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CRUSTAL STRUCTURE OF THE EASTERN MEDITERRANEAN INFERRED FROM RAYLEIGH WAVE DISPERSION

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Rayleigh wave group velocity data from paths crossing the Levantine Sea are presented. We have derived a suite of models for the crustal structure of the Levantine Sea for extreme values of data errors and of the data corrections which were applied in order to account for lateral heterogeneity.

We conclude that models with a crustal thickness less than 30 km are not consistent with the data. Our preferred models are characterized by a crustal thickness of 35–40 km. These results and the presence of an extremely thick sedimentary sequence point to a passive continental margin type of structure underlying the Levantine Sea. Additional data from the path Sicily–Jerusalem suggest that this type of structure is representative of the whole of the eastern Mediterranean (Levantine Sea *and* Ionian Sea).

1. Introduction

Knowledge of the crustal structure of the Mediterranean basins can provide important constraints for evolutionary models of the Alpine-Mediterranean region [1].

Most of the earlier geophysical investigations have concentrated on the western Mediterranean where, from surface wave studies [2] and refraction work [3], the presence of thin "oceanic" type of crust has been inferred.

The results of surface wave studies in the eastern Mediterranean by Payo [2,4] and Papazachos [5] yielded Moho depths of 23 and 19 km, respectively.

Since then, DSDP results [6] and extensive refraction surveys [7,8] carried out during the last few years have provided a considerable amount of information on the velocity-depth structure of the upper part of the crust in the eastern Mediterranean. However, the presence of a thick pile of sediments (often exceeding 10 km), including thick evaporitic beds, limit penetration of explosion generated seismic waves further down. Information on the position of the Moho is ambiguous, but the fairly large (minimum) thicknesses of crustal material detected and the widespread occurrence of a layer with "granitic" velocities (5.5–6.5 km/s) [7,9] indicate that the crust is not necessary of standard oceanic type.

In a previous paper [10] we have pointed out that group velocity analysis provides a powerful tool for investigations of crustal properties of passive margins. We showed that short-distance group velocity measurements, even with reduced accuracy, resolve the Moho depth to a precision of 5 km or better.

In the present paper we analyse Rayleigh wave group velocity data to investigate the average properties of the crust and the position of the Moho in the Levantine Sea. The results available now from refraction studies were incorporated in the starting models used for the inversion of the surface wave data.

2. Description of the data

2.1. Paths

For the investigation of the eastern Mediterranean we used events from the Dodecanese Islands, Crete and Sicily, recorded with the long-period instruments of the WWSSN stations Helwan (HLW) and Jerusalem

