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Seismic refraction profiles between Cyprus and Israel and their interpretation

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Summary. A long seismic refraction profile was carried out between southern Israel and Cyprus. The seismic energy was generated by 33 sea shots each of 0.8 t explosives and was recorded by land stations in Israel and Cyprus and by ocean bottom seismographs deployed along the profile.

The results showed that the continental crust of southern Israel thins towards the Mediterranean underneath a northward thickening sedimentary cover. Cyprus is underlain by a 35 km thick continental crust thinning southwards and extending to Mt Eratosthenes. Between Mt Eratosthenes and the Israel continental shelf the crystalline crust is composed of high velocity (6.5 km s^{-1}) material and is about 8 km thick. It is covered by 12–14 km of sediments and may represent a fossil oceanic crust.

1 Introduction

The Eastern Mediterranean has long been recognized as a tectonically complex region. It is still considered one of the least understood areas in spite of numerous geophysical surveys conducted there in recent years. In particular the origin and nature of the Eastern Mediterranean crust has been disputed. Most of the seismic soundings carried out there have failed to produce information on the deep crustal structure due to the intensive tectonization and the large thickness of sedimentary layers which overlie the crystalline crust. In general, some scientists believe the crust is continental (e.g. Malovitsky *et al.* 1975; Woodside 1977), while others claim it is oceanic (e.g. Ryan *et al.* 1976) or a mixture of both (Nur & Ben Avraham 1978) and that its thickness varies between 25 and 28 km. A comprehensive summary of the present state of knowledge is given by Lort (1977).

The extent of the sedimentary sequence and the ages involved are also not very well known. As a result, a large number of speculations regarding the age of the basal sediments and even their depth have been published in recent years. The velocities were not very clearly observed and no seismic velocities typical of oceanic layer 3 (about 6.6–6.9 km s^{-1} according to Condie 1976) were reported in previous works. In a recent seismic refraction study of southern Israel and northern Sinai, a marked thinning of the crust towards the Mediterranean Sea was noted, accompanied by a thickening of the sedimentary column in the same direction (Ginzburg *et al.* 1979). Based on onshore and offshore well data and multichannel seismic data in Israel and northern Sinai, Ginzburg & Gvirtzman (1979) concluded that the base of the sedimentary prism overlying the transition zone and the oceanic crust is of Lower Cretaceous (Albian) and possibly Jurassic age. The results published so far for the Eastern Mediterranean basin show a large variability and are inconclusive.

In order to provide answers to the questions regarding the nature and the deep structure of the crust in the Eastern Mediterranean between Israel and Cyprus, a long range refraction experiment was conducted in 1978 October.

The programme was based on a cooperative effort by the following institutions: the Institute of Geophysics of the University of Hamburg, the Oceanographic and Limnologic Research Ltd of Israel, the Institute of Geophysics of the Free University of Berlin, the Department of Geophysics and Planetary Sciences, Tel Aviv University, the Institut de Physique du Globe, Pierre et Marie Curie Université, Paris, the Institute of Oceanographic Sciences, Wormley, and the Geological Survey of Cyprus, Nicosia. (Abbreviations are: IfG, Hamburg; OLRI, Haifa; IfG-FU, Berlin; DGPS, Tel Aviv; IPG, Paris; IOS, Wormley; GSC, Cyprus.)

2 The experiment

Shotpoints and seismic recording stations are shown on the location map (Fig. 1). The experiment comprised 33 shots fired in the Mediterranean between southern Israel and western Cyprus. The entire marine operation was carried out by *R/V Shikmona*.

The charges fired were 800 kg each. They were suspended at a depth of 80 m from a buoy and detonated from the ship by remote control at 2 hr intervals. Their positions were determined by a *Magnavox* land satellite navigation system, when a satellite pass was available, and by dead reckoning between satellite fixes. Water wave travel times to the ocean bottom seismographs (OBS) were used to check the shot positions.

The shots were recorded on land by mobile seismic stations of the MARS 66 type provided by Hamburg University and the Free University of Berlin. Fourteen such stations were placed in the Negev, re-occupying the sites used in the 1977 refraction experiment (Ginzburg *et al.* 1979). Nine stations were deployed in western Cyprus along the main road leading from Paphos to Polis.

In addition to the land stations, six ocean bottom seismographs were distributed at roughly equal distances between the Israeli continental shelf and the Eratosthenes seamount.

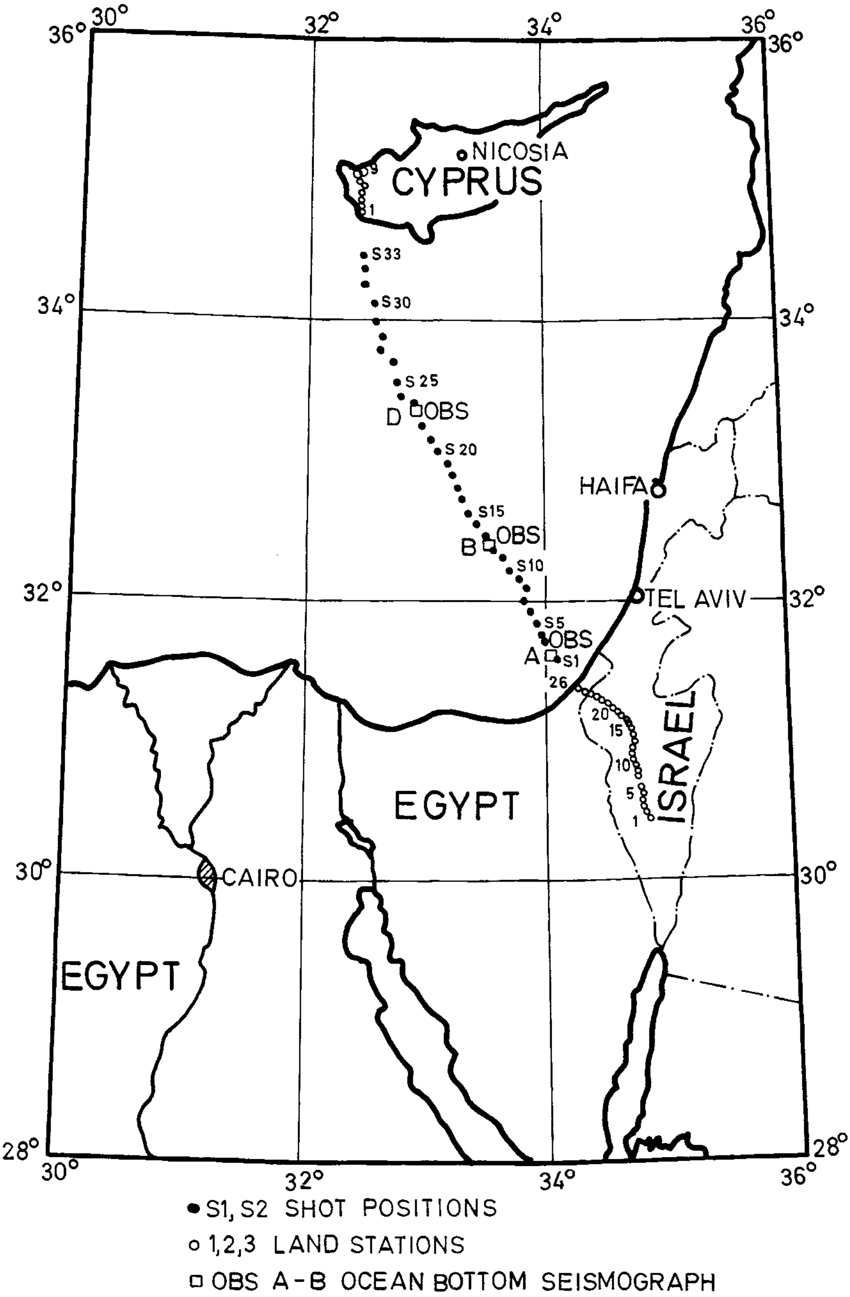

Figure 1. Distribution of shots and stations between Israel and Cyprus.

