκτονική δραστηριότητα στο τμήμα αυτό του Ελληνικού τόξου σε συνδιασμό με διαπειρική τεκτονική που σχετίζεται με την παρουσία Τριαδικών εβαποριτών.

INTRODUCTION

In order to investigate the crustal structure of the western Hellenic margin in the area of Zakinthos - W. Peloponnesus, deep refraction and wide angle reflection profile (figure 1) was carried out during fall 1987 by the Geophysics-Geothermy Division of the Athens University in collaboration with the Institute for Meteorology and Geophysics of the Johann Wolfgang Goethe University in Frankfurt. The results of this effort, motivated by the high seismological interest and geological complexity of that area of W. Greece, due to its relative location with respect to the subduction zone, the existence of Triassic evaporites and associated salt tectonics, are presented in this study.

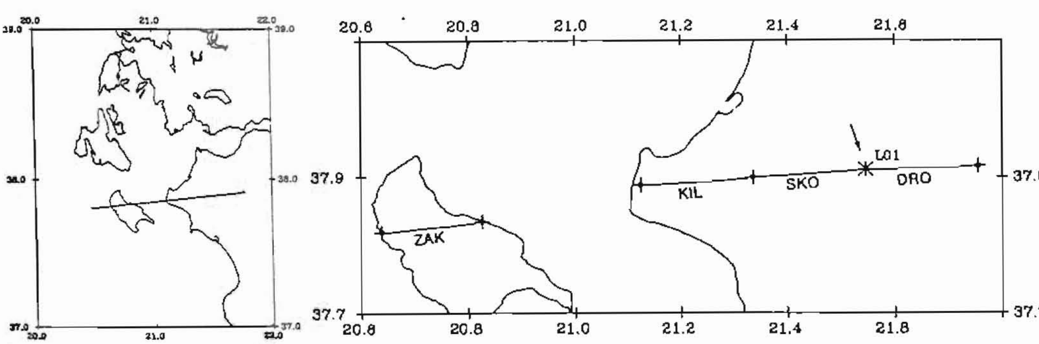


Fig.1. Location map of the seismic profile and its four sections in NW Greece.

The first investigations for the determination of crustal and velocity structure in the area of Greece were based on the analysis of seismological data (Papazachos et al, 1966, Panagiotopoulos, 1984). The geophysical method of deep refraction and wide angle reflection was first used for the investigation of the Hellenic margin by the University of Hamburg during the years 1971-1974 (Makris, 1976, 1977) and in association with the University of Athens in October 1982 (Delibasis et al., 1988). The results of those studies allowed the successful examination of velocity variations with depth in the earth's crust and upper mantle, in various areas of Greece. For that reason this method was selected in order to investigate the crust and locate the Mohorovicic discontinuity at depths of 30-40 km. Furthermore, this was also the most appropriate method in order to overcome the seismic energy absorption by the Triassic evaporite formation and obtain information for the underlying geological layers and structures.

GEOLOGICAL AND TECTONIC SETTING

The geological structure of the investigated area, located along the outer Hellenic arc, is dominated by the Alpine formations of the external geotectonic units which display a NNW-SSE trend (Aubouin, 1959) and the seismic survey was carried out along a WSW-ENE direction.

Along the profile axis three of the external geotectonic units are encountered. The first one is the Paxos unit appearing on Zakinthos island, where the western part of the profile was located on carbonates of Upper Cretaceous - Eocene age while in the eastern part more resent sediments of Upper Miocene - Plio-Pleistocene are present. The tectonic thrust contact between the Paxos and the Ionian which is the next unit to the east can be recognised southeastern part of the island. However, along the profile axis this contact is located in the offshore area between Zakinthos and northwestern Peloponnesus (Monopolis and Bruneton, 1982).

On northwestern Peloponnesus the formations of Ionian unit are mostly cover by recent Plio-Pleistocene sediments with the exception of the Cretaceous limestones and Triassic evaporites in the area of Kastro. The position of the contact between the Ionian and the third unit of Gavrovo to the east along the profile is located, according to Kamberis (1987), south of mount Skolis. In this eastern part of the profile the stations were located on recent Plio-Pleistocene sediments and the Gavrovo flysch formation with the exception of the two last station to the east which were installed on carbonates.