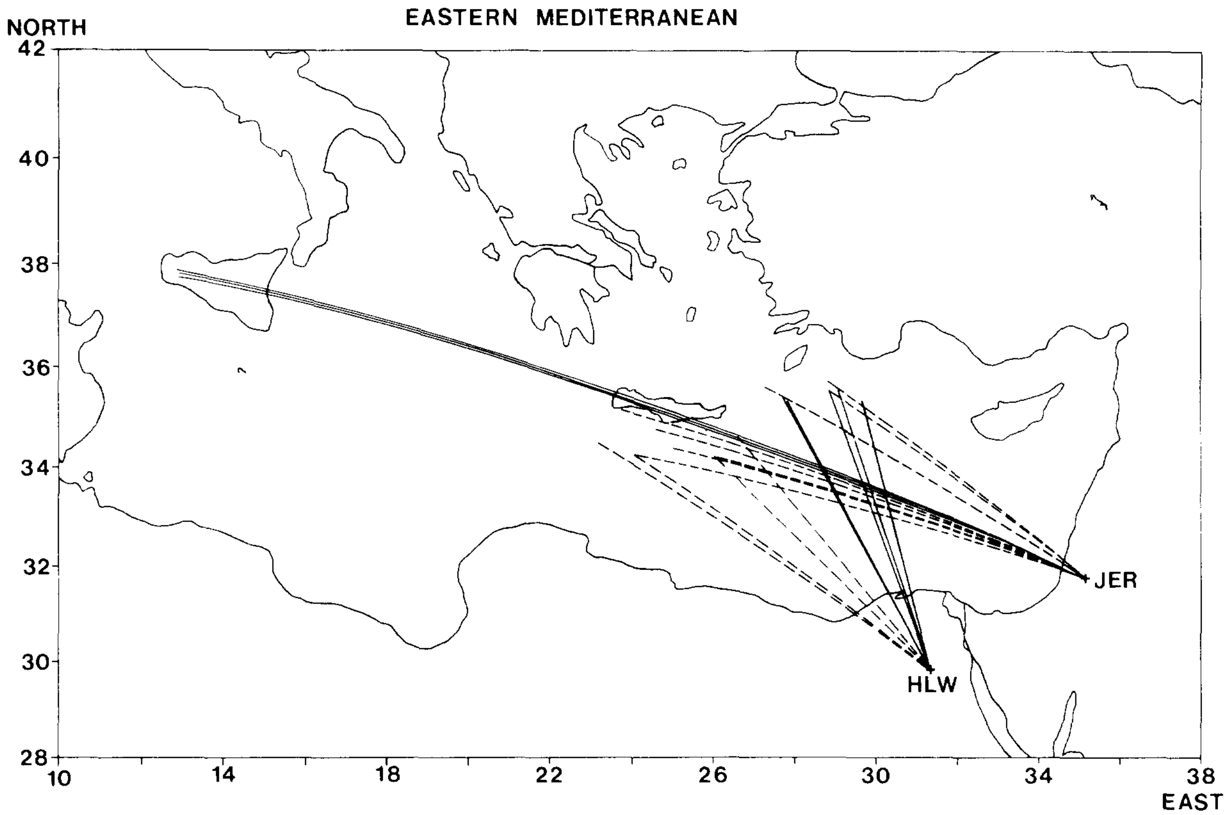

Fig. 1. Stations and great circle paths investigated in this study. The data from the paths indicated by solid lines are shown in Fig. 3.

(JER). The paths are shown in Fig. 1. Only the data of the paths perpendicular to the strike of the northern African margin and the long-period (periods longer than 30 seconds) data from the paths along the east-west axis of the eastern Mediterranean were of sufficient quality for further analysis.

As expected from theoretical considerations [11] the data from the paths crossing the margin at an angle showed a considerable scatter. The average level of these data, however, was consistent with the average data curve inferred from the other paths. In the following we confine ourselves to the data from the

TABLE 1

Events used in this study

Data	Origin time	Depth (km)	Δ (km)	Coordinates	Station
82764	19.31.59.7	38	672.8	35.56N, 28.84E	HLW
91864	00.08.47.6	40	659.1	35.59N, 29.07E	HLW
121163	07.06.32.0	73	632.7	35.38N, 29.64E	HLW
112271	19.26.45.7	34	692.2	35.34N, 27.81E	HLW
42564	12.44.15.0	61	708.7	35.46N, 27.70E	HLW
11568	02.01.04.1	3	2129.7	37.78N, 13.03E	JER
11668	16.42.46.0	25	2134.9	37.86N, 12.99E	JER
12568	09.56.46.0	4	2125.6	37.17N, 13.06E	JER