The ocean bottom seismographs were constructed, provided and operated by the IPG, Paris and the IOS, Wormley.

The time base for the experiment was provided by two mobile transmitters, one in Israel and one in Cyprus, which transmitted a coded timing signal, synchronized with the Moscow time signal, to the land stations. Digital quartz clocks, also synchronized with the Moscow time signal, provided the time base for the time break station on board *R/V Shikmona* and for the ocean bottom seismographs.

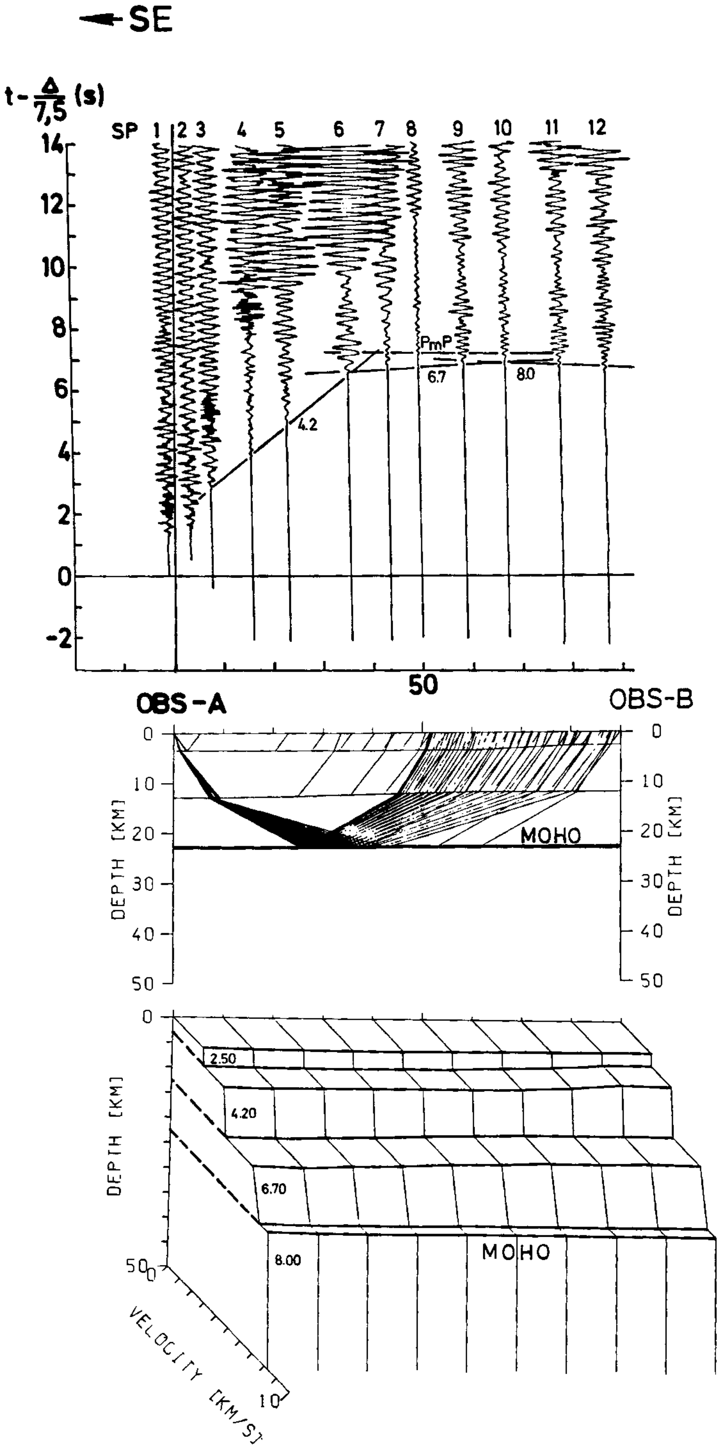

Figure 2. OBS–A: Travel-time plot and model developed by ray-tracing.

3 The data – general remarks

The quality of the land seismic data, which were recorded on analogue tape, was generally good. These recordings were played back, filtered and plotted using a 6.0 km s^{-1} reduction velocity with normalized amplitudes. The OBS data were digitized and plotted at the IPG, Paris and filtered record sections were constructed using a reduction velocity of 7.5 km s^{-1} (Figs 2, 3 and 4). These record sections show all shots into each of the three OBS which functioned properly.

Two types of record sections for the land data were constructed. One shows individual shots recorded by all stations (Figs 7, 8 and 9) and the other shots recorded by individual land stations (Figs 5, 6, 10 and 11). This provides reversed profiles for different segments of the refracting horizons. Information on the near surface parts of the crust was obtained from the OBS data.

Several refracted events were correlated on the record sections. On the OBS sections

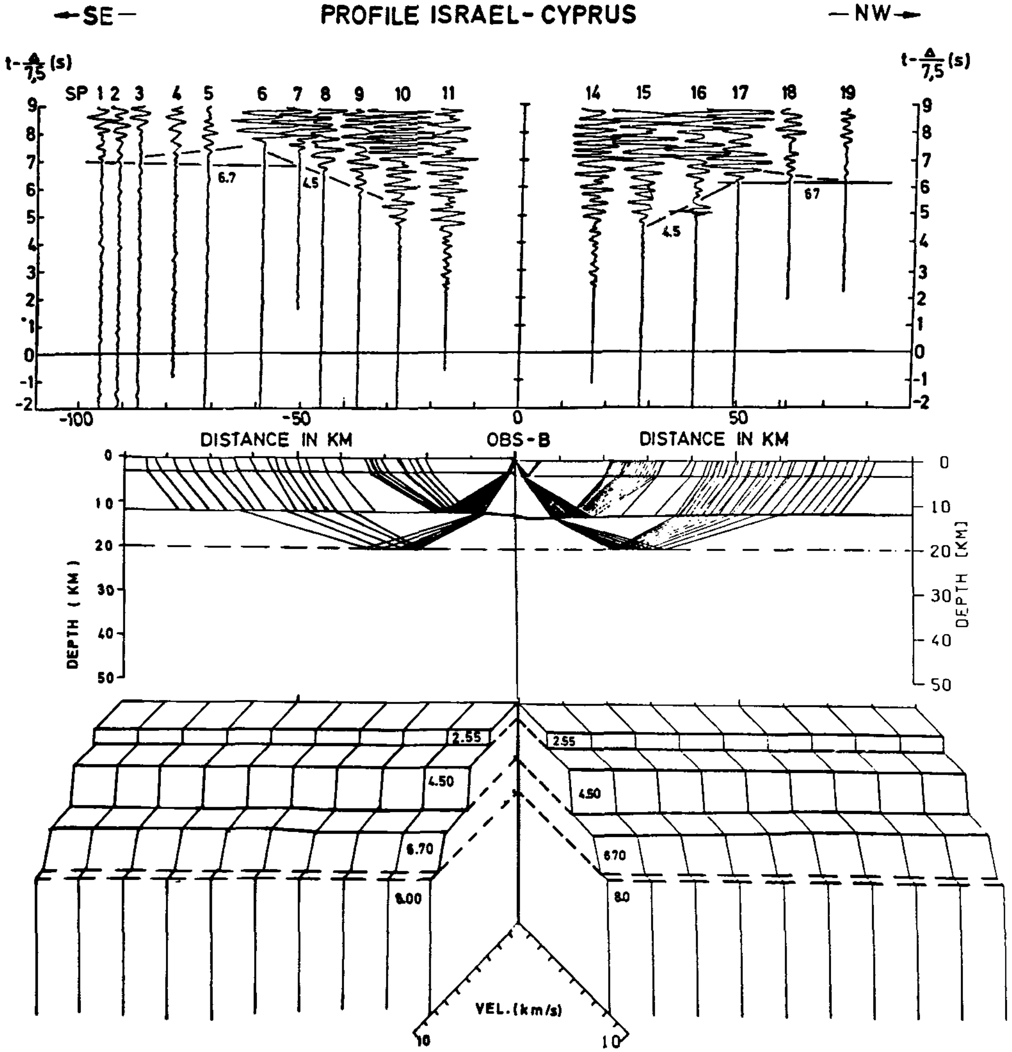

Figure 3. OBS–B: Travel-time plot and model developed by ray-tracing.