The dominant tectonic trend in the investigated area is the alpine one expressed by the existence of NNW-SSE directed thrusts and folds. A secondary group of faulting trending NNE-SSW can also be observed. In the formations of the Paxos unit the tectonic deformation favoured the generation of anticlines and normal faults, while in the Ionian unit tectonic deformation is expressed by successive thrusts and reverse faulting. Finally, the tectonic deformation in the Ionian unit is also influenced by the diapir movements and salt tectonics associated with the Triassic evaporites (Monopolis and Bruneton, 1982; Nikolaou, 1986; Kamberis, 1987).

DATA ACQUISITION - PROCESSING

During field work operations, the seismic signals were recorded by 12 MLR-II analog magnetic tape stations, located 2 km apart. In addition, 12 MEQ-800 smoked paper analog stations placed between the MLR-II stations, provided more detailed information by reducing the distance between stations to 1 km. The required seismic energy was provided by a total of 4 land and 11 underwater explosions, the locations of which can be seen in figures 1 and 2. As a result of the above shot-recorder configuration and in order to complete the 120 km long profile obtaining sufficient coverage of the offshore area between Zakinthos and W. Peloponnesus, the profile was subdivided into four sections ZAK, KIL, SKO and DRO (figure 1). Field operations for every segment involved instrument installation, drilling of the corresponding boreholes in preparation of the land shots, execution of land and sea shots and relocation of the recording stations along the next segment.

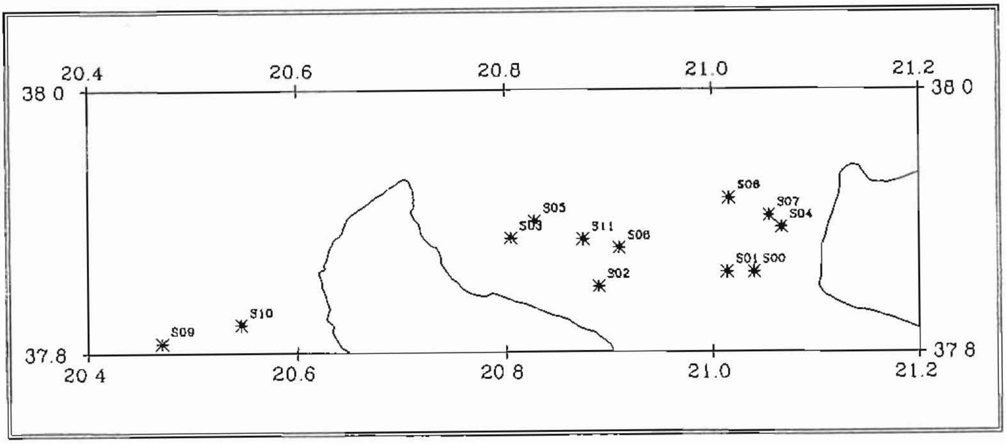


Fig.2. Location map of the underwater explosions.

In order to produce the reduced travel time seismic sections required for the interpretation of the profile, the seismic signals recorded by the MLR-II stations were decoded along with the corresponding DCF time signal and digitised using an A/D converter. The signals recorded by the MEQ-800 stations were first photographed and enlarged and after hand-digitisation the necessary corrections were made in order to compensate for digitisation and timing system errors. In the next step, after spectral analysis of the digital data from the two instrument types was performed, the seismic signals were filtered using a Butterworth band-pass filter. Finally, after elevation datum corrections the seismic signals of every shot were selected and the corresponding reduced travel time section was produced using a 6.0 km/sec reduction velocity (figure 3).

INTERPRETATION

For the interpretation of the seismic profile 2D ray tracing techniques, based on the Gaussian beam method (Cerveny et al., 1982), were applied using the algorithms developed by Weber (1988) for the implementation of the method. This method can be used for reliable travel time and synthetic seismogram calculations in complicated laterally inhomogenous media and has several advantages, since in contrast to the ray method it does not fail in the most interesting regions of the wave field such as critical regions, caustics and shadow zones, allowing thus for amplitude calculations in those regions (Muller, 1984). An additional advantage of the Gaussian beam is that since it does not require time consuming two point ray tracing, computational efficiency is greatly improved.