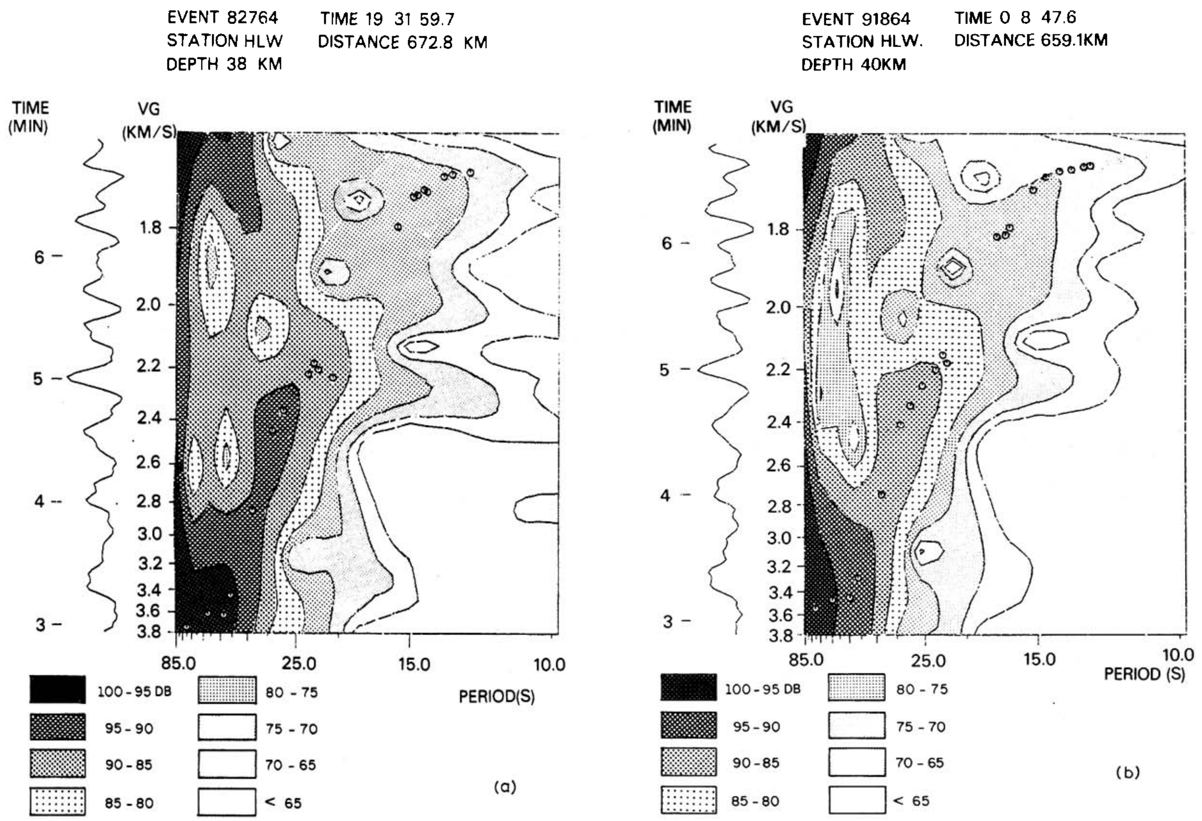

Fig. 2. (a) Time-energy diagram for the 27 August, 1964, event in HLW. Time is in minutes, velocity in km/s and period in seconds. The symbols ⊕ indicate the group velocities computed with the modified moving-window method [12]. (b) Time-energy diagram for the 18 September, 1964, event in HLW. Units and symbols as in (a).

paths Dodecanese Islands–Helwan (Levantine Sea) and Sicily–Jerusalem (Levantine Sea *and* Ionian Sea). The events are listed in Table 1.

2.2. Group velocities

Two of the events used in this study have also been analysed by Payo [4] with the classical peak-and-trough method. For the calculation of the group velocities we have used the more sophisticated modified moving-window technique [12]. Despite differences in measurement techniques, differences in the group velocities were found to be small. To give an impression of the quality of the data the time-energy diagrams of two of the events are reproduced in Fig. 2a, b. From the scatter of the frequency-corrected energy maxima (symbols ⊕) in these diagrams we estimate uncertainties of 0.10–0.15 km/s in the group velocities. The errors in the data may have several causes of which the presence of noise, due to reflected and multipathed phases, is probably the dominating factor [10]. The group velocity data, including the errors, are given in Fig. 3.

3. Inversion and results

3.1. Dodecanese Islands–Helwan

For the inversion of the Dodecanese Islands–Helwan group velocities we used a wide range of starting models all having the same set of layer velocities but differing in layer thicknesses and Moho depths. The compressional velocity-depth structure of the upper part of the crust is adopted from the refraction results. The rati of compressional velocity and