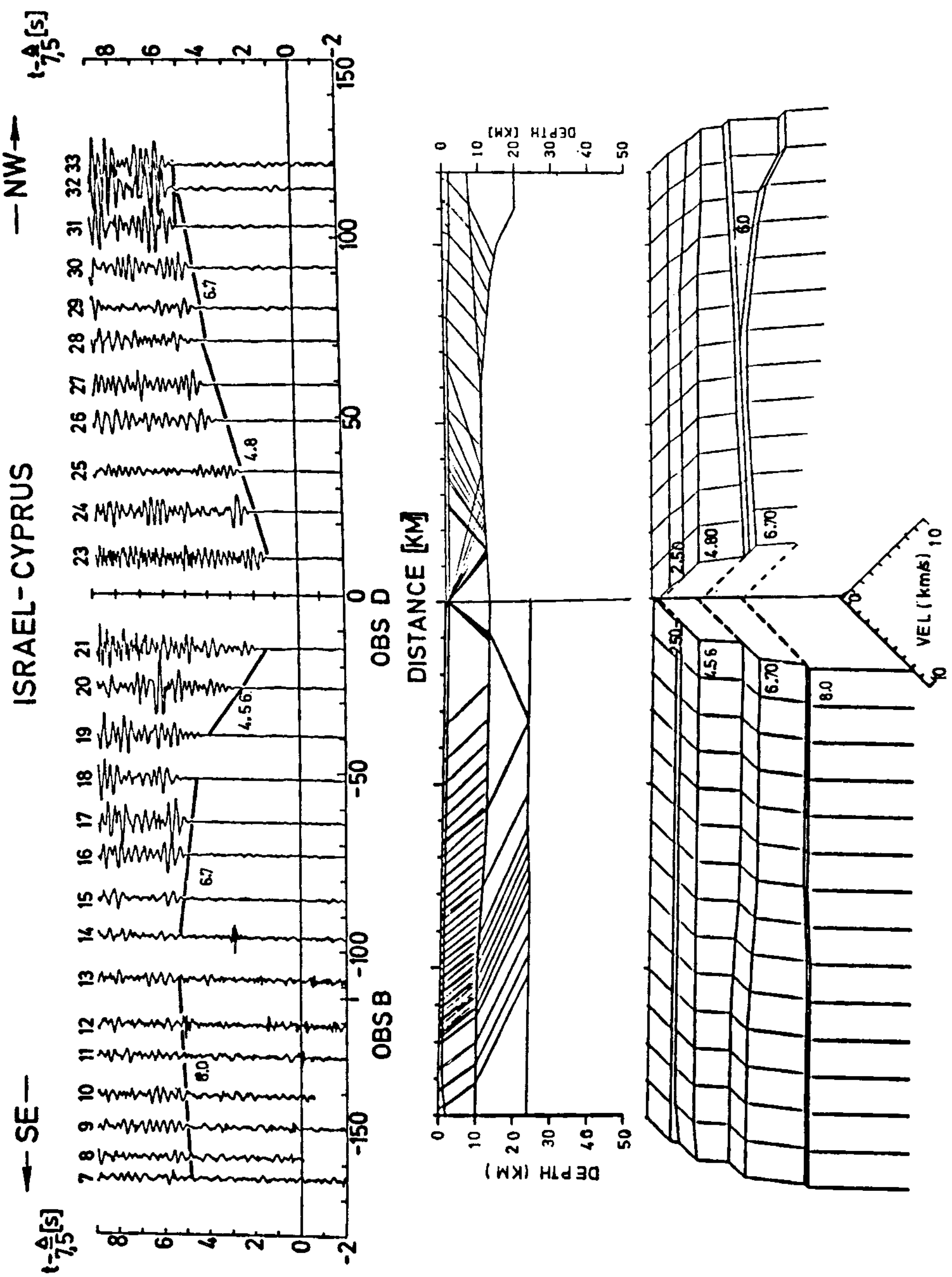

Figure 4. OBS–D: Travel-time plot and model developed by ray-tracing.

seismic arrivals refracted from the sedimentary sequences were identified having apparent velocities of 3.4–5.0 km s^{-1}. These are followed by arrivals with apparent velocities of 6.5–7.0 km s^{-1} representing energy critically refracted in the crystalline basement (P_g). Events recorded beyond 50 km show apparent velocities above 8.0 km s^{-1} identified as the P_n Moho branch (Figs 2, 3 and 4).

Record sections from land recordings, both in Israel and Cyprus, show P_g arrivals with apparent velocities of about 6.0 km s^{-1} (Figs 5, 6, 7, 8, 10 and 11) and P_n arrivals with velocities of about 8.0 km s^{-1}.

The various travel-time branches, which were identified on the record sections, form the basis for the interpretation presented below.

4 Results

Preliminary interpretation of the record sections was carried out by simple model calculations using apparent velocities and intercept times. The preliminary models and the calculated true velocities were used as an initial input into a ray tracing program (Makris 1977), which was used to adjust the parts of the models corresponding to the forward and reversed profiles for the various segments of the refraction line. The results are presented

