EVOLVING MIOGEANTICLINES OF THE EAST MEDITERRANEAN (HELLENIC, CALABRIAN AND CYPRUS OUTER RIDGES)

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With an appendix on the side-scan sonar system
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[Plates 1–8]

CONTENTS

Extensive surveys with long range side-scan sonar, as well as an air-gun sub-bottom profiler and a narrow beam echo-sounder, are described for the eastern half of the Mediterranean Sea. The main structural trends are shown in plan view to follow the curve of the Hellenic Outer Ridge (previously known as the Mediterranean Ridge,

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East Mediterranean Ridge or Mediterranean Rise), and suggest a structural continuation into the Ionian Islands west of Greece. To the west a similar but smaller feature, the Calabrian Outer Ridge (external to the Calabrian Arc) is described. This is partly welded to the Hellenic Outer Ridge along a narrow suture zone. To the east the Hellenic Outer Ridge is shown to merge into the Cyprus Outer Ridge (external to the Cyprus Arc). The Hellenic Outer Ridge is clearly asymmetrical in cross section, with its steeper slope facing towards the interior of its Arc System.

Folds and strike faults have been recognized on sonographs, particularly those of the Hellenic Outer Ridge. Cross-faults (possibly strike-slip) are numerous on the northern slope of this Outer Ridge. Cross-faults are especially well developed where the Ridge is narrowest and highest between Crete and North Africa, and where it may have been thickened by thrusting. In general the intensity of deformation decreases southwards across the Hellenic Outer Ridge. Slumping is probably responsible for progressively reducing the height of the relief produced by folding and faulting.

The Hellenic, Calabrian and Cyprus Outer Ridges are interpreted as miogeanticlines related to the Plio-Quaternary phase of the continuing southwards outgrowth of the Hellenic, Calabrian and Cyprus Arc Systems. The large and small scale structures are of particular interest because they show the surface relief of some early evolutionary stages of dominantly compressional submarine mountain ranges before they are subject to subaerial erosion or modified by later tectonism. The driving force of the continuing orogeny is seen as resulting from local mantle diapirs spreading outwards from the Tyrrhenian, Aegean and Turkish regions, rather than from a simple closure of the Eastern Mediterranean due to the supposed convergence of the Eurasian and African 'Plates'.

1. Introduction

The floor of the Eastern Mediterranean (Ionian Sea in the west and Levantine Sea in the east, figure 1) is remarkable for its broad, medial swell, with an ubiquitous relatively small scale surface relief which contrasts strongly with the predominantly smooth floor of the Western Mediterranean. The gross form of this main swell, here called the Hellenic Outer Ridge (figure 2), is generally attributed to tectonic activity. Four somewhat related explanations have been proposed.

(1) Miocene uparching of the outermost ground beyond the Hellenic Arc, followed by general Plio-Quaternary tension and subsidence (Giermann 1966, 1969).

(2) Late Pliocene to Quaternary back-tilt and subsidence of its internal portion (including an Upper Tertiary allochthonous blanket) to form the Hellenic Trough Complex, so leaving the Hellenic Outer Ridge upstanding (Mulder 1973).

(3) A Miocene gravity nappe which was subsequently thickened tectonically in front of a younger subduction zone (Biju-Duval *et al.* 1974).

(4) Post-Miocene thickening of crust by underthrusting and décollement in the vicinity of a subduction zone, due to *northwestward* motion of a supposed Levantine plate (Ryan *et al.* 1971), and involving supposed former oceanic crust of the African plate which (by coincidence) has only at the present moment been finally 'consumed' (Finetti & Morelli 1973).

The present paper provides regional data about the real trends and nature of the relatively small scale relief on the Hellenic Outer Ridge shown in plan view by the side-scan sonar on R.R.S. *Discovery* during 1971 and 1973 (figure 3). It also describes two further features of similar origin, the Calabrian and the Cyprus Outer Ridges, and puts forward an explanation for the existence of the three Outer Ridges in relation to the regional tectonics. Because each of these Outer Ridges is geographically related to its own arc system it seems more appropriate to name them in a systematic manner. Thus, Hellenic Outer Ridge will be used in this paper in preference to Mediterranean Ridge or to its variants East Mediterranean Ridge or Mediterranean Rise.

2. Geological setting

(a) *The orogenic arc systems*

The eastern half of the Mediterranean Sea lies on the southern side of (and external to) three Tertiary arc systems which are still active. These are the Calabrian, Hellenic and Cyprus Arc Systems. They exhibit in varying degrees of development the successive series of major structural zones typical of many other arc systems. The modern Hellenic Arc System, for example, includes an inner volcanic arc, then outside that the Hellenic Arc of strongly thrust and folded Tertiary and older sedimentary rocks, including metamorphics, reaching far above sea level, and beyond again is the submarine Hellenic Outer Ridge of folded and faulted sediments up to Quaternary in age, each arc being separated by troughs. The two deformed sedimentary arcs stand in marked contrast with the North African margin where virtually undeformed marine Miocene occurs extensively. On the European side the tectonic development of the Hellenides fold belt started during the late Mesozoic and reached peak intensity during the mid-Tertiary, with the zone of most intense thrusting moving southwards in time (Aubouin 1965).

(b) *Recent earth movements*

There is manifold geological evidence for post-Miocene vertical movements and marginal warping throughout the Mediterranean region. During the past 3000 years substantial vertical movements of the crust are also indicated by the altitude of both drowned and raised coastal archaeological sites with respect to modern sea level (Flemming, Czartoryska & Hunter 1971; N. C. Flemming, private communication). The observed displacements of coastal sites along the Hellenic Arc, southern Turkey and Cyprus, range between uplift of 3 m and subsidence of 5 m with respect to present sea level. The implications of this work are that the flanks of the western part of the Hellenic Arc are being downwarped, the islands of the Hellenic Arc are tilting as blocks, while the southern coast of Turkey, bordering on to the Antalya Basin, is relatively stable.

Modern seismicity, together with historical and archaeological evidence, show that fault movements are abundant and widespread in parts of the Eastern Mediterranean and neighbouring lands. In addition to this it has been argued that much movement takes place by a process of creep (North 1974). Seismic recordings of gradually improving quality, made during the past two decades, show a distribution of epicentres along the Hellenic, Calabrian and Cyprus Arcs in belts bounded by less seismically active blocks (Papazachos 1974) or 'plates' (see, for example, McKenzie 1972). The belt of modern seismicity along the Hellenic Arc is broad, extending from the Aegean volcanic arc in the north to the southern boundary of the Hellenic Trough Complex and to some extent reaching into the northernmost part of the Hellenic Outer Ridge between Crete and Cyrenaica called the 'Upper Plateau'. The numerous shallow to intermediate depth earthquakes have been considered to lie in an ill-defined Benioff zone estimated to dip at between 20° and 35° towards the Aegean Sea. A Benioff zone beneath the Calabrian Arc is also suggested by intermediate and deep focus (200–500 km in depth) earthquakes (Ritsema 1970, 1972; Caputo, Panza & Postpischl 1972). This is of limited lateral extent (about 200 km) and dips towards the Tyrrhenian Sea with a curvature that follows the Arc.

Study of the focal mechanisms of earthquakes (fault-plane solutions) perhaps helps to make a distinction between events of normal faulting, reverse or thrust faulting and strike slip faulting, and to determine the direction of movement along the fault-plane. Unfortunately there are few reliable fault-plane solutions along the Calabrian Arc, but the available ones do show a compressional axis parallel to that Arc (Caputo *et al.* 1972). The more reliable post 1962 earthquake recordings, used by McKenzie (1972) for the Hellenic Arc and the Aegean, show that every type of faulting occurs. Least complicated is the southeastern margin of the Hellenic Arc where there is thrusting in a north–south direction, probably on planes dipping to the north beneath the Hellenic Trough Complex. In the western part of the Hellenic Arc the suggested relative motion of thrusting is about northeast–southwest. A normal component of displacement is usually found in fault-plane solutions for mainland Greece and Western Turkey.

Archaeological and historical data for much of the region suggest that during the past 2000 years intense activity in one area may last for perhaps a few centuries and then shift elsewhere (Ambraseys 1971) so that modern data should be used with caution.

There have been several attempts to explain the tectonics of the region in terms of 'plate' motions. For instance, McKenzie (1972) supposed that the collision of Arabia with Eastern Turkey and Western Iran was pushing away the two small 'plates' of Western Turkey and the Aegean. This allowed the motion between Africa and Arabia, and Eurasia to be taken up by 'consumption' of Eastern Mediterranean oceanic plate rather than by thickening of continental plate near the Caucasus. Other authors dispense with plate tectonics as an explanation for the seismicity. For example, Van Bemmelen (1972) explains the orogenesis in terms of mainly vertical, and lesser horizontal, movements in the mantle, using the Tyrrhenian as his main test case.

(*c*) *Crustal character*

Seismic refraction experiments to determine crustal character under the Eastern Mediterranean are usually spoilt by side-echoes from the very disturbed relief. In the Ionian Sea beneath the Messina Abyssal Plain the top of the mantle was reached at about 20 km beneath relatively low velocity material, in contrast to about 44 km beneath the mountains of the Peloponnese (Hinz 1974), and up to 35 km under Sicily (Colombi *et al.* 1973). About 27 and 25 km of crust was found at the foot of the Nile Cone by Lort, Limond & Gray (1974) and Finetti & Morelli (1973), respectively. Low magnetic relief and low heat-flow values suggest that the crust is of broadly comparable nature and thickness throughout the Eastern Mediterranean. Thus the deep floor of the Eastern Mediterranean is intermediate in character and has a more continental style crust than much of the Western Mediterranean where the mantle is found at appreciably shallower depths.

A discontinuous belt of strongly negative free air gravity anomalies is associated with the Hellenic Trough Complex and lesser ones with the Hellenic, Calabrian and Cyprus Outer Ridges (Woodside & Bowin 1970; Ryan *et al.* 1971). Positive free-air anomalies are associated with the Southern Trough and African continental margin, and also with the Aegean Sea.

(*d*) *The uppermost sediments*

The presence of Upper Tertiary strata in the Eastern Mediterranean is shown in DSDP boreholes (Ryan, Hsü *et al.* 1973; DSDP Leg 42A, *Geo Times* **20** (8), 16–19, 1975), spread between the Hellenic Trough Complex, Hellenic Outer Ridge, Messina Abyssal Plain and Florence Rise. Messinian evaporites were found in five of these holes (125, 129, 374, 375 and 376, located in figure 3). The top of the evaporites has been recognized throughout much of the Eastern Mediterranean as a group of strong reflectors known as the 'M' horizon. Finetti & Morelli (1973, p. 329) state that the evaporites are thin to very thin or absent within part of the Hellenic Outer Ridge but that north and south of this feature the evaporite interval is thick in most of the Eastern Mediterranean (maximum about 3.5–4.0 km). Such deposits are shown as virtually absent on the Libyan and Tunisian continental slope and the Apulian Plateau.

Plio-Quaternary deposits cover the evaporites. They are up to 200 m thick on the Hellenic Outer Ridge (Biju-Duval *et al.* 1974; Hinz 1974) and are shown as increasing in thickness towards the Nile Cone where several kilometres are present (Carte Géologique et Structurale des Bassins Tertiaires de Méditeranéen, I.F.P.–C.N.E.X.O. 1974): in the Hellenic Trough Complex the young deposits may be thicker than 1500 m. The Quaternary deposits have been sampled in the DSDP holes mentioned above, together with holes 128, 130 and 131 (figure 3), as well as in the widespread short cores of earlier workers. Stanley (1973) has drawn attention to the modern flysch-like sediments now accumulating in the many small sediment ponds of the Hellenic Trough Complex, as well as in the larger abyssal plains south of the Hellenic Outer Ridge.