According to the requirements of the method 2D model of the profile with first-order velocity and density discontinuities was first constructed, taking into account the available geological, geophysical and drilling information in the area (Nikolaou, 1986, Kamberis, 1987) as well as the preliminary results of the velocity analysis for each seismic section. Next, the medium was described by subdividing the model into triangles controlled by linear density and velocity laws, a technique allowing both for flexible modelling of complicated structures and faster computations during ray tracing.

In the first computational stage the kinematic ray tracing was performed, calculated travel times were compared with the observed ones and the model adjusted accordingly until a satisfactory agreement was obtained. This procedure was repeated for every shot along the profile and conformity between forward and reverse shots was ensured. In the second stage dynamic ray tracing and the calculation of synthetic seismograms was performed with special attention given to the selection of the appropriate parameter which controls the with and phase-front curvature of each beam and the accuracy of the calculated synthetic seismograms. By comparing the resulting seismograms with the recorded seismic signals, and especially the onset times of the different phases and the amplitude ratios of the phases within the same signal it was possible to make minor adjustments to the model. However, it should be noted that due to inherent problems in refraction data (Weber, 1988), such as environmental noise which can reach 50% of the maximum signal amplitudes, reverberations after the arrival of strong seismic signals due to the bad coupling of the seismometers to the ground, multiples and diffractions from small inhomogeneities and problems associated with the attenuation of the seismic signal of the explosive source, a direct comparison between observed and computed seismic signals is not possible since the above mentioned problems allow only relative comparisons. An example of the output of the computational procedure for both forward and reverse shots is presented in figures 3 and 4.

RESULTS AND DISCUSSION

The final model obtained from the iterative computer modelling of the four sub-sections of the seismic profile, using all available shots, is presented in figure 5. In the same figure a structural interpretation of the geophysical model, obtained by talking into account the available geological and tectonic information (Monopolis and Bruneton, 1982, Nikolaou, 1986, Kamberis, 1987), as well as the resolution limitations of the applied geophysical method, is also attempted.

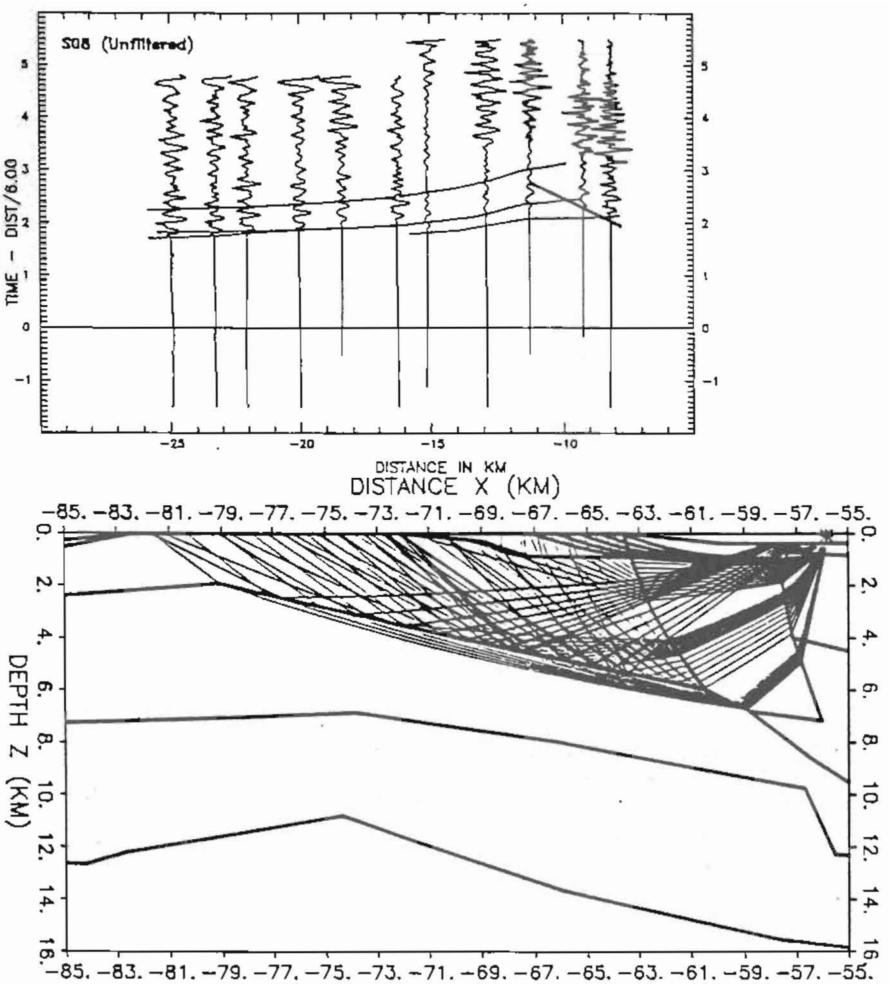
From the ray tracing interpretation procedure (Voulgaris, 1991) it was possible to distinguish 9 different seismic units from the surface down to a maximum depth of 36 km and determine the corresponding interface geometry.