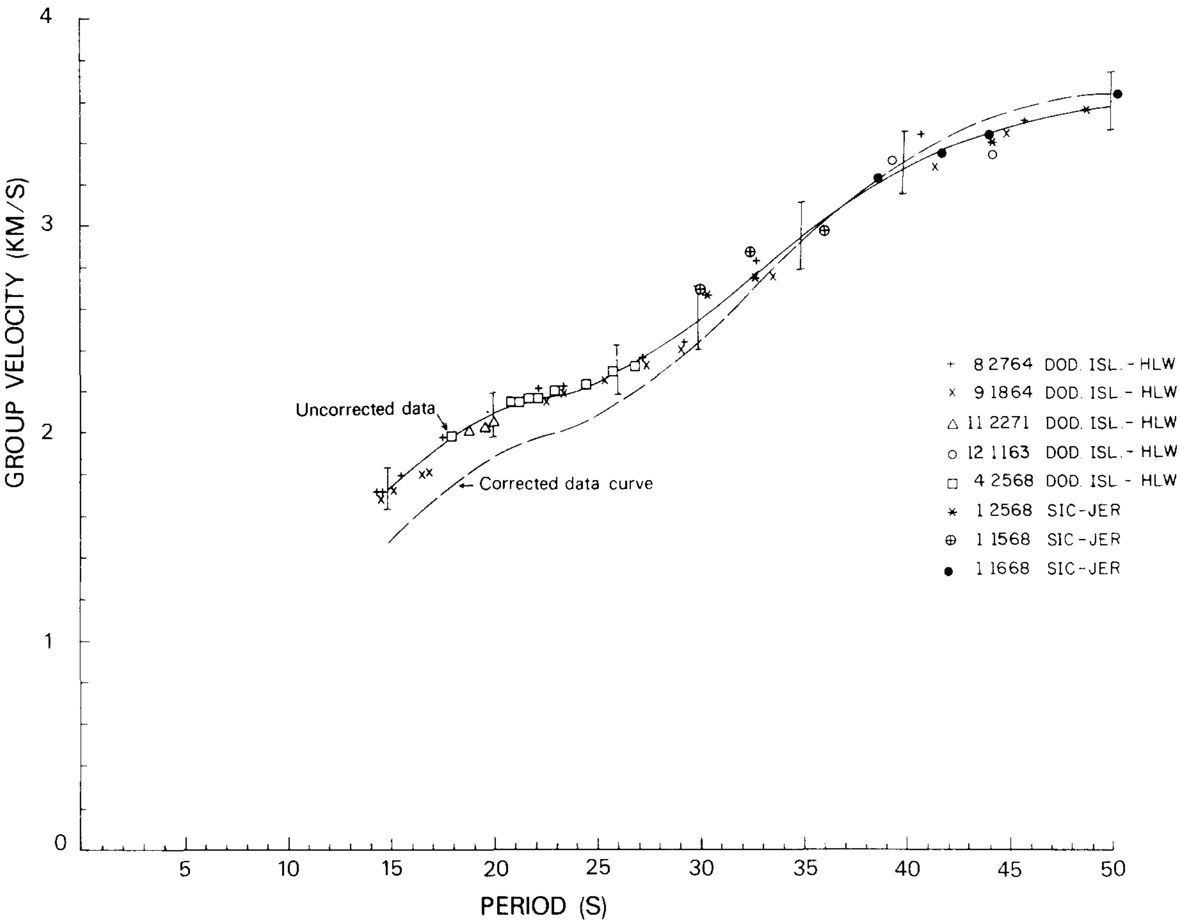

Fig. 3. Group velocity data from the paths Dodecanese Islands–Helwan and Sicily–Jerusalem. Average dispersion curves for the uncorrected data and the Dodecanese Islands–Helwan data corrected for northern Egypt.

shear velocity in the Pliocene-Quaternary sediments was fixed at a value of 2, a value considered to be appropriate for unconsolidated sediments [13]. In the other parts of the upper crust variarions in this ratio were allowed. For the deeper parts of the crust the compressional and shear velocity were coupled by a Poisson's ratio of 0.25. The crustal thicknesses of the starting models cover the range 25–45 km, in steps of 5 km. On top of our models a water layer of 2.5 km is present and the crustal thicknesses mentioned here and hereafter refer to the *solid* crust.

The approach of using different starting models is preferable to varying the depths during the inversion, because the dependence of the dispersion on the depth of some of the interfaces is highly non-linear [14].

In every starting model we perturbed the P- and S-velocities (keeping Poisson's ratio fixed) to obtain the best possible fit to the group velocities for the given layer geometry, using a Backus-Gilbert type of inversion. The inversion of the uncorrected data showed us that only models with a thickness of the solid crust of 30 km or more, gave acceptable fits to the measured group velocities. This is about 10 km thicker than the value reported by Payo [2,4] and Papazachos [5].

One of the causes that must be considered as an explanation for this descrepancy is that part of the wave path crosses the African continent, since the station HLW is located about 200 km inland. One may tackle this kind of problem by correcting the group arrival time of the wave for the time needed to travel over the continental part of the path. If this part is short with respect to the total path length, the accuracy of the travel time corrections is not very important. However, in this study, the continental part of the path makes up about 30% of the total epicentral distance. This means that we need to know the group velocities over the continental part with quite high accuracy, if we want to correct for it.

Although the upper part of the Egyptian crust, north of Helwan, is known from Soviet geophysical studies (summarized in Malovitskiy et al. [15]) and borehole data [16], many uncertainties remain. The thickness of the sedimentary sequence varies; its average thickness is about 5 km. However, it may be necessary for an adequate correction, to include the Egyptian continental shelf in the calculations, in which case the average sedimentary thickness is 6 km over a longer correction path length.