3. SURVEYS BY R.R.S. *DISCOVERY*

The main purpose of the surveys, made by R.R.S. *Discovery* during 1971 and 1973, was to determine the structural trends in plan view for a large and representative part of the Eastern Mediterranean floor (figure 3). This broad approach was thought to provide the best chance of obtaining enough data to narrow the choice between the several modes of origin for the relief that have been suggested already, as well as allowing for other unspecified possibilities. Specific search was made for indications of the western end of the Hellenic Outer Ridge and any relationship with Italy, as well as for the location of its eastern end and any relationship with the island of Cyprus or the Nile Cone.

The main tool was the long range side-scan sonar (GLORIA), details of which are given by M. L. Somers in the Appendix. Except for brief periods at 7 or 22 km ranges this device was mostly used to examine a 14 km wide swathe of ground, which was the most suitable range for studying the Hellenic Outer Ridge style features. Those features that were several kilometres long and several hundred metres or so high showed up well even when they had gentle slopes. Larger features showed up less well, while slopes less than about 100 m high tended to be too small to be resolved in detail unless they were relatively steep, such as fault scarps which can be obvious even when as little as 10–20 m high.

Unfortunately such small relief shows up poorly on the profiles produced by conventional echo-sounders (p.e.s.), because of numerous and prominent side echoes. Therefore use was also made, during the 1971 cruise, of a narrow beam sounder (10° × 2°) which gave more realistic profiles even of rough floors (Belderson, Kenyon & Stride 1972). During the 1973 survey sub-bottom profiles were provided by an air-gun reflexion profiler with a chamber of either 650 cm^3 or 2620 cm^3. The ship's position during both cruises was determined by means of satellite navigation equipment.

Most of the ship's courses were chosen to cross the Hellenic Outer Ridge obliquely, so as to have the greatest chance of revealing a variety of structural trends, bearing in mind that the side-scan method tends to reveal preferentially any features extending parallel with the course followed by a ship. Small errors in the orientation of relief features with respect to the ship's course may result from variations in the velocity of sound as it travels through different water masses, or from the vehicle (housing the transducers) towing at a small angle to the ship's course. This latter error would be zero for features extending parallel with the ship's course. For any other features their apparent trend will be slightly in error such that the trend of the feature will be pushed ahead or astern of its true bearing, depending on whether the vehicle was nosing to right or left of the ship's course respectively (assuming that the beam was pointing to starboard). There are instances of a given set of features seeming to have a somewhat different trend when viewed before and after a large change in ship's course, which could be attributed to vehicle yaw, but in general this is not thought to be a major problem. Short period fluctuation in yaw which can produce a characteristic sinuosity in linear features (see, for example, Cooper 1974) was generally not a nuisance and, indeed, there are some long linear features which show no sign of such an effect (e.g. figure 13).

The only region where sound refraction, due to density stratification within the sea, was recognized as causing a distinctive pattern on the sonographs was in the approaches to the Adriatic, where there is an episodic overflow through the Strait of Otranto of dense bottom water formed in the southern Adriatic.

4. Relief and structural trends

The sonographs provide widespread, plan view, indications of well developed structural trends on the floor of the Eastern Mediterranean, all of which should be illustrated if space were available. In practice an abbreviated version of the data was produced in laboratory analysis, while the present paper provides a simplified version (figure 4) of those working sheets, together with some representative samples of the sonographs. The relationship between the surface relief and geological structure of the Eastern Mediterranean, as compared with that of the adjacent land, will be brought out by considering the major divisions of the active Hellenic Arc System, which extends from the modern volcanoes of the Aegean in the north to the Southern Trough in the south. This sequence of structural zones will then be applied to the Calabrian Arc System in the west, and to the Cyprus Arc System in the east.

(a) *The modern Hellenic Arc System*

(i) *The Aegean Basin*

The Aegean may be considered as the tensional, marginal sea of the modern phase of the evolving Hellenic Arc System, within which has grown the inner volcanic arc of youthful andesitic-type volcanoes. These are separated from Crete by the Cretan Trough (figure 2). The break up of this region into blocks and its subsidence interrupts the continuity of the older fold belts extending from Greece to Turkey (see, for example, Boccaletti, Manetti & Peccerillo 1974).

(ii) *The Hellenic Arc*

The most obvious structural link remaining between western Greece and Turkey is the orogenic island arc that stretches from the Peloponnese through Crete and Rhodes to Turkey, and separates the Aegean from the Mediterranean. Its mountains rise more than 2 km above sea level. Both the vergence (outward inclination) of the folding and thrusting and the orogenic polarity (direction of orogenic migration) of the Tertiary Hellenides is directed towards the

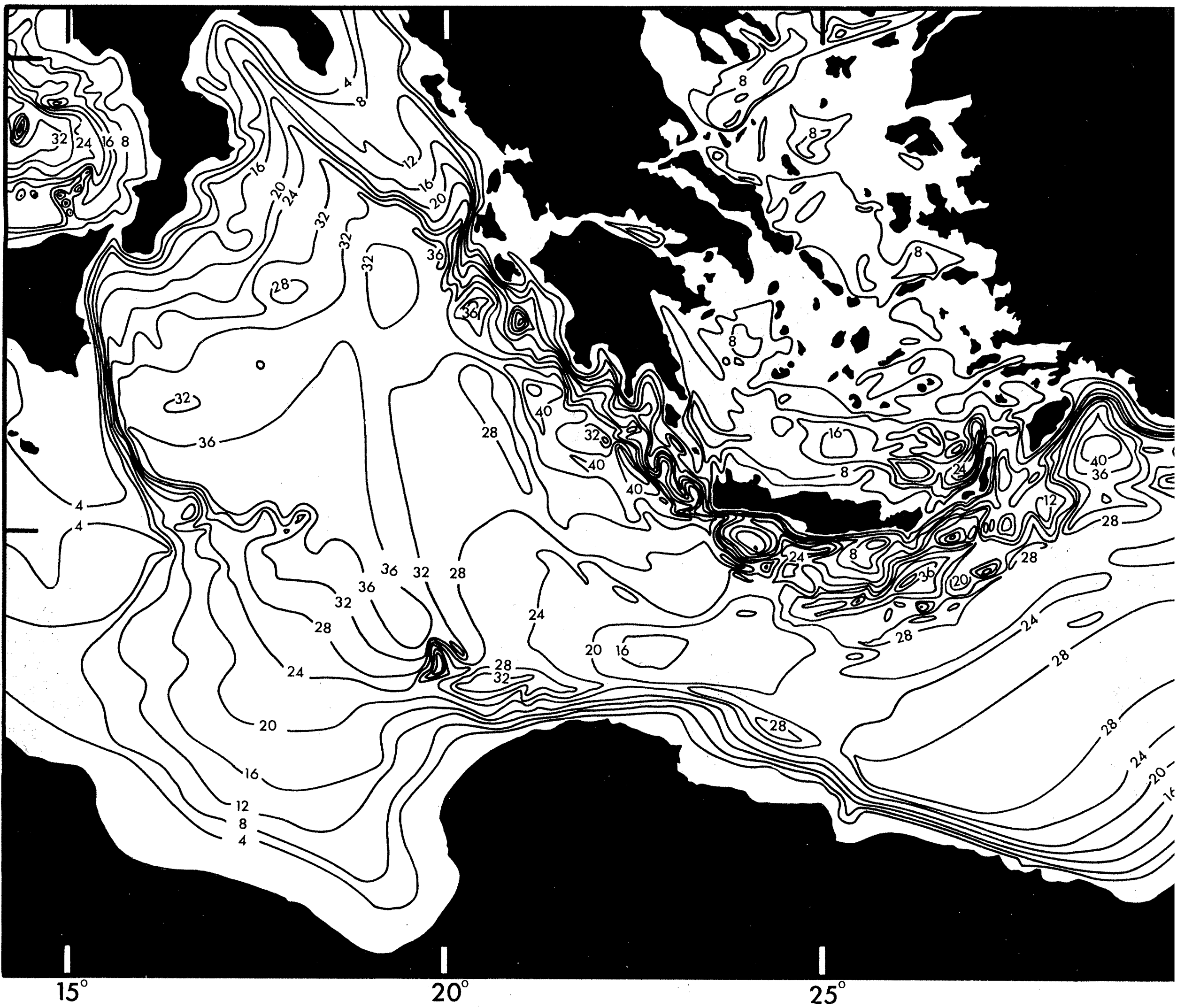
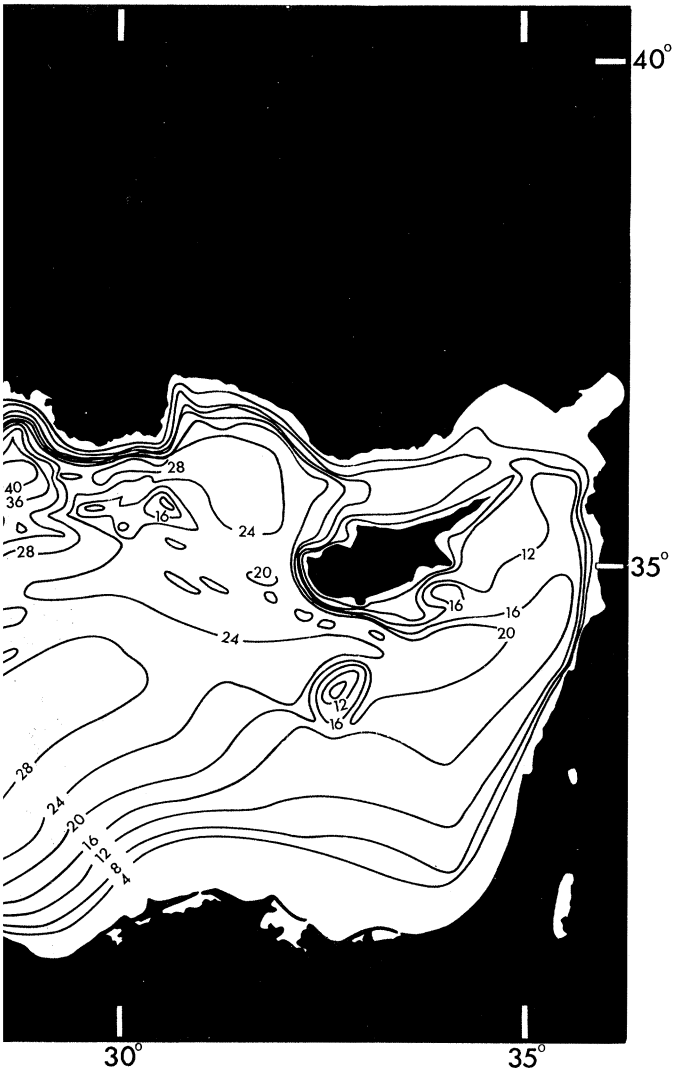


FIGURE 1. Generalized depth contours, at 400 m intervals, show the gross relief of the Eastern Mediterranean se
charts; U.S. N.O. 310 (Defence Mapping Agency Hydrographic Center 1972) and on Wright *et al.* (1975)



anean sea floor. Based mainly on bathymetric
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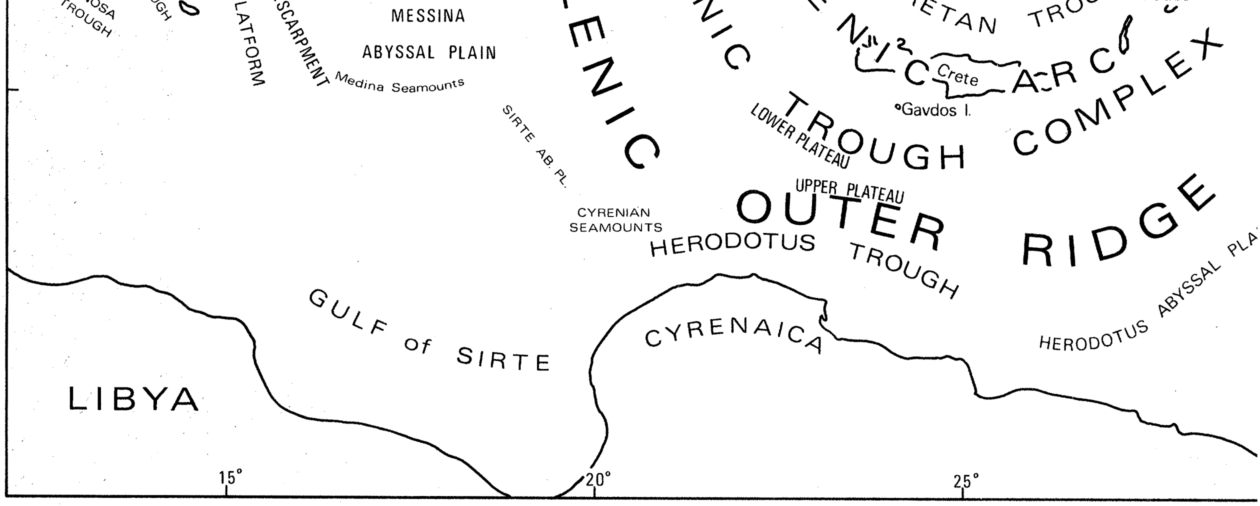

FIGURE 2. Location map for the Eastern Mediterranean showing the geographical names used in this paper.
Herodotus Trough and the Herodotus Abyssal Plain are all part of the Southern Trough.