The first unit, with P-wave seismic velocities ranging from 2.2 to 2.9 km/sec, extends along most of the profile displaying important thickness variations. The velocity interval, the geological data and the geometry variations along the profile indicate that this unit represents the post-Alpine and recent sediments in the area, which were deposited in various basins. In addition, the relatively lower velocity interval observed for this unit in the offshore areas (2.2-2.7 km/sec) as opposed to the land areas (2.7-2.9 km/sec), can be attributed to the newer sediments in these regions, where sedimentation is still continuing. The fact that the margins of the 5 separate basins distinguished along the profile display significant dips, indicates that tectonic activity is a significant factor controlling basin development in the area. The most prominent example is the basin located in the offshore area between northwestern Peloponessus and Zakinthos island the depth of which exceeds 7000 m.

The second unit is only located in small area near the position of the land shot points has a thickness of 700 m and the corresponding velocity interval of 3.8-3.95 km/sec, indicates a different lithology than the overlying first unit. For the third unit a similar velocity interval of 4.05-4.15 km/sec was observed indicating shale and sandstone materials as it is also verified by the outcrop of this unit east of the land shot location. The small velocity difference between the second and the third unit can be attributed to minor lithological and age differences related to the degree of compaction.

The fourth seismic unit observed along the profile corresponds to the limestone formations of the area. This conclusion is supported by the available geological, geophysical and drilling data (Monopolis and Bruneton, 1982, Nikolaou, 1986, Kamberis, 1987), as well as by the obtained velocity ranging from 5.7 to 6.1 km/sec. The presence of this unit along the profile, with an average thickness of 3000 m, is extensive and very important since in most cases it represents the basement of the post-Alpine sedimentary basins, emphasising the tectonic movements contributing to their evolution.

The interpretation of the profile revealed that presence of the fifth seismic unit, representing the geophysical equivalent of the Triassic evaporite formation, is limited only in northwestern Peloponnesus and the eastern part of the offshore area between Zakinthos and Peloponnesus. The modelling of this unit required special attention since its lower seismic velocity of 5.3 to 5.7 km/sec in relation to that of the overlying fourth unit, created the effect of a blind zone. Wide angle reflections



Sea Shot 8

Fig.3. Reduced travel time section, calculated travel time curves and corresponding model and ray paths of sea shot 8 section ZAK.

on the upper and lower interface of this unit provided the solution to the problem. The significant thickness variations of this unit (500 to 4000 m) are very important since they directly related to the continuing diapirism and salt tectonic activity in the area (Monopolis and Bruneton, 1982, Nikolaou, 1986, Kamberis, 1987) a fact that is also verified by the several intrusive bodies associated with this unit.