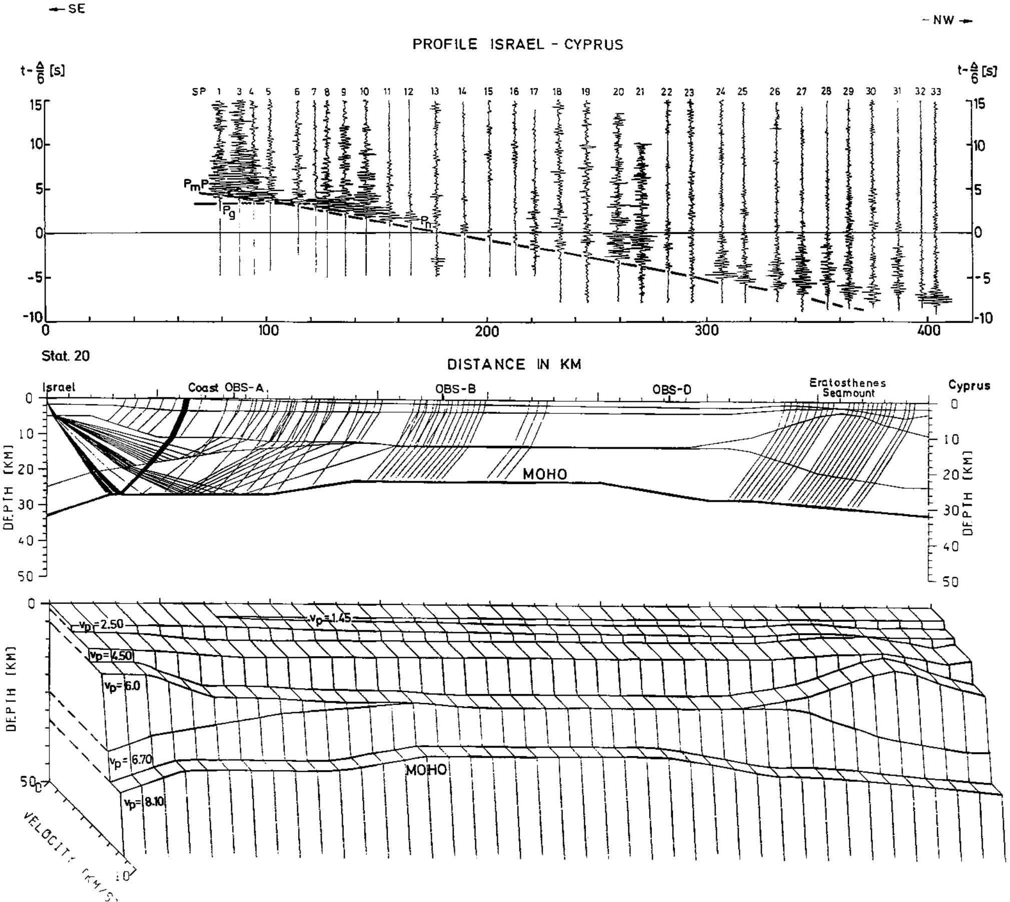

Figure 5. Seismogram section and crustal model of the Levantine Basin developed by plotting all shots recorded by Station 20 on Israel.

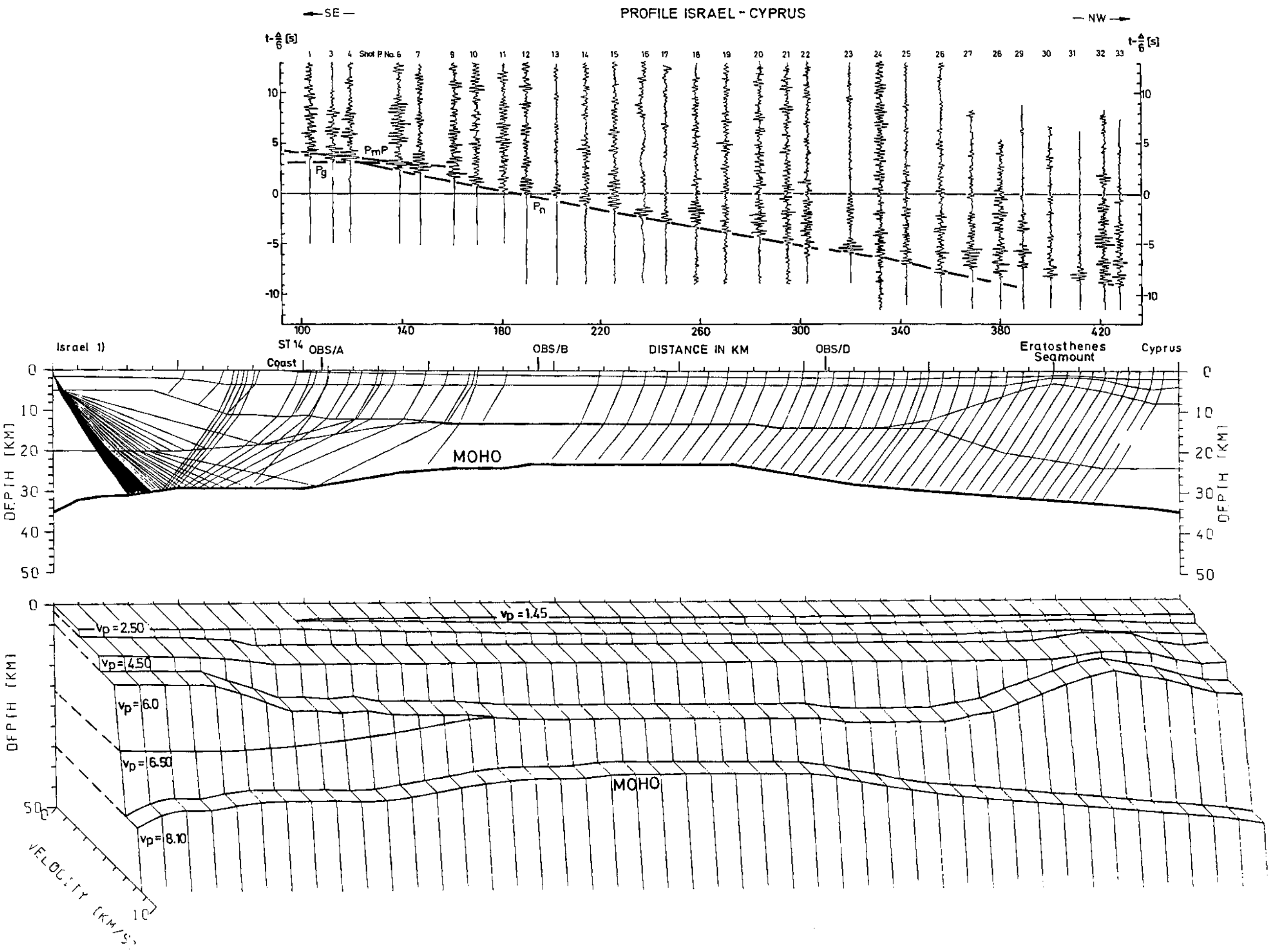

Figure 6. Seismogram section and velocity–depth distribution developed by ray-tracing. All shots were recorded by Station 14 on Israel. (1 indicates data from Ginzburg *et al.* 1979.)