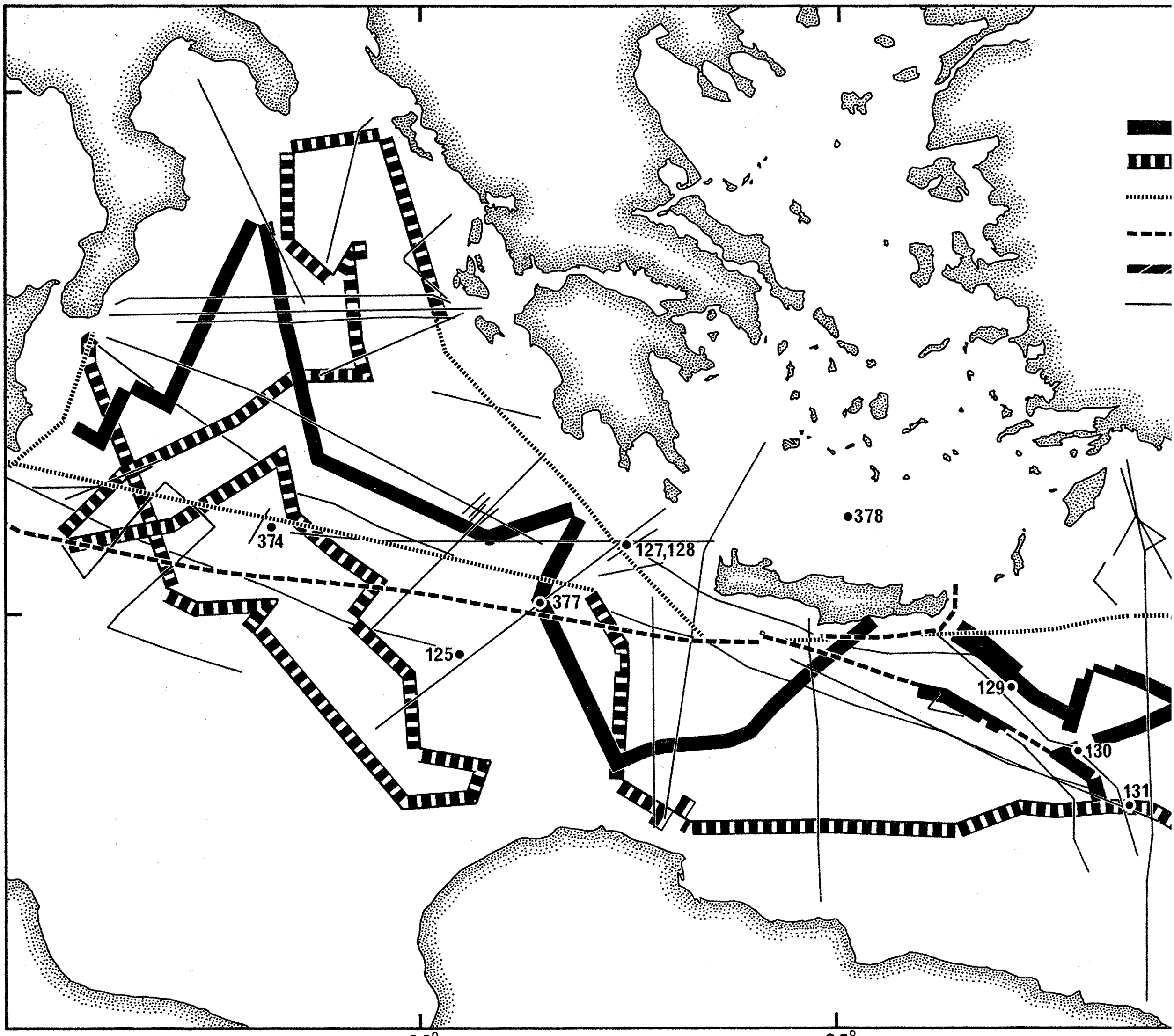

FIGURE 3. Data coverage for the Eastern Mediterranean, mostly from cruises of R.R.S. *Discovery*. In the case of t
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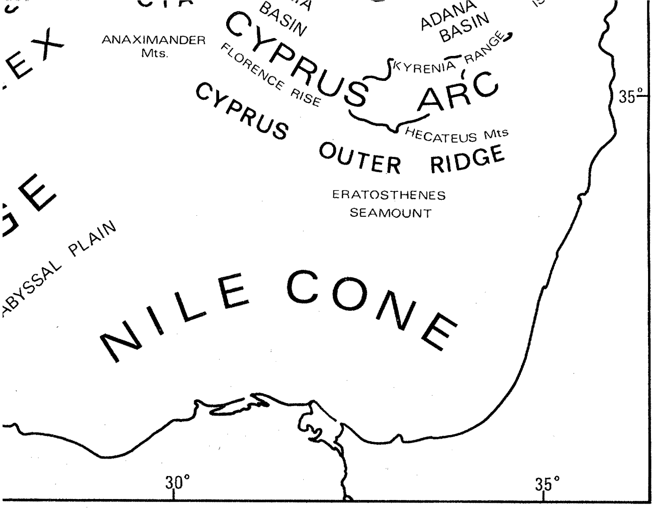
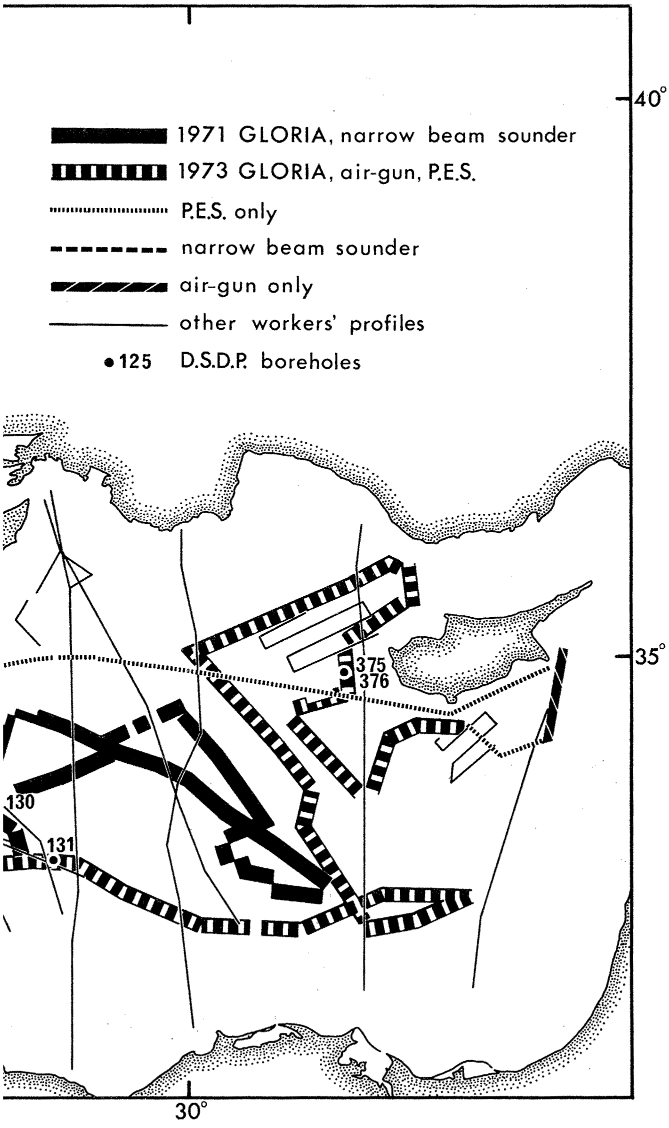


s paper. The Messina and Sirte Abyssal Plains, the



case of the long range side-scan sonar (Gloria)
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Figure 3. Data coverage for the Eastern Mediterranean, mostly from cruises of R.R.S. *Discovery*. In the case of t
the thickness of the line shows the width of ground actually examined. Survey tracks by other workers usi
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Phillips 1971; Hieke *et al.* 1973; Hinz 1974; Lort & Gray 1974.