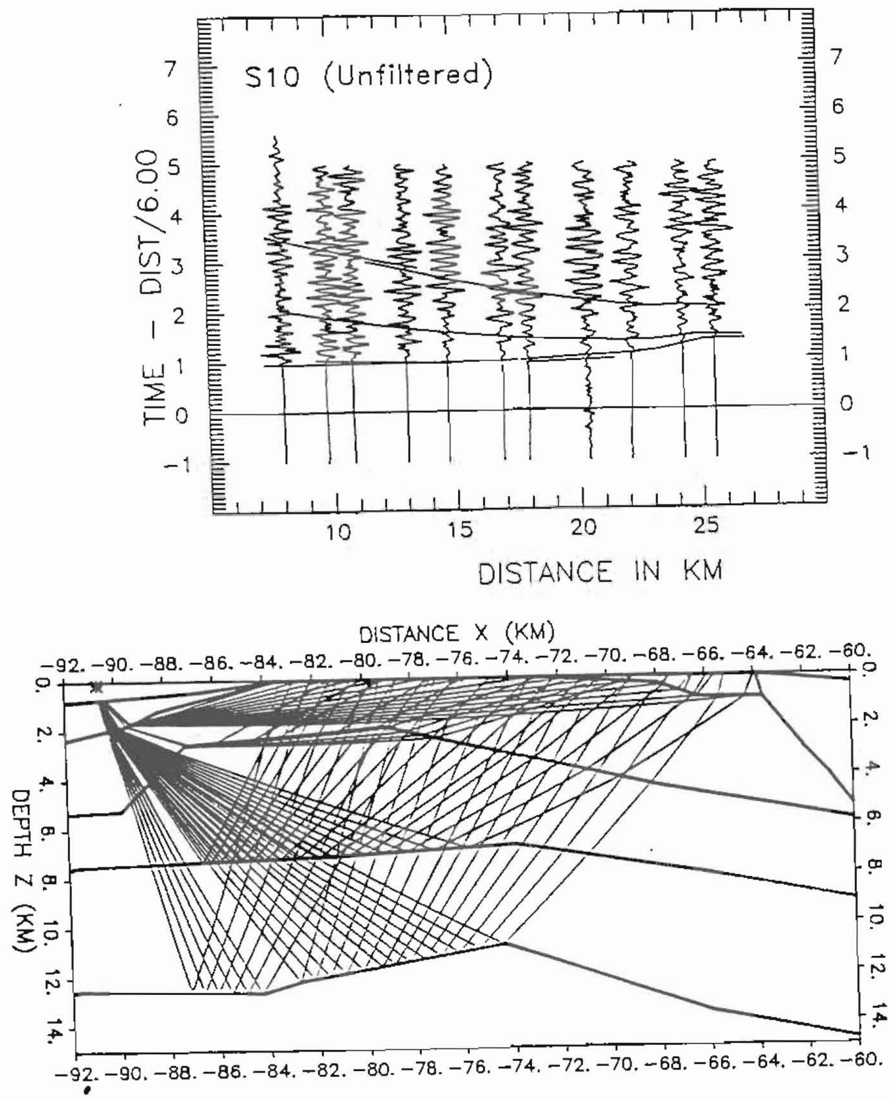


Fig.4. Reduced travel time section, calculated travel time curves and corresponding model and ray paths of sea shot 10 section ZAK.

As it can be seen from figure 5 the sixth unit, with seismic velocity ranging from 6.3 to 6.5 km/sec, extends along the total length of the profile and although it appears significantly affected by tectonic movements its thickness remains relatively