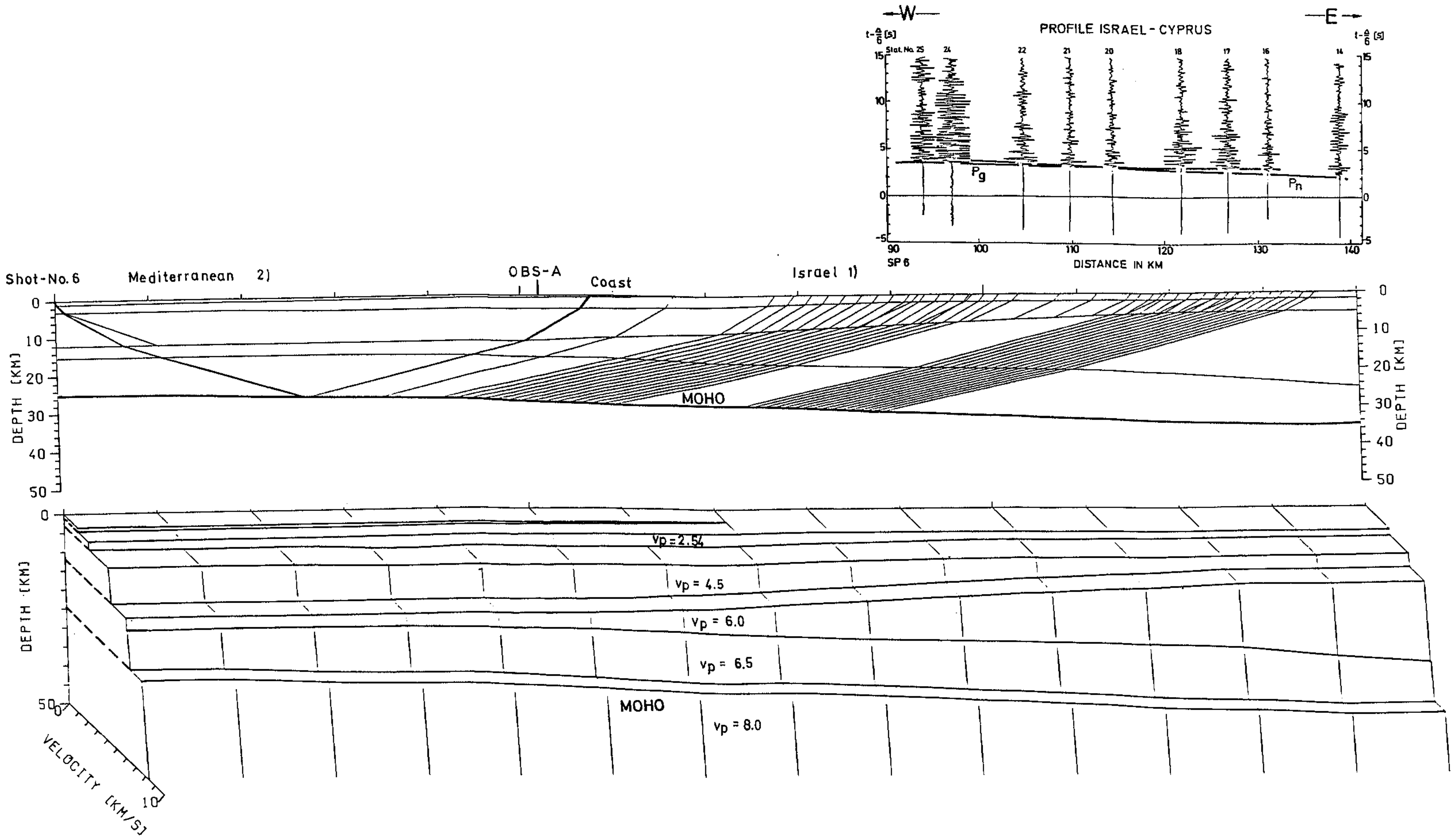

Figure 7. The ocean–continent transition between the Levantine Basin and Israel. The velocity–depth model was developed by using all recordings on the land stations in Israel from shot 6.

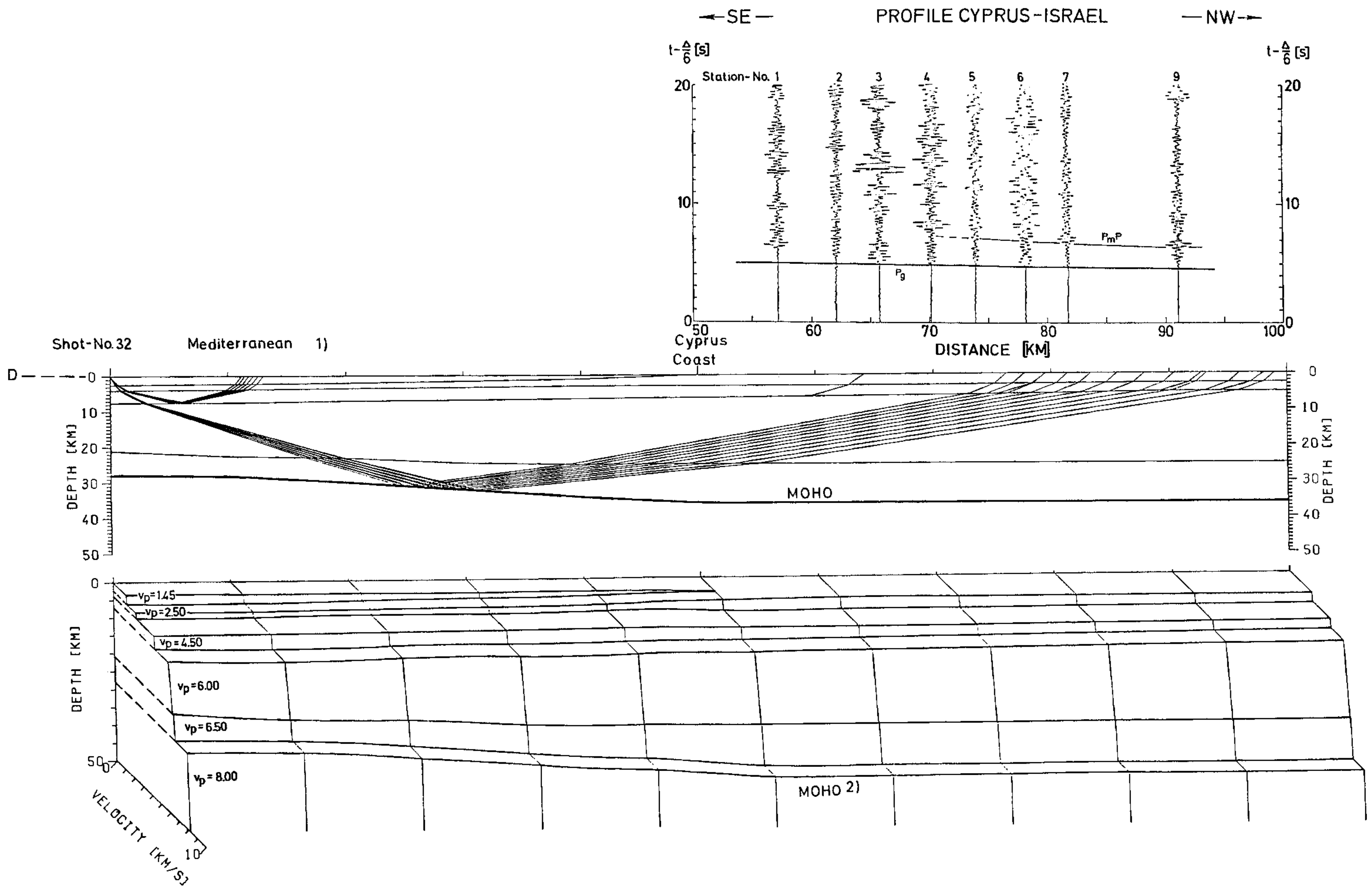

Figure 8. Travel-time plot of seismic recording obtained on Cyprus by land stations 1 to 9 of shot no. 32. The crustal model was developed by ray-tracing using the results of Figs 5 and 6. **(1 indicates data from OBS–D; 2 indicates Moho depth from shot no. 21.)**