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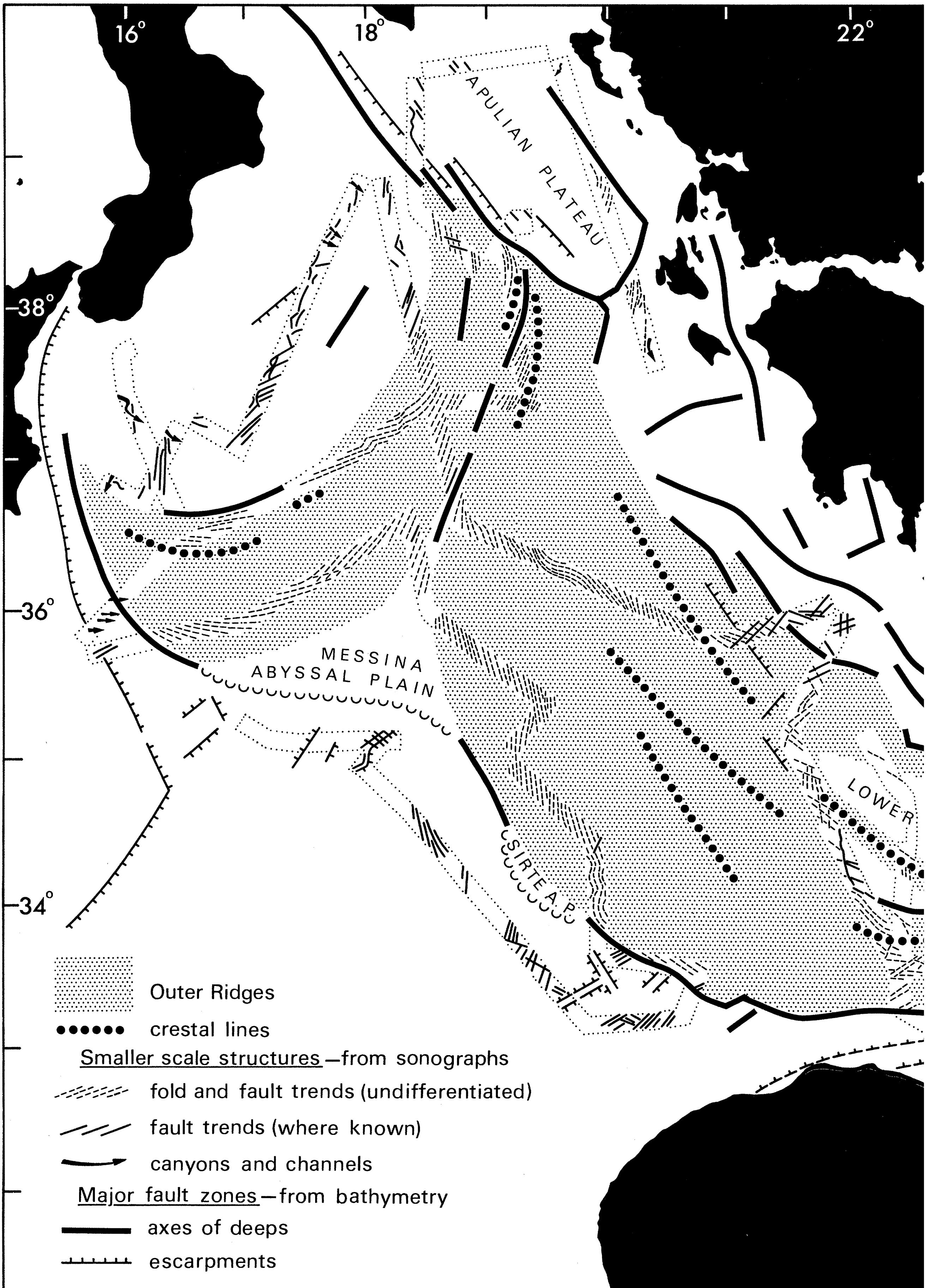
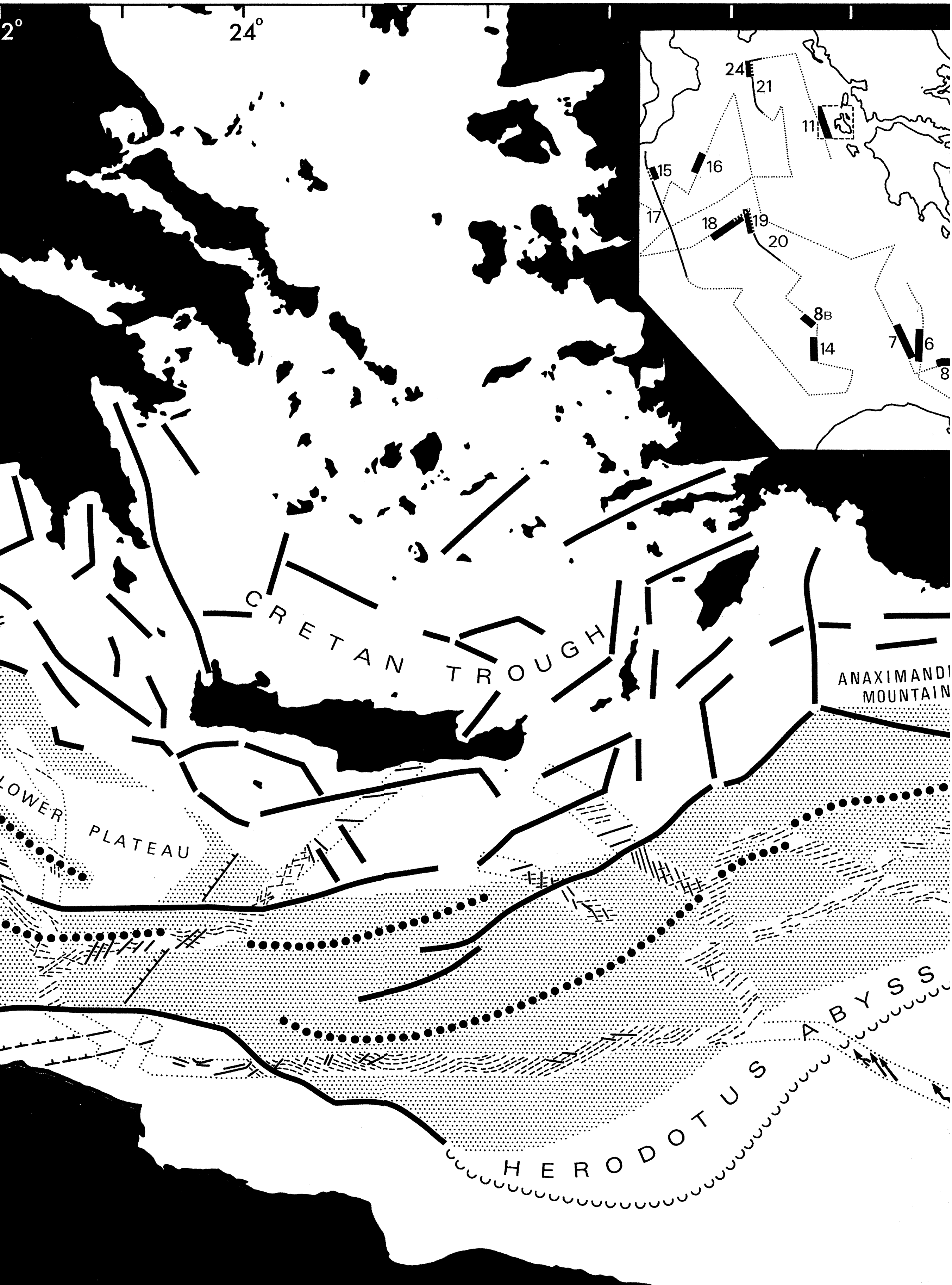

16°
18°
22°
38°
36°
34°
APULIAN PLATEAU
MESSINA ABYSSAL PLAIN
SIRTE A.P.
LOWER
Outer Ridges
crestal lines
Smaller scale structures—from sonographs
fold and fault trends (undifferentiated)
fault trends (where known)
canyons and channels
Major fault zones—from bathymetry
axes of deeps
escarpments


2°
24°
24
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11
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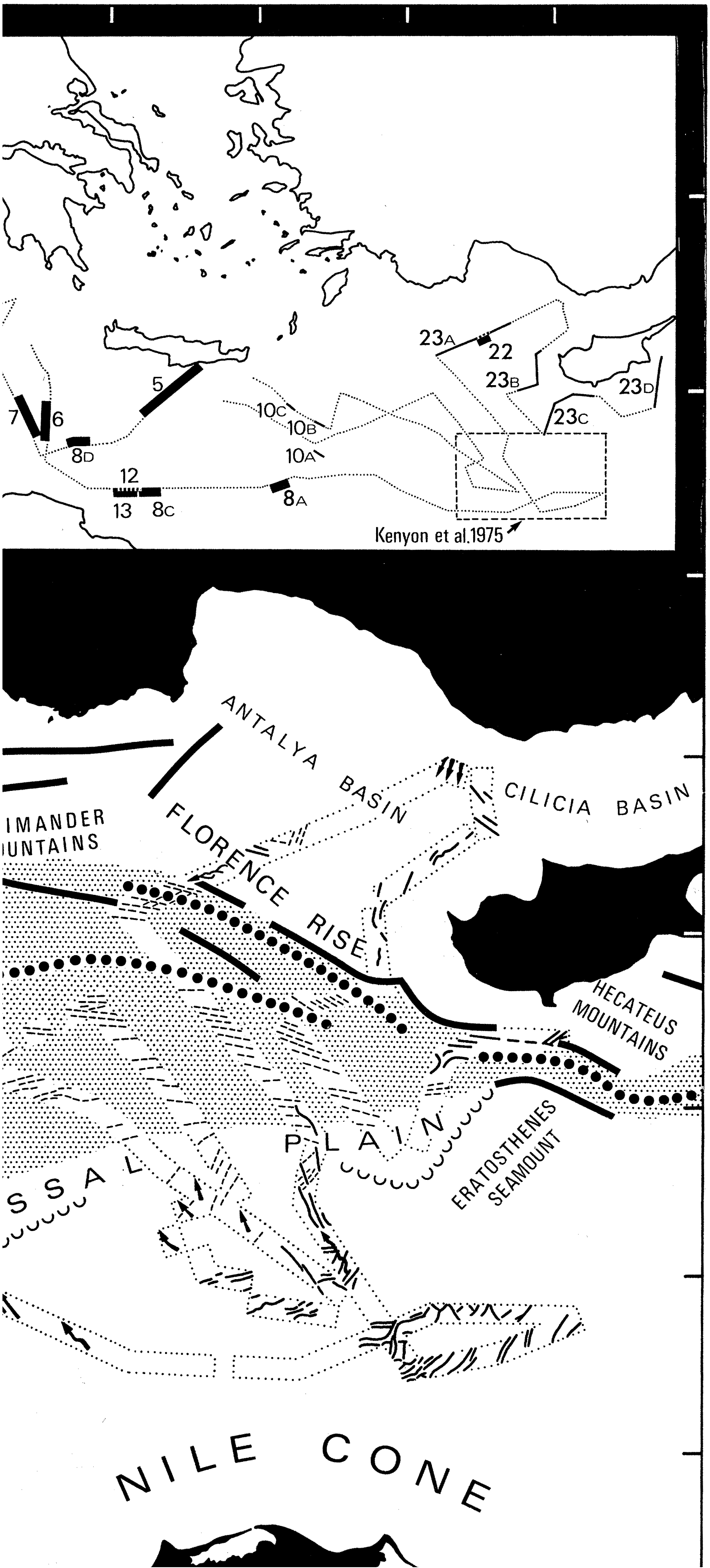
23A
22
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Kenyon et al.1975
ANTALYA BASIN
CILICIA BASIN
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PLAIN
SSAL
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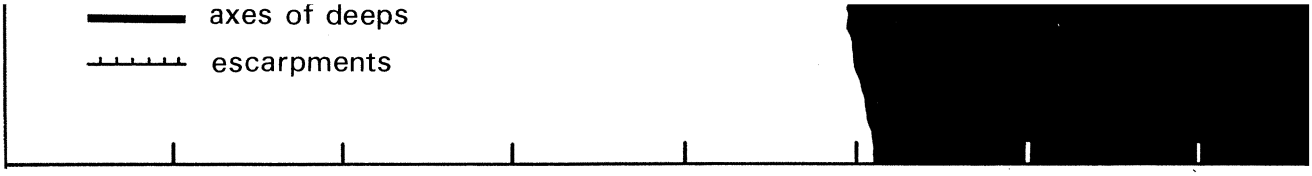

FIGURE 4. Simplified trends of structural relie
published bathymetric data. The bounda
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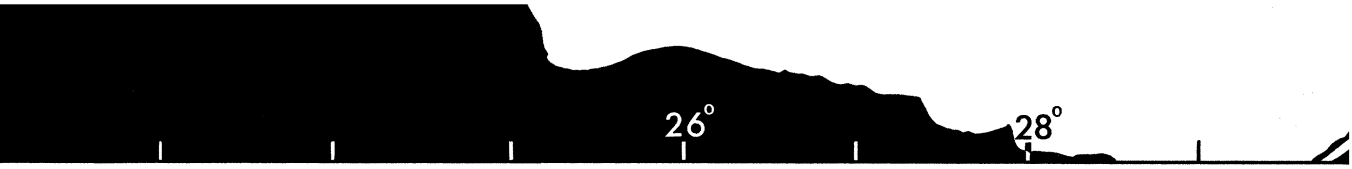
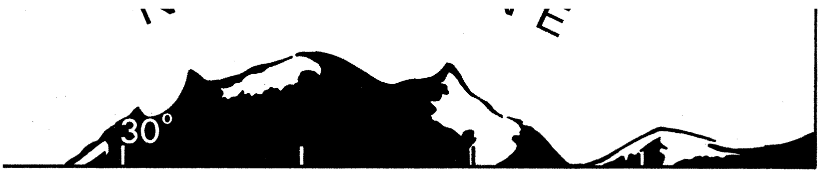
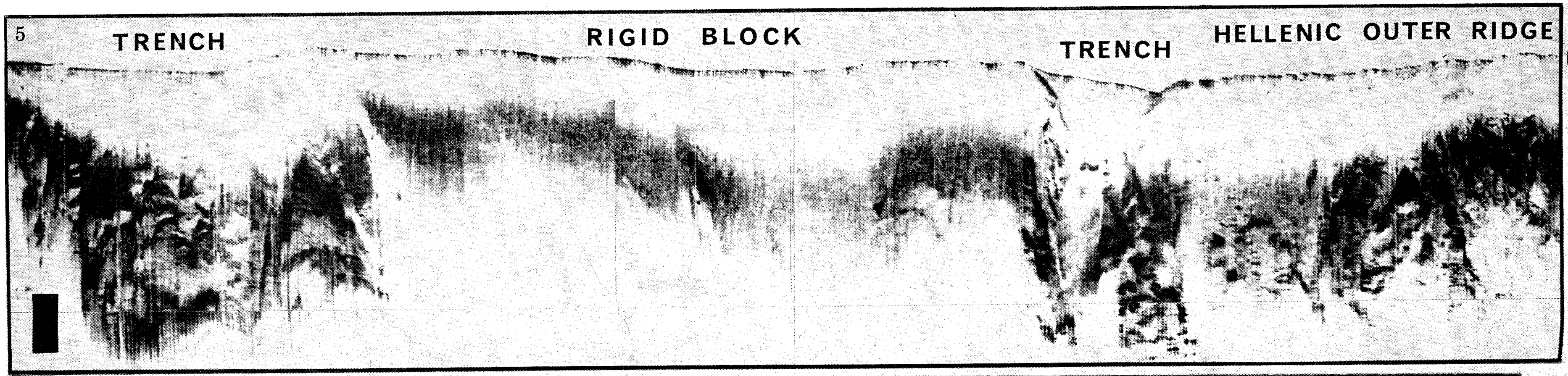
air-gun profiles and narrow beam echo-s



ural relief shown on sonographs of the Eastern Mediterranean, together with the trends of gross relief derived from e boundary between the Hellenic Trough Complex and the Hellenic Outer Ridge is difficult to define. The south-ges is placed at the outer limit of the smaller-scale structures. The inset figure shows the positions of sonographs, am echo-sounder profiles that are figured in this paper.