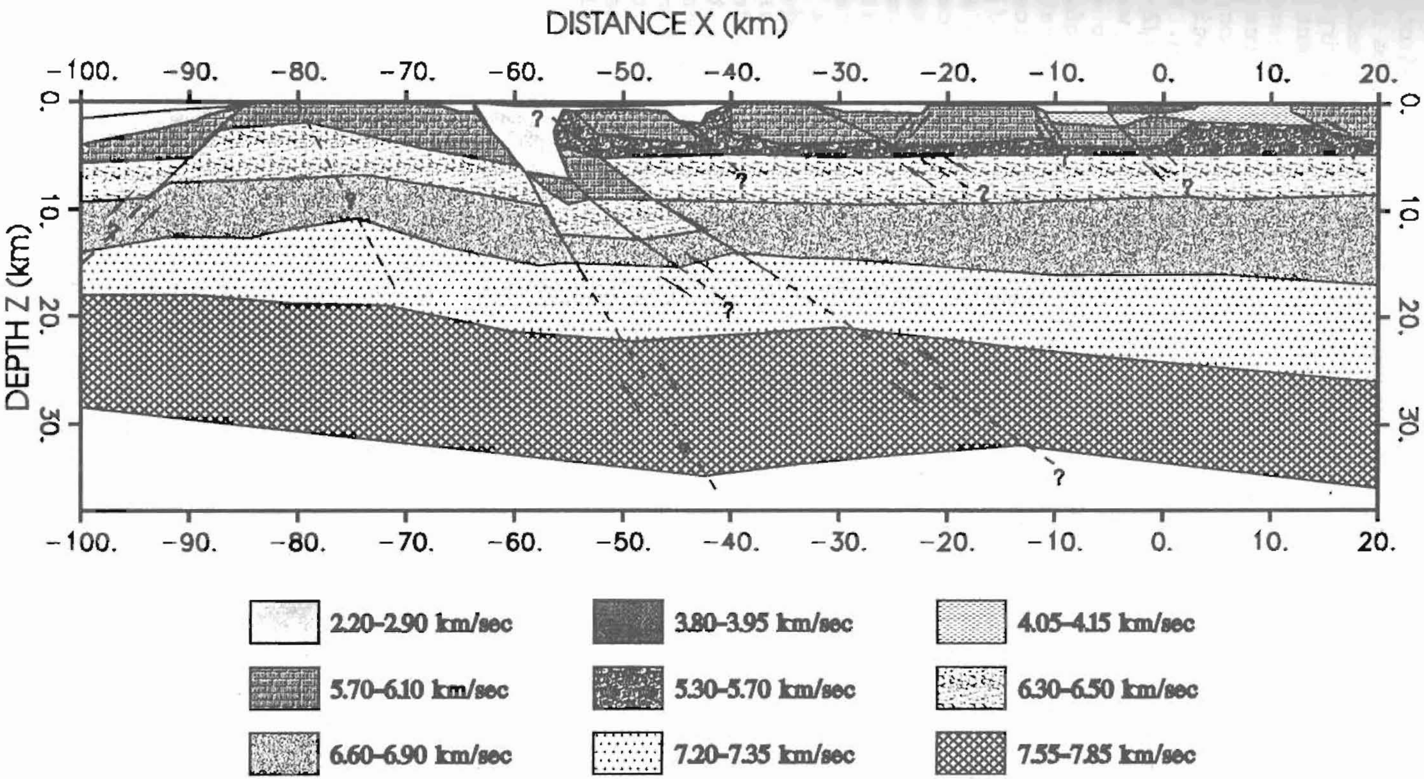


Fig.5. Final model obtained by the combined interpretation of the four sections of the refraction profile.

constant ranging from 4000 to 5000 m. Since the absence of other geological or geophysical data does not permit this seismic unit to be directly related to a geological formation and the obtained velocity could be attributed to carbonate, igneous or metamorphic character this unit must be regarded as geophysical basement of pre-Triassic age.

The remaining three seismic units compose the deeper crustal structure in the area. The seventh unit with a seismic velocity of 6.6 to 6.9 km/sec also displays important thickness variations and appears significantly affected by tectonic movements. The velocity remaining two units ranges for the eighth from 7.2 to 7.35 and for the ninth from 7.5 to 7.85. Their geometry is well defined only in the central part of the profile from (-10 to -74 km) since the absence of ray paths at the sides of the profile did not allow reliable modelling. The deepest interface located at depths of 29 to 36 km, using wide angle reflections, corresponds to the Mohorovicic discontinuity.

The most important characteristic of the last two units are the significant variations of interface depths which indicate that tectonic deformation in the area extends down to the depth of the Mohorovicic discontinuity. The influence of tectonic deformation in the structural evolution of the area is also evident if we observe the strong lateral variations, significant dips and vertical displacements of the various seismic units in the final model (figure 5). As expected for this area located on the front of the Hellenic margin, the most important structural features like the Vrachiona anticline in Zakinthos, the deep basin between Zakinthos and northwestern Peloponnesus and the carbonates under Peloponnesus, reflect the Alpine tectonic trends. However, the effects of the post-Alpine extentional tectonic activity can also be recognised in the formation of the basins in northwestern Peloponnesus and the east and west coast of Zakinthos. The contribution of salt tectonic activity associated with the Triassic evaporite formation, can also be considered as an important factor especially in the formation of the offshore basins.

Finally, it should be noted that the satisfactory results obtained using the Gaussian beam theory, in this area of strong lateral inhomogeneities introduced by the various stages of tectonic deformation, indicate that the method is capable in assisting the interpretation of deep refraction data in such areas.

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