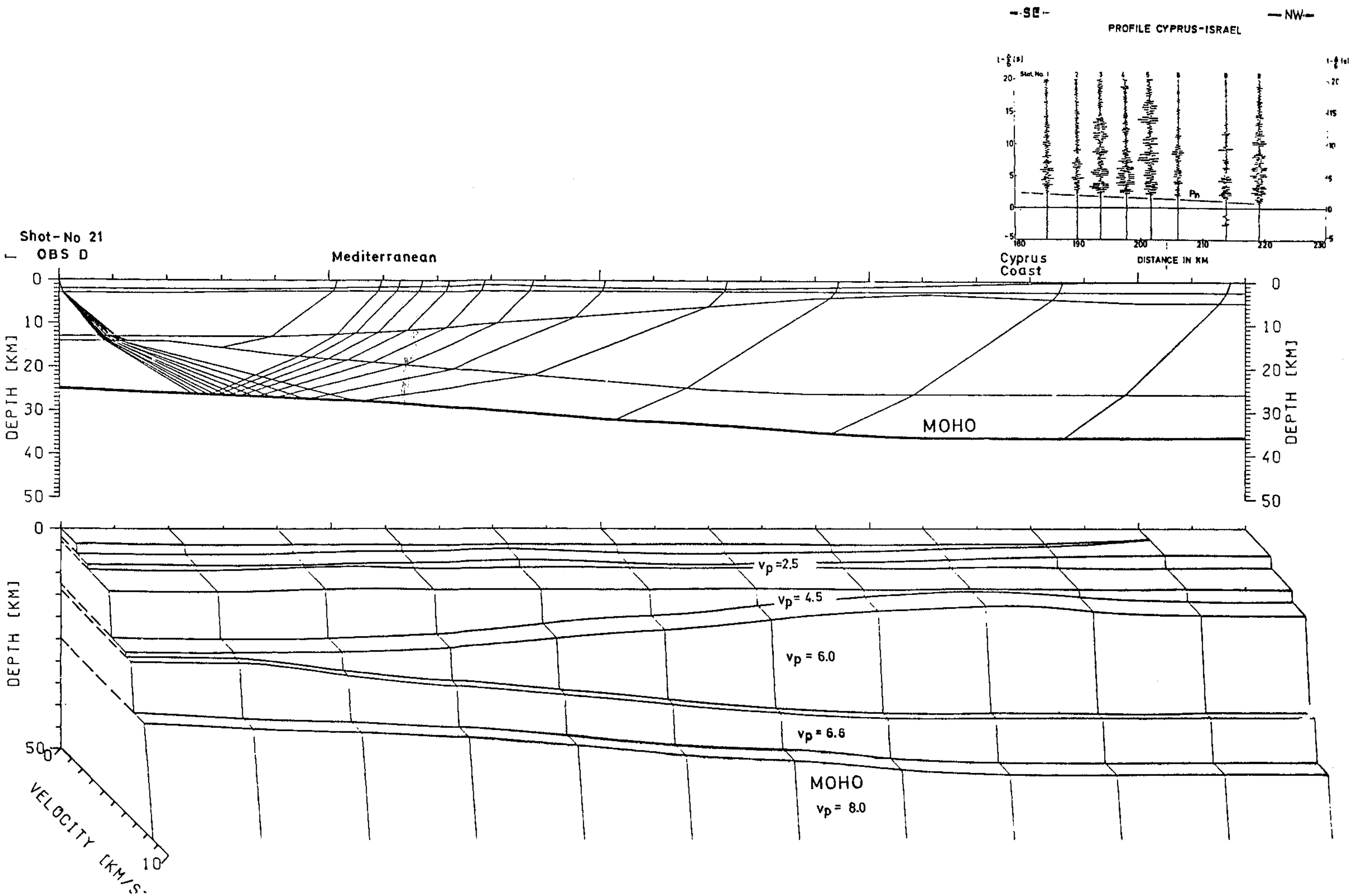

Figure 9. Travel-time plot of seismic recordings obtained in Cyprus from stations 1 to 9. The shot no. 21 gives information of the P_n-arrivals only. The P_n apparent velocity is 8.0 km s^{-1}.

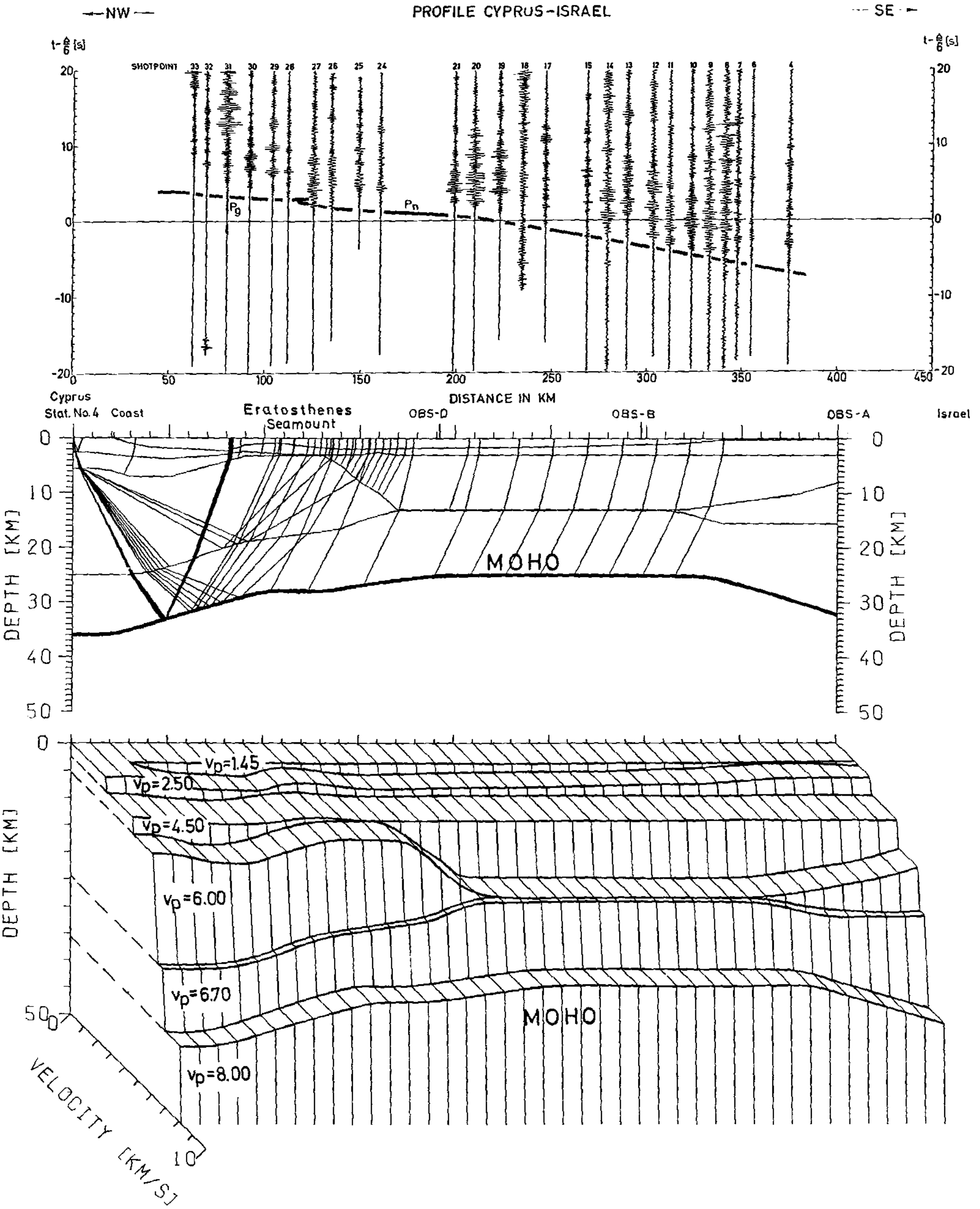

Figure 10. Travel-time plot and velocity–depth model of the Eratosthenes Seamount and the deep Levantine Sea developed by ray tracing from all shots recorded at station 4 on Cyprus.

in three parts corresponding to the OBS observations, those of the land stations in Israel and the corresponding data from Cyprus.