30°

5



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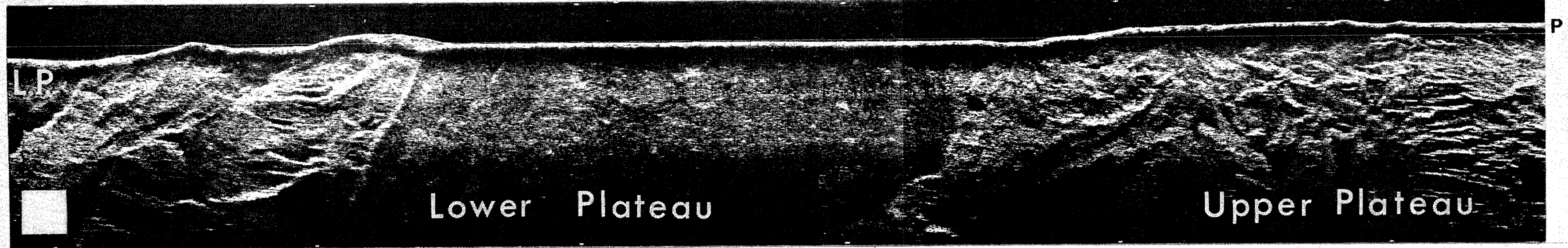

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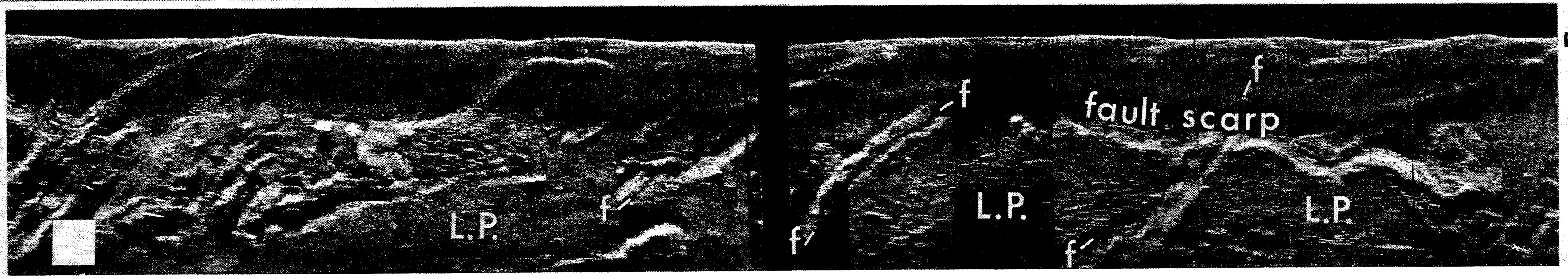

Figure 5. Sonograph showing the smooth surface of a relatively rigid block (Ptolemy Mountains) within the Hellenic Trough Complex. This contrasts with the rough slopes of the two trenches bounding the block and with the small-scale tectonic relief on the northern flank of the Hellenic Outer Ridge. Note the southerly tilted floors of the trenches. In this sonograph (in contrast to all the others) shadows or smooth floors appear as light tones and strong reflexions from steep surfaces appear as dark tones, and there is also a range distortion of about 2.5:1 (as shown by the black rectangle with each side equivalent to 2 km). The area shown is 140 km × 13 km. 'P' is the profile of the floor.

Figure 6. The relatively low relief of the 'Lower Plateau' contrasts with the rougher, more tectonically disturbed 'Upper Plateau'. A ridge of rough ground (left) which fingers into the 'Lower Plateau' is considered to be due either to local buckling along a zone of weakness, or else may result from thrusting. This sonograph, and all subsequent ones are true plan views (except for a narrow zone near to the profile 'P'), and strong echoes appear white and shadows black. The sides of the white square represent 2 km.

Figure 7. Sonograph showing the west facing fault scarp bounding the 'Lower Plateau' (L.P.), which is a relatively undeformed block within the Hellenic Outer Ridge. Large faults (f–f) cut across both provinces but probably do not extend far into the 'Lower Plateau' beyond the area shown by this sonograph. For the location of these and other sonographs see figure 4.

outside of this arc, which has been subdivided into a series of structural zones with outwards decreasing intensity and age (Aubouin 1965). Some of the outer zones have been recognized in Crete and may imply greater outward translations here than in the Peloponnese (Bonneau 1973, 1976). The several islands in the chain are probably separated from one another by fractures of the same general trend as those recognized in the Aegean and further south. Meulenkamp & Drooger (1973) describe the recent faulting in Crete as occuring along older north–south and east–west trends. To the west of Crete the recent faulting tends to be northwest to southeast and to the east of Crete it tends to be northeast to southwest.

(iii) *The Hellenic Trough Complex*

External to the modern Hellenic Arc, but intimately related to it, there is a 100 km wide zone of discontinuous arc-parallel trenches up to almost 5 km deep, that are separated by mountainous blocks and interrupted by subordinate cross trends (figure 4). It seems likely that this band of sea floor contains some of the outermost structural zones of the Hellenides (in Aubouin's 1965 scheme for Greece). The sonographs of three crossings of this Trough Complex show the virtual absence of recent deformation on the surface of the intervening blocks (figure 5, plate 1) except for some disturbance near to the Hellenic Outer Ridge. Earlier deformation, now masked by recent sediments, is likely, however, since intense fracturing is evident on Gavdos Island which is an exposed portion of one of these blocks (Vicente 1970). The trenches southeast of Crete strike west–southwest into the Hellenic Outer Ridge (see also page 262) so that the boundary with this broad arch is rather arbitrary.

The floors of the trenches generally show evidence of some layered and tilted fill. The direction of tilting is not consistent, for in places it is towards the inner arc (Ryan *et al.* 1971; Stanley 1973) and at others in the opposite direction. An example figured by Hinz (1974, Figure 22) even shows early tilting in one direction and later tilting in another direction.

The occurrence of Lower Cretaceous limestone above Pliocene pelagic ooze at DSDP borehole 127 (Ryan, Hsü *et al.* 1973) in the Hellenic Trough Complex (figure 3) suggests either that there has been slumping on a local scarp or else thrusting has taken place at this locality. Earthquake solutions indicate that at least some of these trenches mark the outcrop of thrust planes.

(iv) *The Hellenic Outer Ridge*

South of the Hellenic Trough Complex is the long, broad swell herein called the Hellenic Outer Ridge (previously known as the Mediterranean Ridge, East Mediterranean Ridge or the Mediterranean Rise). Although its overall slopes are mostly gentle it can be followed as a relief feature for about 1300 km from west of Greece to west of Cyprus. It is about 150 km wide. In plan its basic arc-like shape is modified into a flattened W, the base of which wraps around the bulge of Cyrenaica (figure 1). It is both shallowest and narrowest between Crete and Cyrenaica where the 'Upper Plateau' rises above the flatter region called 'Lower Plateau' by Sancho *et al.* (1973). The Ridge mostly stands as much as 2 km higher than the deeps of the Hellenic Trough and about 1 km above the Southern Trough, whereas at its eastern and western ends it is much more subdued and barely detectable as a ridge. Much of the Ridge is asymmetrical in cross section: the northern flank has a general gradient of as much as about 3.5° while much of the southern flank slopes at less than 1°. The Ridge does not everywhere have a single summit line, but rather a series of low interfingering culminations (figure 4).

The Ridge is remarkable for its almost ubiquitous relatively small scale relief. Early interpretations of the nature of this relief were confused by the side-echoes resulting from the use of broad beam sounders. Because of the characteristic rounded appearance produced by the overlapping hyperbolae the relief was at first called 'cobblestone'. Subsequent use of narrow beam echo-sounders provided more realistic profiles and led to the relief as a whole being described as 'blocky' (Belderson *et al.* 1972). A detailed narrow beam survey of a few square kilometres on the south side of the Ridge (Sigl, Hinz & Garde 1973, Figure 4) revealed a 'hummocky and rolling' landscape consisting of small, discontinuous ridges extending parallel with the axis of the Outer Ridge. Large relief of the same general trend was found nearer to Western Greece (Hieke, Sigl & Fabricius 1973).

Three isolated seamounts on the southwestern flank of the Hellenic Outer Ridge shown on the bathymetric chart of Carter *et al.* (1972, Chart N.O. 310) between 35° 35′ N, 19° 10′ E and 35° 16′ N, 19° 37′ E were not detected despite a special search with side-scan sonar. It is concluded that these features probably do not exist.

The new data show that the dominant structural grain follows the length of the Hellenic Outer Ridge and emphasizes that it wraps around Cyrenaica (figure 4). In addition, there is a well defined transverse trend on the northern flank of the Ridge, while on the highest part of the Ridge between Crete and Cyrenaica (the 'Upper Plateau') several trends are present. The adjacent 'Lower Plateau' of Sancho *et al.* (1973) has only a 10–20 m high relief whose structural trends do not show up well on the sonographs. Large scarp-like structures bound the 'Lower and Upper Plateaus' (see, for example, figures 6 and 7, plate 1). It is possible that this ground is transitional with the Hellenic Trough Complex as described on page 273. In general it seems likely that the segment of the Hellenic Outer Ridge between Crete and Cyrenaica is bounded by major faults (possibly thrusts). The eastern boundary is seen as the southernmost trench which noses into the Hellenic Outer Ridge as far as 33° 25′ N, 25° 25′ E together with a line of deeps extending west–southwest seemingly almost as far south as the Southern Trough (at about 33° 10′ N, 24 °E). The main western boundary fault may be that shown in figure 7 (plate 1).

Variation in the styles and intensity of deformation of the Hellenic Outer Ridge is shown in figure 8 (plate 2) and the geographical zonation of these styles in figure 9.

Folds. Well developed simple folds can be positively identified on the southeastern and southwestern flanks of the Hellenic Outer Ridge, where it merges into the Herodotus and Messina Abyssal Plains, respectively. The absence of simple folds and the lack of an abyssal plain in the narrow Southern Trough north of Cyrenaica probably denote a more advanced stage of tectonic evolution there.

Sonographs show that the southern folds have a wavelength of about 1–2 km and crest lengths of up to 35 km. They are rather sinuous, interfinger with one another, and have suggestions of bifurcation. Some of these details are seen in figure 8, style A. The sinuosity does not result from vehicle yaw since the undulations are not synchronous across the width of the record.

Narrow-beam echo-sounder profiles (figure 10, plate 3, styles A and B) show that the outermost simple folds (up to about 300 m high) give way rapidly and progressively to more irregular forms of lower height, showing occasional residual fragments of crest until, on the uppermost part of the Ridge, few original crests can be identified.