Information on the deeper part of the crustal structure is not at hand. To allow for our lack of knowledge we studied the effect of different correction models on the data. A range of correction models for northern Egypt was constructed through superposition of a sedimentary sequence on top of models for the crust and upper mantle. The latter are based on the AFRIC model given by Gumper and Pomeroy [17] for the African shield and differ only in the velocities of the subsedimentary crustal layers.

It appears that every possible correction for northern Egypt lowers the group velocities over the Levantine Sea for periods up to 38 seconds. Thus the data corrected for northern Egypt, yield an even greater crustal thickness for the Levantine Sea than the uncorrected data. To illustrate how the correction for northern Egypt affects the original data curve, we give in Fig. 3 the corrected curve obtained with the "slowest" Egypt model. In view of the large uncertainty attached to our correction procedure, we have

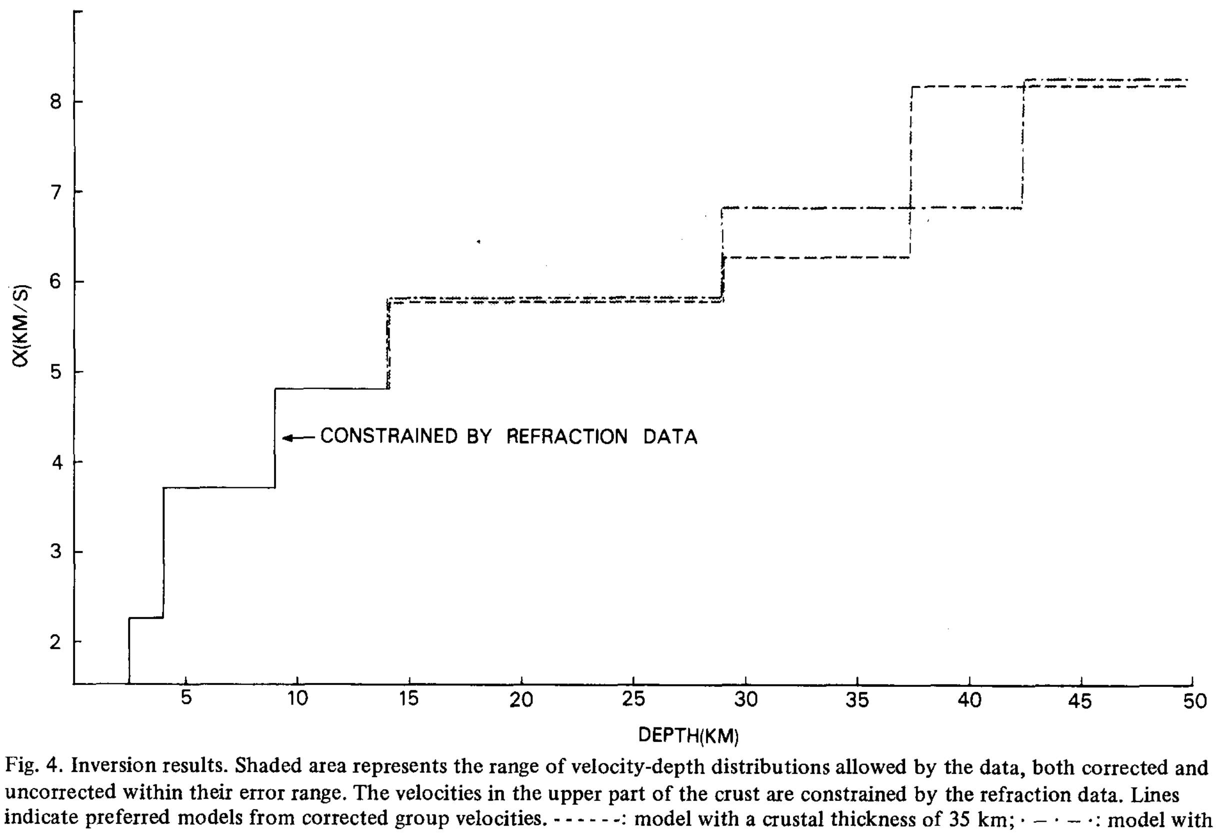

Fig. 4. Inversion results. Shaded area represents the range of velocity-depth distributions allowed by the data, both corrected and uncorrected within their error range. The velocities in the upper part of the crust are constrained by the refraction data. Lines indicate preferred models from corrected group velocities. - - - - - -: model with a crustal thickness of 35 km; · — · — ·: model with a crustal thickness of 40 km. For the deeper part of the crust compressional and shear velocities are coupled by a Poisson's ratio of 0.25.

taken a conservative approach to the data inversion.