4.1 OBS OBSERVATIONS

The main information obtained from the OBS data concerns the sedimentary cover between the continental shelf of Israel and the Eratosthenes seamount. Between OBS A and B the

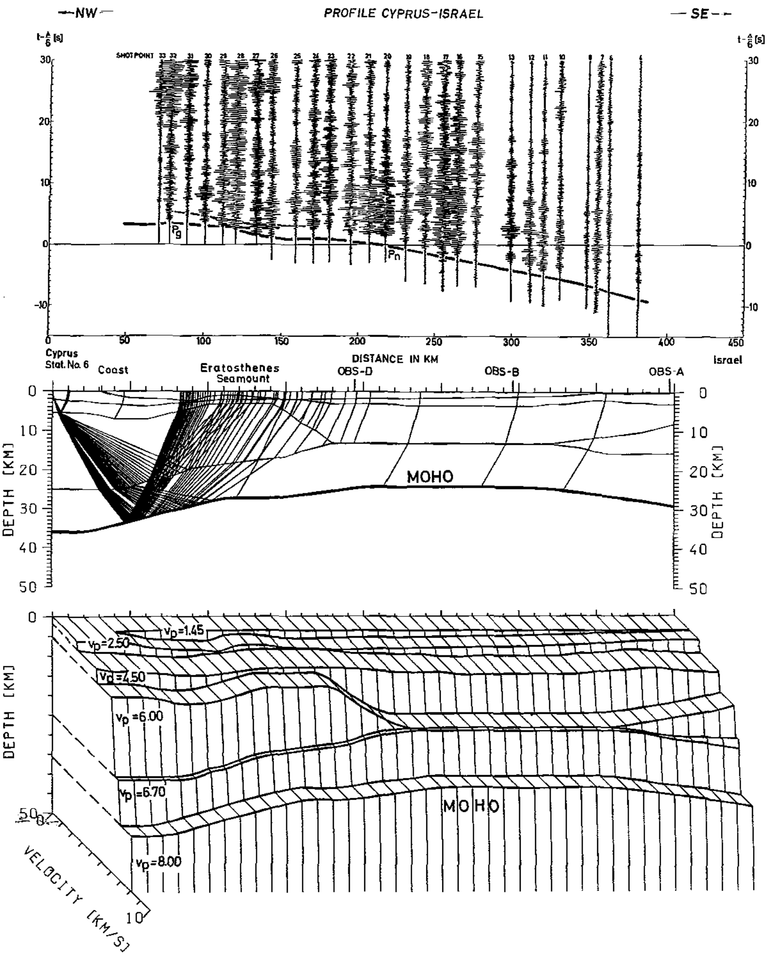

Figure 11. Travel-time plot and velocity–depth model of the Eratosthenes Seamount and the deep Levantine Sea developed by ray tracing from all shots. The recordings were obtained at land station no. 6 on Cyprus.

following velocities were obtained from reversed profiles: 4 km of 2.5 km s^{-1}. The total sedimentary section has a thickness of 12 km (Figs 2 and 3), which is consistent with results obtained in previous investigations (Ginzburg *et al.* 1979).

As is known from other geophysical and geological studies (Ginzburg & Gvirtzman 1979) the distribution of the Pliocene evaporites begins not far north of the Israeli continental shelf, the beds thickening considerably to the north. It is possible that the 4.2 km s^{-1} velocity represents the top of the evaporites, in which case the presence of low-velocity material below cannot be detected by refraction. Therefore, the thickness of the sedimentary column computed is most probably minimal.

The sedimentary cover overlies a layer with a velocity of 6.7 km s^{-1}, which corresponds to the crystalline crust. Its thickness is approximately 10 km. Between OBS B and D the seismic structure is similar to the one described above (see Fig. 4).

North of OBS D, as the Eratosthenes seamount is approached, an abrupt change occurs. The upper low velocity (2.5 km s^{-1}) part of the sedimentary section thickens northwards, while the 4.5–5.1 km s^{-1} sedimentary layer thins, and its base is located at shallower depths in the vicinity of Eratosthenes. The depth to the 6.7 km s^{-1} layer increases northward

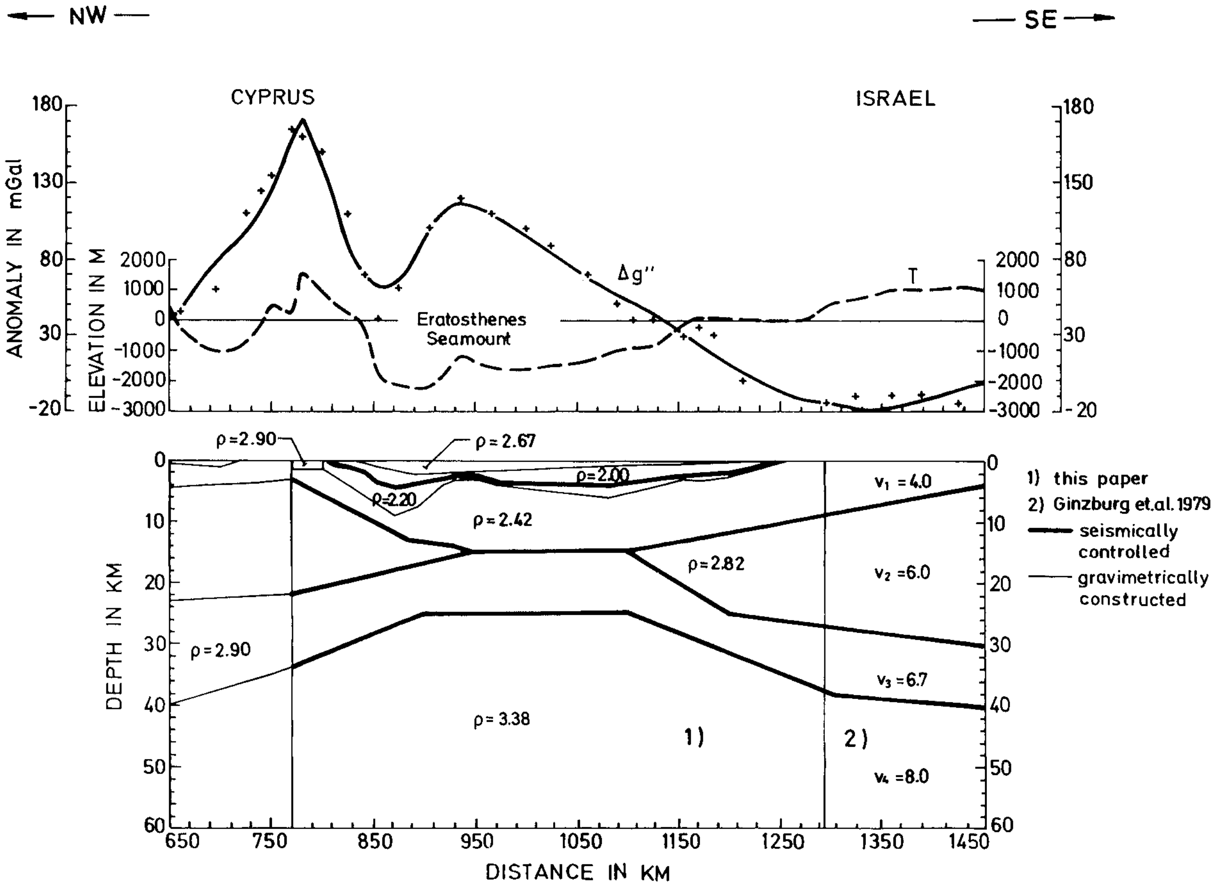

Figure 12. A composite crustal model between Cyprus and Israel based on gravity data and constrained by seismic velocities and discontinuities. T = topography, $\Delta g''$ = computed and interpolated Bouguer values, + = observed Bouguer values.

(Fig. 4) possibly due to the appearance of the 6.0 km s^{-1} layer identified on the Cyprus land station sections. On the record sections of OBS A and D (Figs 2 and 4) probable upper mantle P_n arrivals were identified with an apparent velocity of 8 km s^{-1}. Total crustal thickness computed using all the OBS data is about 23 to 24 km. Based on the above data, the long sections of the land seismic stations were interpreted mainly in terms of depth to the crust–upper mantle boundary.

4.2 ISRAEL LAND OBSERVATIONS

Figs 5 and 6 present record sections of all the sea shots recorded at stations 20 and 14 in Israel. The P_g velocity on both sections is 6.0 km s^{-1} and is in agreement with the velocity structure observed by Ginzburg *et al.* (1979). As can be readily seen on the record sections of Figs 5 and 6 the 6.0 km s^{-1} layer can be traced in the continental shelf off Israel to about the location of OBS A. It is evident from the OBS A data that this velocity is missing north of OBS A. It can therefore be concluded that the thinning of the upper crust noted from onshore data by Ginzburg *et al.* (1979) continues northward and that the 6.0 km s^{-1} continental upper crust disappears completely near OBS A. The models shown in Figs 5 and 6 are based on this conclusion.