Our air-gun profiles, and those of other workers, show the transition from incipient folds with continuous internal stratification (mainly due to turbidite layers) to those further north in which bedding is only observable on one side (due to unequal steepness of the limbs), and to

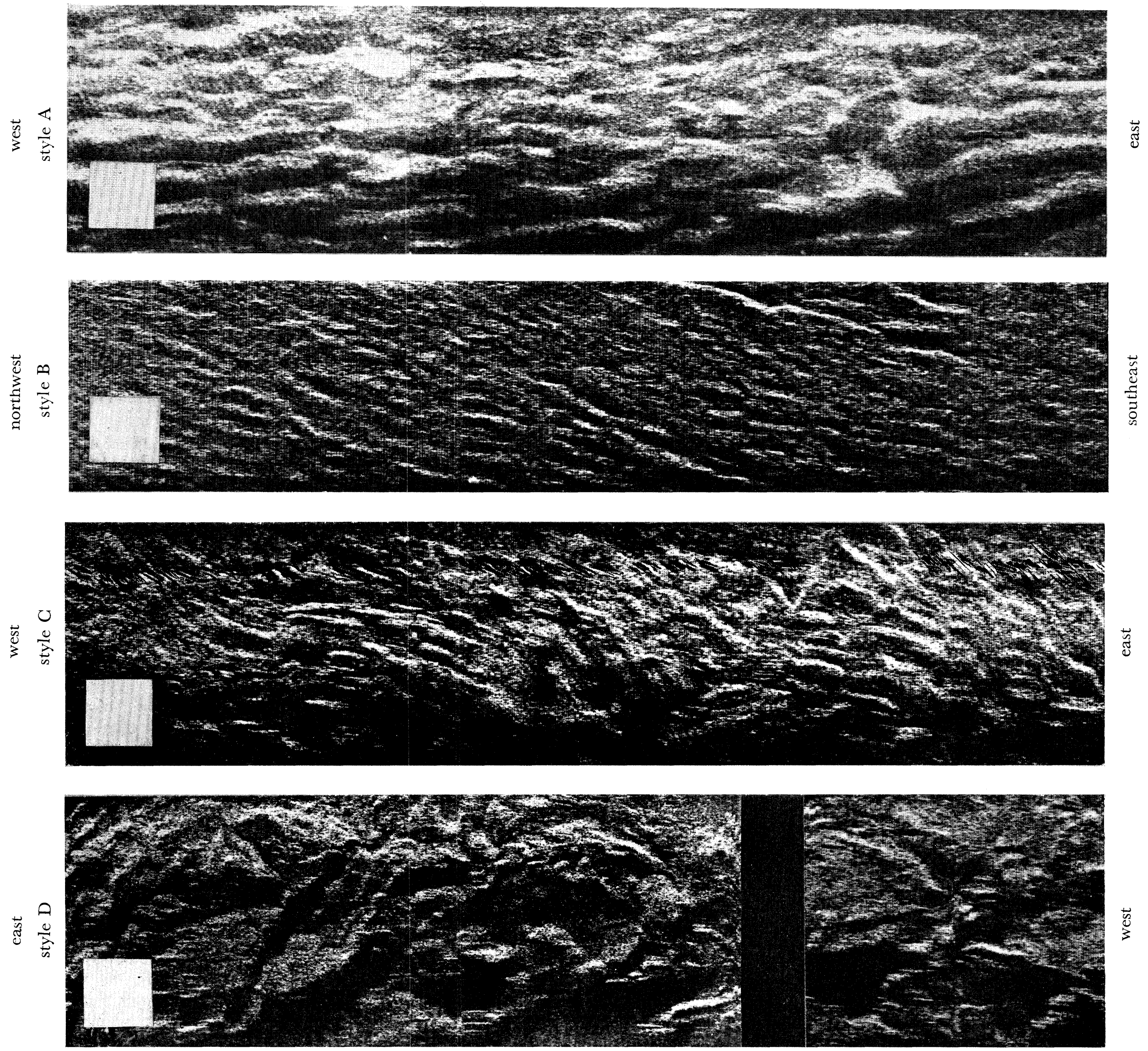

FIGURE 8. Sonographs of four characteristic styles of small scale tectonic relief recognized on the Hellenic Outer Ridge (and applicable to the other two Outer Ridges). These sonographs extend more or less along the line of the Ridge in order to show the relief to best advantage.

Style A. Simple folds with an amplitude of about 270 m and a wavelength of about 1–1.5 km. They are slightly sinuous in plan and up to about 20 km long. The interfingering and bifurcation of the folds is made more obvious if the sonograph is viewed along its length.

Style B. The folds are intensively faulted parallel to their strike, the resulting lineation having a smaller separation of about 0.7 km. The height and overall gradient of the original folds have been reduced by faulting and associated slumping to about 35–70 m.

Style C. On the north side of the Ridge cross faulting is as well developed as the longitudinal structures, but no sonograph of suitable quality is available to show this. The present sonograph illustrates a transition between tectonic styles B and C, in which Ridge-parallel structures are kinked and interrupted by incipient cross faults and relief is reduced by slumping to about 35–70 m.

Style D. The Ridge-parallel structural trends are dissected by cross faults of various trends. Thrusting and strike-slip faulting are suspected. The relief is about 35–55 m but shows up well because this ground, the 'Upper Plateau', is in relatively shallow water so that the shadows are correspondingly long.

those where bedding is barely traceable even beneath the gently sloping convex crests of the folds. Further north again the slopes are too steep and irregular for the air-gun to determine bedding. In general there is no marked preferential asymmetry in the folds, but merely a suggestion that steeper south-facing limbs tend to predominate in the outermost zone.

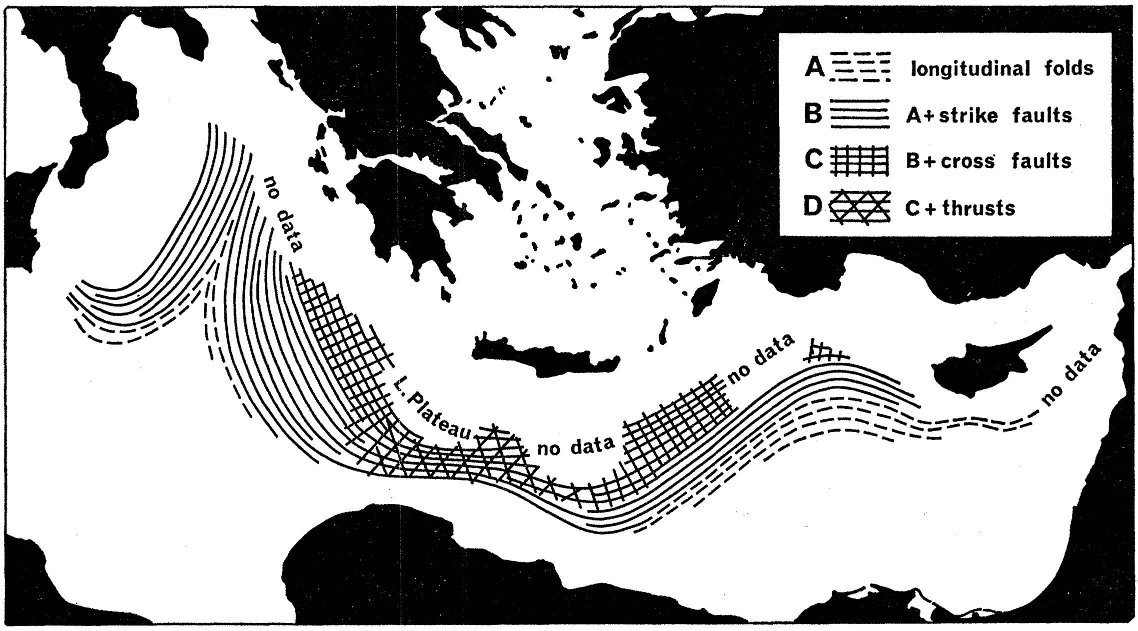

Figure 9. Geographical distribution of deformation styles A–D on the Outer Ridges (figures 8 and 10). Deformation increases in intensity from south to north across the Outer Ridges, and is greatest on the 'Upper Plateau' between Cyrenaica and Crete. The structural trends are shown diagrammatically and the boundaries are rather arbitrary as the figured styles are parts of a continuum.

Strike faults, cross faults and gravity slides. Slump scars and slickensides, horizontal and vertical shears, small grabens and loose blocks of sedimentary debris have been seen in photographs, while microfaults and slump microbreccias have been seen in cores from the Hellenic Outer Ridge (Ryan *et al.* 1971). Slump structures and normal faults with average dips of 70°, some with a filling of exotic material suggesting that they were once open fissures and thus tensional in origin, were also noted in cores by Hieke *et al.* (1973).

Narrow beam echo-sounder profiles indicate that as the slopes of the simple folds steepen a series of small steps with vertical separation of about 10–20 m first appear. These are probably slumps. Northwards towards the Hellenic Outer Ridge's crest such steps become more numerous and larger, with abrupt slopes up to about 50 m high. All relatively steep slopes are affected, and thus it is not surprising that a mass of intersecting parabolae spoil the profiles of the sea floor produced by conventional broad beam echo-sounders. The origins of these features become more apparent when they are seen in plan view.

It is evident on the sonographs that much of the medial part of the Hellenic Outer Ridge is characterized by a finer textured Ridge-parallel grain (plate 2, style B). Narrow linear features, sometimes in parallel groups, traceable for at least 7 km along the flanks of some large fold-like structures towards the southeastern side of the Outer Ridge, are interpreted as successive parallel strike faults (step faults). The true nature of these faults is difficult to determine, especially as air-gun profiles fail to provide much evidence of internal structure in this region. The features may be gravity slides along bedding planes beneath the flanks of the folds. Two such features on either flank of a fold and detaching near the crest may also explain the crestal grabens noted on some of the folds. There are probably all gradations between these larger features and the micro-faults and slump structures seen in photographs and cores. Indeed, it is this process which is probably responsible for the progressive overall reduction in height of the original folds towards the top of the Hellenic Outer Ridge.

The relief on the northern slope of the Hellenic Outer Ridge is higher in the west (Hieke *et al.* 1973) than in the east, where it is between 20–50 m high and where numerous cross-faults intersect the Ridge-parallel trends at high angles, such that these latter trends are almost obscured. An intermediate stage in the evolution of style C relief is shown in figure 8, plate 2. Cross-faults are also particularly numerous on the 'Upper Plateau'. Here the main Ridge-parallel trends show an abrupt swing in direction and are cut boldly by cross-faults of various trends so that the ground appears to be broken into a series of small blocks (plate 2, style D). It is possible that the cross-fractures represent strike-slip faults, particularly as there are indications elsewhere on the Outer Ridge of a transition from sinuous to kinked folds and then to strike-slip faults of limited displacement. If these faults are related to or give way at their limits to outward directed thrusting, then it is also possible that some of the Ridge-parallel structures represent the outcrop of thrust planes within the already folded and slumped sediments. Should any such thrusting be well enough developed to produce an imbricate structure this ought to manifest itself in a preferred asymmetry in the topography. However, on the available narrow beam sounder profiles preferred asymmetry does not seem to be common, except along one line towards the western end of the Ridge between about 35° 50′ N, 20° 40′ E and about 36° 30′ N, 18° 40′ E where there is a predominance of steeper slopes facing outwards (i.e. as expected, away from the Hellenic Arc).

Slumping along new lines, initiated by the cross faulting, is thought to have been responsible for the low relief of the northern part of the Ridge. The effect of this slumping has been to further reduce the relief of the faulted folds (the final stage of a 'slump cycle' perhaps).