For the determination of the crustal thickness we have inverted two extrema data curves (shown in Fig. 3) for: (1) the uncorrected data with the uncertainties in the data added to it; (2) the data corrected with the "slowest" model for Egypt with the uncertainties subtracted.

The range of models resulting from the inversion is given by the shaded area in Fig. 4. We found that models with a crustal thickness less than 30 km are not consistent with the data. Moreover, all models with crustal thicknesses of 30 km are characterized by low-velocity layers just above the Moho. Although models with low-velocity layers in the crust have been advocated [18], no geophysical evidence has as yet been found that support the presence of lower crust material with velocities just above the Moho as low as 5.60 km/s. These low velocities are difficult to reconcile with petrological models of the lower crust [19]. All models without such a low-velocity layer are characterized by a crustal thickness of *at least 35 km.* These results apply for both the corrected and the uncorrected "extremal" data sets. Two models, with crustal thicknesses of 35 and 40 km and an excellent fit to the corrected data, have been selected, in part on subjective grounds, to give an idea of the actual velocity-depth distribution found in the inversions.

3.2. Sicily–Jerusalem

The high values that we found for the crustal thickness in the Levantine Sea stimulated us to investigate whether these results are only locally valid, or whether a large part or all of the eastern Mediterranean has a crustal structure of this type. To this end we undertook a similar group velocity analysis of recordings in Jerusalem from three events in Sicily. The paths of these waves sample the crust under the Ionian and Levantine Seas. At periods longer than 30 seconds, the Sicily–Jerusalem data are in excellent agreement with the Dodecanese Islands–Helwan group velocities (Fig. 3).

Unfortunately, the lack of short-period data, presumably due to scatting in the upper crust, precludes a detailed analysis of the data set. Thus, all that can be inferred from the Sicily–Jerusalem data is that they do not provide compelling evidence against a westward extension of the structure found beneath the Levantine Sea.

4. Discussion

A crustal thickness of 35–40 km for the Levantine Sea inferred from our surface wave study points to a continuation of the northern African crustal structure under this sea, and possibly under the whole of the eastern Mediterranean. This view is supported by the continuity of geological features, notably the fault systems, and the trends of gravity and magnetic anomalies [8].

Our results are at variance with those of Payo [2,4] and Papazachos [5]. An important point appears to be that these workers hardly had any refraction data at their disposal, as until 1971–1972 these data were extremely scarce (see Ryan et al. [20]). Model velocities for the upper part of the crust had to be assumed on the base of presumed geological similarity of the eastern Mediterranean to other areas (notably the Gulf of Mexico).

Recently Papzachos and Comninakis [21] revised the Papazachos [5] model, incorporating the present-day available refraction data. The crustal thickness of their new model is 21.4 km. We have calculated the group velocities for this model, assuming a Poisson's ratio of 0.25 and found that this model is by far not consistent with our data. A satisfactory fit, however, can be obtained if we retain the upper part of the model and change the crustal thickness from 21.4 to 35 km.

In addition to the supporting evidence mentioned above it is interesting to note that the preliminary refraction results of the seismic project Egypt-Crete carried out recently by the Hamburg group (L. Möller, personal communication) also points to a considerably thicker crust under the Levantine Sea than hitherto assumed.

In a paper, presented at the School for Applied Geophysics in Erice, 1980, P. Faruggia argued on the basis of preliminary results from a surface wave study in the Ionian Sea area that there, too, the crust must be of a thickness comparable to the values found in this study.

On this other hand, results obtained by Makris [22] and Weigel [23] point to significant local variations in the crustal structure beneath the Ionian Sea, with reported values for the Moho depth as low as 18 km in the central Ionian Sea.

The dispersion curve measured for our eastern Mediterranean paths is similar to the ones for the Barents Sea [24] and the Italian Adriatic region [25]. These areas are all characterized by the presence of a very thick sedimentary sequence and crustal thicknesses of 35–40 km. The present results for the eastern Mediterranean point to a close analogy in crustal structure of these areas.

Although a crustal thickness of 35–40 km is a feature typical of continental models this structure is different from a standard continent by the presence of the extremely thick sedimentary sequence. In that respect the structure of the Levantine Sea (and possibly of the whole of the eastern Mediterranean) resembles a continental margin structure of the Atlantic type.

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