The P_n arrivals correlate in both sections with an apparent velocity of 8.0 km s^{-1}. This apparent velocity is identical with the apparent velocity observed in the reversed direction both at OBS A and OBS D, and therefore 8.0 km s^{-1} is the true upper mantle velocity below the marine part of the profile. This seismic phase can be followed from a distance of 110 km to approximately 350 km. Beyond this distance strong arrivals of a new seismic phase correlating at a lower apparent velocity can be seen in Fig. 5. This event is probably a reflexion from a first order discontinuity within the lithosphere. By using the results obtained from the OBS evaluation and the crustal structure below Israel (Ginzburg *et al.* 1979) a model of the crust between Israel and the Eratosthenes seamount was developed. This model was also checked by travel-time computations for record sections of individual shots into all land stations. An example of such a computation is shown in Fig. 7. In this model the continental crust thins from 32 to 28 km at the coastal area. At the central part of the section the total crustal thickness is only 24 km and the high velocity crystalline part of it is approximately 10 km thick. Toward the Eratosthenes seamount the crustal thickness increases again.

4.3 CYPRUS LAND OBSERVATIONS

By combining the calculated models derived from the record sections for shots 32 and 21 (Figs 8 and 9) and by using the results of the crustal structure developed previously, a first approximation of the crustal conditions below Cyprus can be deduced. These results indicate that the crustal structure of Cyprus is continental.

This is further validated by the data shown in Figs 10 and 11. These record sections of all sea shots recorded at stations 4 and 6 show P_g arrivals of 6 km s^{-1}. The computed model shows that the continental structure of Cyprus extends to the Eratosthenes seamount.

The data of OBS D discussed previously indicate that south of the Eratosthenes seamount the 6.0 km s^{-1} layer is missing. It can be concluded, therefore, that this layer thins rapidly between Eratosthenes and OBS D and that the transition from a continental to a thin high-velocity crust occurs in this zone.

Two features of the record sections are noteworthy. First, the energy propagation to the south is much more efficient than to the north. Secondly, the character of the seismic records on Cyprus is different from those recorded in Israel. Seismograms from Cyprus have a higher frequency content and include many reverberations.

5 Conclusions

The crust between Cyprus and Israel can be divided into the following velocity layers from the surface downwards:

A 2.5 km s^{-1} layer probably corresponding to Miocene shales (Ginzburg & Gvirtzman 1979). This layer is 3.0 km thick in the south and reaches a minimum thickness of 0.5 km over Mt Eratosthenes.

A 4.5–5.0 km s^{-1} layer probably corresponding to Tertiary evaporites (in the north) and Cretaceous to Jurassic carbonates. Its thickness varies from 6.0 km in the south to 9.0 km, reaching a maximum thickness between the Israeli continental shelf and Mt Eratosthenes.

A 6.0 km s^{-1} layer representing the crystalline upper crust. This layer thins from the continental areas in the north and south and is missing over the central portion of the profile. Its maximum thickness is 20 km underneath Cyprus.

A 6.7 km s^{-1} layer, 8–10 km thick, representing the crystalline lower crust underneath the Israeli and Cyprus–Eratosthenes portions and the entire crystalline crust over the central portion of the profile approximately between OBS A and OBS D.

A 8.0 km s^{-1} layer representing the upper mantle.

The geological interpretation of the seismic refraction models (Fig. 12) is as follows:

Southern Israel is underlain by a continental crust. Underneath the northern Negev and the continental shelf there is a transition zone, where the crust thins rapidly. The thinning takes place in the low-velocity upper crust, while the sedimentary cover thickens considerably towards the Levantine Basin. In the north, Cyprus is underlain by a 35 km thick continental crust thinning southwards. South of Mt Eratosthenes a major transition of the crustal structure was detected, indicating a major structural boundary. The seismic evidence presented above shows that the structural boundary observed separates two different types of crust: the continental Cyprus–Eratosthenes block to the north and an oceanic region in the Levantine basin to the south, which extends right up to the coastal areas of the Sinai and Israel.

Well data and reflection seismic data from the surrounding areas (Ginzburg & Gvirtzman 1979) indicate that the earliest sediments of the sedimentary cover which is up to 14 km thick are of pre-lower Cretaceous and possibly Jurassic age.

The seismic model was cross-checked with gravity information published by Woodside (1975) for the Eastern Mediterranean and by the Geological Survey Department, Government of Cyprus (1974). Velocities were converted to densities by using the Nafe & Drake (1963) curves and the Birch (1960/61) formula.

The 2-D density model computed is presented in Fig. 12. The south-eastern part of the section is seismically controlled by data published by Ginzburg *et al.* (1979).

The model was adjusted so that the computed gravity anomalies were close to those observed without any significant modifications of the seismically obtained geometry.

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References

Birch, F., 1960/61. The velocity of compressional waves in rocks to 10 kilobars, *J. geophys. Res.*, **56**, 66.

Condie, K. C., 1976. *Plate Tectonics and Crustal Evolution*, Pergamon Press, New York, 288 pp.

Finetti, I. & Morelli, C., 1973. Geophysical exploration of the Mediterranean Sea, *Bull. Geofis. teor. appl.*, **14**, 291–342.

Ginzburg, A. & Gvirtzman, G., 1979. Changes in the crust and in the sedimentary cover across the transition from the Arabian Platform to the Mediterranean Basin: evidence from seismic refraction and sedimentary studies in Israel and in Sinai, *Sedim. Geol.*, **23**, 19–36.

Ginzburg, A., Makris, J., Fuchs, K., Prodehl. C., Kaminski, W. & Amitai, U., 1979. Seismic study of the crust and upper mantle of Jordan-Dead Sea rift and their transition toward the Mediterranean Sea, *J. geophys. Res.*, **84**, 5605–5612.

Lort, J. M., 1977. Geophysics of the Mediterranean Sea basins, in *Ocean Basins and Margins, Vol. 4A (Eastern Mediterranean)*, pp. 151–213, Plenum Press, New York.

Makris, J., 1977. Geophysical investigation of the Hellenides, *Hamburger geophys. Einzelschr.*, **34**, 124 pp.

Malovitsky, Ya.P., Emilyanov, E. M., Kazakov, O. V., Moskalenko, V. N., Osipov, G. V., Shimkus, K. M. & Chumakov, I. S., 1975. Geological structure of the Mediterranean sea floor (based on geological-geophysical data), *Mar. Geol.*, **18**, 231–261.

Nafe, J. E. & Drake, C. L., 1963. Physical properties of marine sediments, in *The Sea*, **3**, 794–814, ed. Hill, M. N., Wiley, New York.

Nur, A. & Ben Avraham, Z., 1978. The Eastern Mediterranean and the Levant: tectonics of continental collision, *Tectonophys.*, **46**, 297–312.

Ryan, W. B. F., Stanley, P. J., Hersey, J. B., Fahlquist, D. A. & Allan, T. D., 1976. The tectonics and geology of the Mediterranean Sea, in *The Sea*, **4**, 387–492, ed. Maxwell, A. E., Wiley, New York.

Woodside, J. M., 1975. Evolution of the Eastern Mediterranean, *PhD thesis*, University of Cambridge.

Woodside, J. M., 1977. Tectonic elements and crust of the Eastern Mediterranean Sea, *Mar. geophys. Res.*, **3**, 317–354.