Lateral limits of the Hellenic Outer Ridge. The relationship between the eastern and western ends of the Hellenic Outer Ridge and the equivalent Outer Ridges of the Cyprus and Calabrian Arc Systems, respectively, will be discussed in the following sections concerning these Arcs. There is, however, the problem of whether the Hellenic Outer Ridge continues in some modified form into the region between the northwestern coast of Greece and the Apulian Plateau. This seems likely because its shallowest part (see the 2800 m isobath in figure 1) almost reaches a ridge extending south from the island of Kefallinia (figure 2). Typical Hellenic Outer Ridge structures can be traced on sonographs as far as the Apulian Escarpment which bounds the southern side of the Apulian Plateau (figure 4). The eastern side of the Plateau is skirted by a trough, and between this and the Greek mainland lie the Ionian Islands. A westward directed major thrust passing through these islands was considered by Aubouin in 1965 to mark the outer boundary of the Hellenides. The region west of this boundary he then considered to be a foreland zone (his 'pre-Apulian zone'). However, there is at present much earthquake activity beneath the islands, and mapping has revealed Plio-Quaternary compressional structures (Mercier *et al.* 1973). One earthquake and its aftershock sequence suggested motion on a large almost horizontal thrust with a lateral extent of at least 50 km, resembling the base of a large alpine nappe (McKenzie 1972, figure 5B). This suggests that compression is continuing at the present time. The very thick Mesozoic shelf-carbonates and their overlying Miocene marls have been compressed into large, open, faulted folds of 1 km or more wavelength (B.P. 1971; Smith & Moores 1974). This is in contrast to the undeformed yet very similar Mesozoic sequence of the Apulian Platform in Southern Italy. On the western side of the island of Kefallinia (which shows evidence of recent uplift in the presence of raised beaches and uplifted Pleistocene marine marls) these folds trend north–south (B.P. 1971). A sonograph taken 10 km to the west of here revealed a well defined series of north–south relief features with separation of about 2 km (figure 11, plate 4). The close alignment of those features with the open folds on the westermost part of the nearby island of Kefallinia, which are apparently superimposed upon a geanticlinal structure (interpretative sections in plate 5 of B.P. 1971), all of which trend parallel to the Hellenides, suggest that this is a narrow structural continuation of the Hellenic Outer Ridge. Differences in morphology, as reflected in the appearances of the sonographs, may be accounted for by the contrast in lithology and facies between the two regions. The more competent Mezozoic carbonate series of the Kefallinia region contrast with the incompetent young sediments of the Hellenic Outer Ridge. This interpretation implies that the deep between the Ionian Islands and Greece is the structural equivalent of the Hellenic Trough Complex. Like the latter this trough is associated with thrusting (figure 11, section A–B).

(v) *The Southern Trough*

South of the Hellenic Outer Ridge (and in contrast to the discontinuous deeps of the Hellenic Trough Complex to the north of it) there is a continuous trough, partly filled in places to form the Messina-Sirte Abyssal Plains in the west and the Herodotus Abyssal Plain in the east (figures 1 and 2). The Herodotus Abyssal Plain is the largest but, as was noted by Ryan *et al.* (1971), even this abyssal plain, when compared with others located below sedimentary cones as large as the Nile Cone, is obviously a 'dwarf'. The fact that the sediments of the Hellenic Outer Ridge include Quaternary turbidites indicates that the early Quaternary abyssal plains were formerly much more extensive but have recently been caught up in the folding and uplift. Towards the eastern end of the Herodotus Abyssal Plain, and on the lower slopes of the Nile Cone the sonographs show a series of acoustically rough yet gently sloping, rather ill defined, northeasterly trending mounds. These may represent the summits of rising diapirs, probably with small scale surface-relief (Kenyon, Stride & Belderson 1975). It is possible that some of the larger ridges located north of the base of the Nile Cone result from the imposition of Hellenic Outer Ridge folding on these supposed diapirs.

Our air-gun profile across the trench at the base of the continental slope north of Cyrenaica shows an absence of any horizontally layered modern infill at the present-day deepest point (figure 12, plate 3). Instead there are signs of northward tilted young fill under the lower part of the continental slope, and there is a step up to a bench-like feature on the southermost slope of the Hellenic Outer Ridge. This bench of deformed former trench fill (seen in plan view in figure 13, plate 5) may now be separated from the tilted fill at the axis of the trench by a thrust front. The indications, therefore, are of youthful compressional tectonic activity along the base of this section of the African continental slope. Further west from here the grain of the Hellenic Outer Ridge is also seen to be bent around the base of the Cyrenian Seamounts (figure 14, plate 5).

If the Hellenic Outer Ridge has a structural continuation through and to the west of the Ionian Islands, then the deep between the Islands and the Apulian Plateau may be considered as the structural continuation of the Southern Trough (figure 11).

(*b*) *The modern Calabrian Arc System*

The western part of the modern Hellenic Arc System is opposed across the Ionian Sea by the modern Calabrian Arc System, where a similar sequence of tectonic zones can be recognized, in mirror image as it were (figure 2). Modern seismic activity is concentrated in the central segment of arc including northeastern Sicily and Calabria, as indicated by the concentration of both deep and intermediate depth earthquake foci and also by the modern structural deformation of the Calabrian Outer Ridge beneath the Ionian Sea. The limits of this more active segment may be defined by strike-slip faults both on land and on the sea floor.

(i) *The Tyrrhenian Basin*

The innermost zone is the relatively deep Tyrrhenian Basin which probably resulted from Plio-Pleistocene foundering (Selli & Fabbri 1971), associated with tensional faulting and the building of basaltic volcanoes. This basin has unusually high heat flow (Morelli 1970) in contrast to the low heat flow of the Ionian–Levantine Basin. Between the central Tyrrhenian main 'back-arc basin' and the Calabrian Arc is the chain of more andesitic type Aeolian Island volcanoes (the volcanic arc). These bear indications of northwest and northeast aligned tensional structures which are also observed on sonographs of the surrounding sea floor (Belderson, Kenyon & Stride 1974*a*). Between this volcanic arc and the Calabrian Arc there is a largely sediment filled trough analogous to the Cretan Trough.

(ii) *The Calabrian Arc*

The polarity of this orogenic belt, which includes the Calabride Metamorphic Complex (Structural Model of Italy, 1973, ed. L. Ogniben), is directed outwards (as with the Hellenides) in the form of late Tertiary nappes, thrusts and olistostromes. The considerable uplift of Sicily took place after the Lower Pliocene.

(iii) *The Messina Rise*

On land and extending on to the adjacent part of the Messina Rise there are filled troughs known as the Crotone-Spartivento and Sibari Basins. The general appearance of the floor on sonographs of this region, as with the Hellenic Trough Complex, is markedly different from the adjacent Calabrian and Hellenic Outer Ridges. Four down-slope trending canyons have been recognized on our traverse (e.g. figure 15, plate 6), in contrast to the many shown by Carter *et al.* (1972). Instead, the dominant pattern is of curved features extending approximately along the contours for tens of kilometres (figure 16, plate 6). Much of this relief has heights of about 200 m and gives rise to strong reflexions and acoustic shadows on the sonograph, indicating prominent scarps. Some of the associated hollows have flat floors, showing that they are now serving as sediment traps. The relief may be due to large-scale gravity slides or possibly thrusts. This would be in agreement with the conclusion of Finetti & Morelli (1973) and Biju-Duval *et al.* (1974), although the latter would also include the Calabrian Outer Ridge with the entire Messina Rise in a vast allochthonous complex. Many of the slopes of the larger features mentioned above are seen on narrow-beam echo-sounder profiles to have steps about 10–20 m high that can be interpreted as fault or slump scars. At the base of the Messina Rise, between it and the Calabrian Outer Ridge, there is a small and probably discontinuous trench (figure 17, plate 6), which is partly filled with layered sediment.

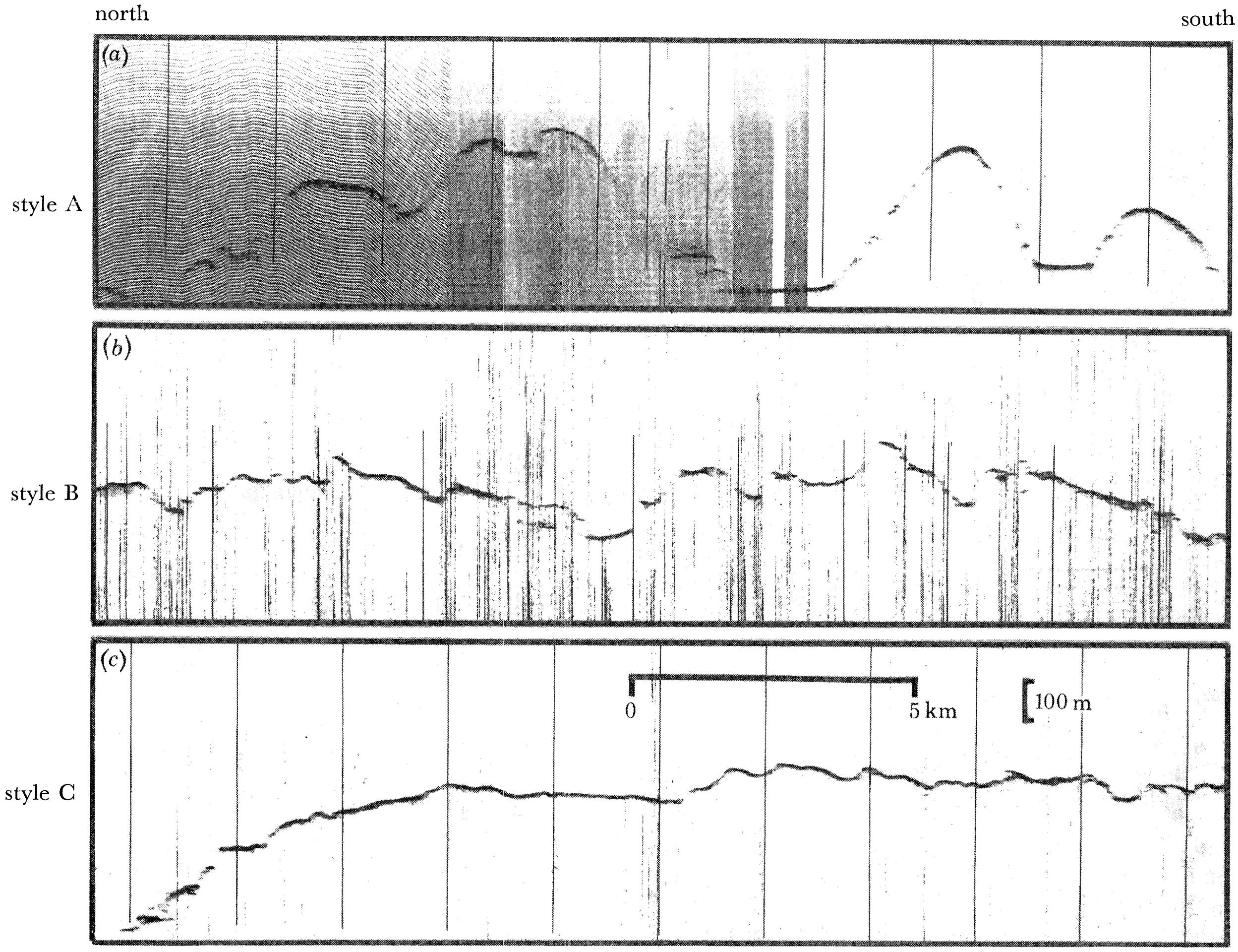

Figure 10. Narrow-beam echo-sounder profiles of the small-scale relief styles of the Hellenic Outer Ridge (the profiles, at about right angles to the Ridge, are located in figure 4).

Style A. The right hand side shows two gentle folds at the outer (southern) edge of the Ridge. The small steps are interpreted as slumps. The troughs have a flat fill of young sediment. To the left the folds become more broken by faulting and gravity slides. Note the crestal graben.

Style B. Irregular, lower amplitude relief which characterizes much of the middle part of the Ridge.

Style C. Relatively low relief of the northern part of the Ridge. The steps on the relatively steep northern slope are due either to faulting or possibly renewed slumping. The relief of Style D is similar, and is therefore not shown.

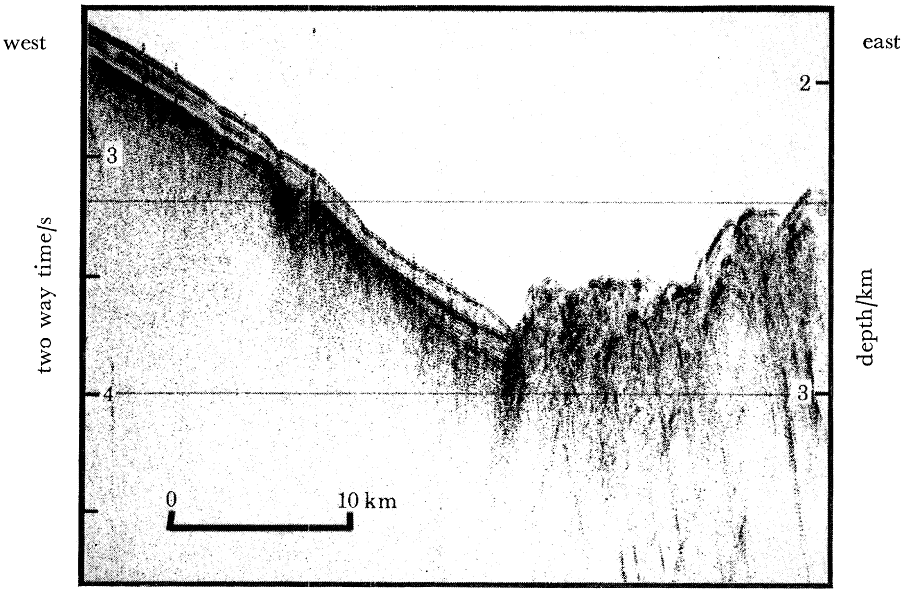

Figure 12. Air-gun profile showing the abrupt transition from the rough surfaced Hellenic Outer Ridge (right) to the relatively smooth North African continental slope. Note the absence of any flat lying fill in the bottom of the intervening Southern Trough.

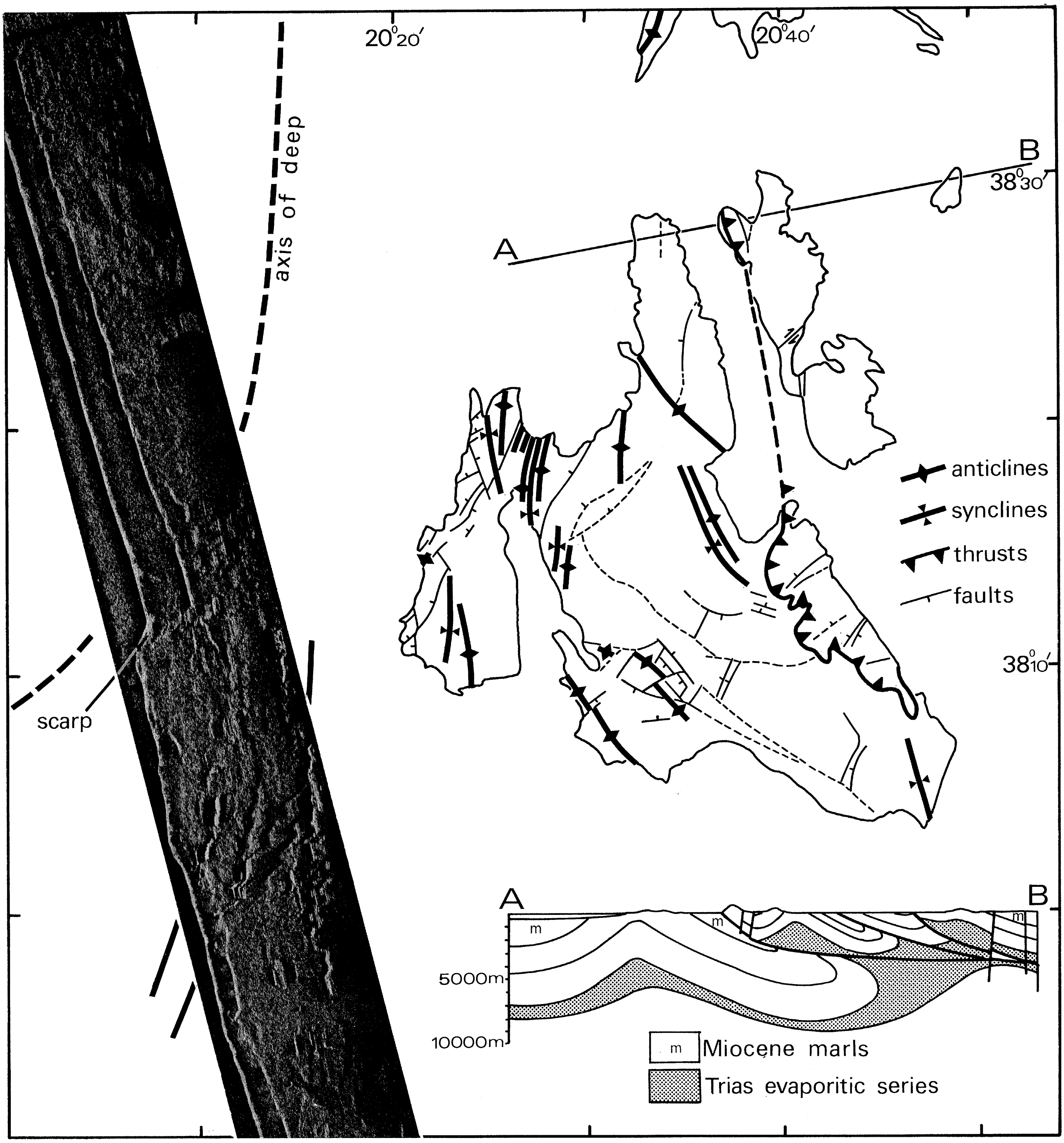

FIGURE 11. The island of Kefallinia is considered to be part of a narrow structural continuation of the Hellenic Outer Ridge. Fold and fault trends on the island are similar to the structures seen on the sonograph of the neighbouring sea floor. These are emphasized by short lines drawn alongside (*n.b.*: The apparent sinuosity of some of the features results from vehicle yaw). The deep is the structural equivalent of the Southern Trough. North of this (top left) the sonograph shows part of the almost undisturbed eastern slope of the Apulian Plateau. (The structural map and section of Kefallinia are based on B.P. 1971. Between the Trias and the Miocene there are Mesozoic to Eocene carbonates. The Miocene is overlain by Plio-Quaternary sediments.)

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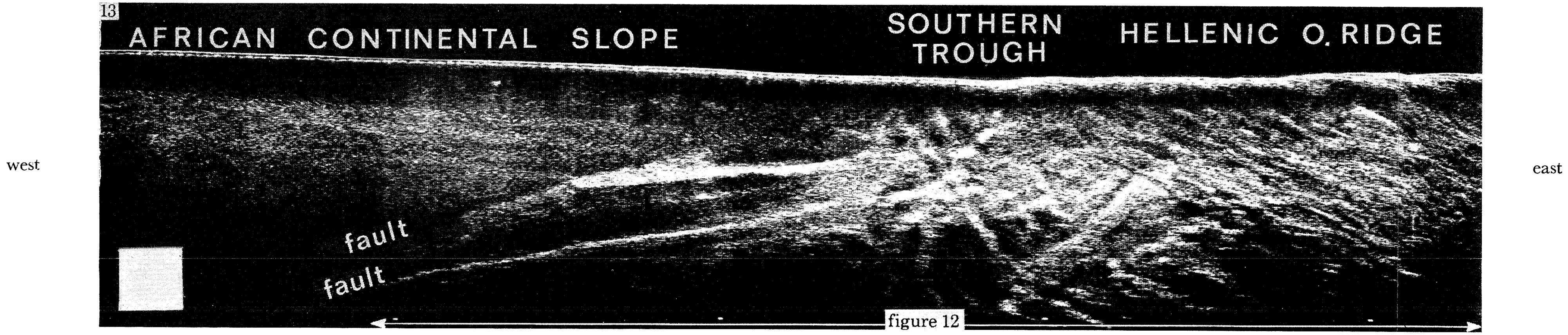

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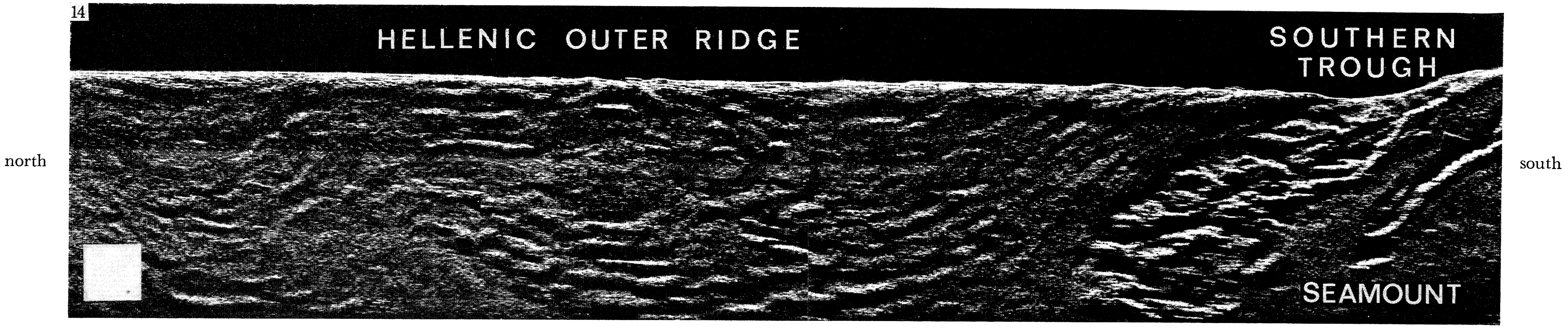
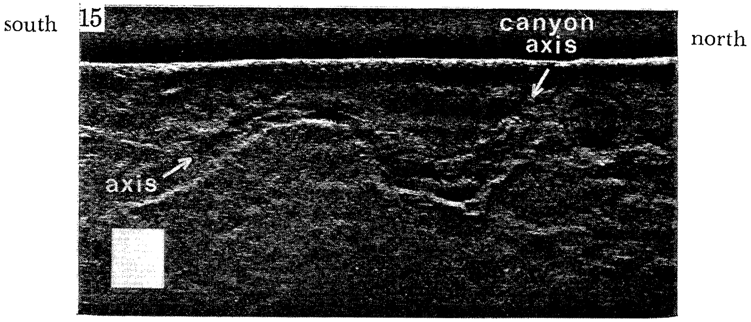
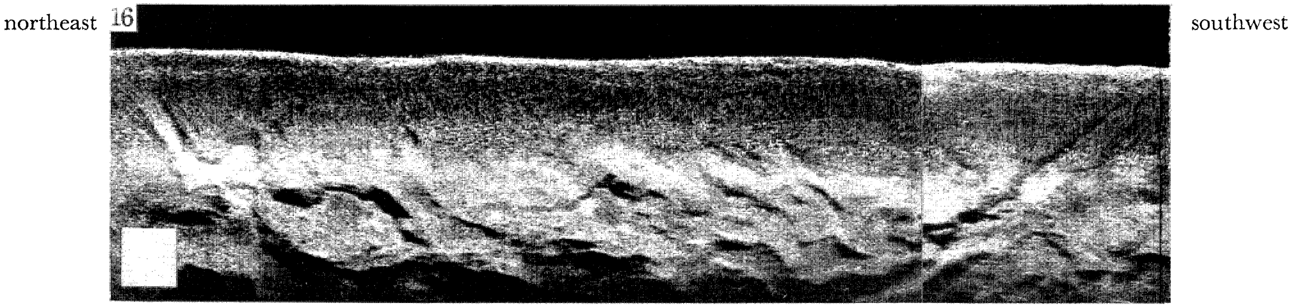
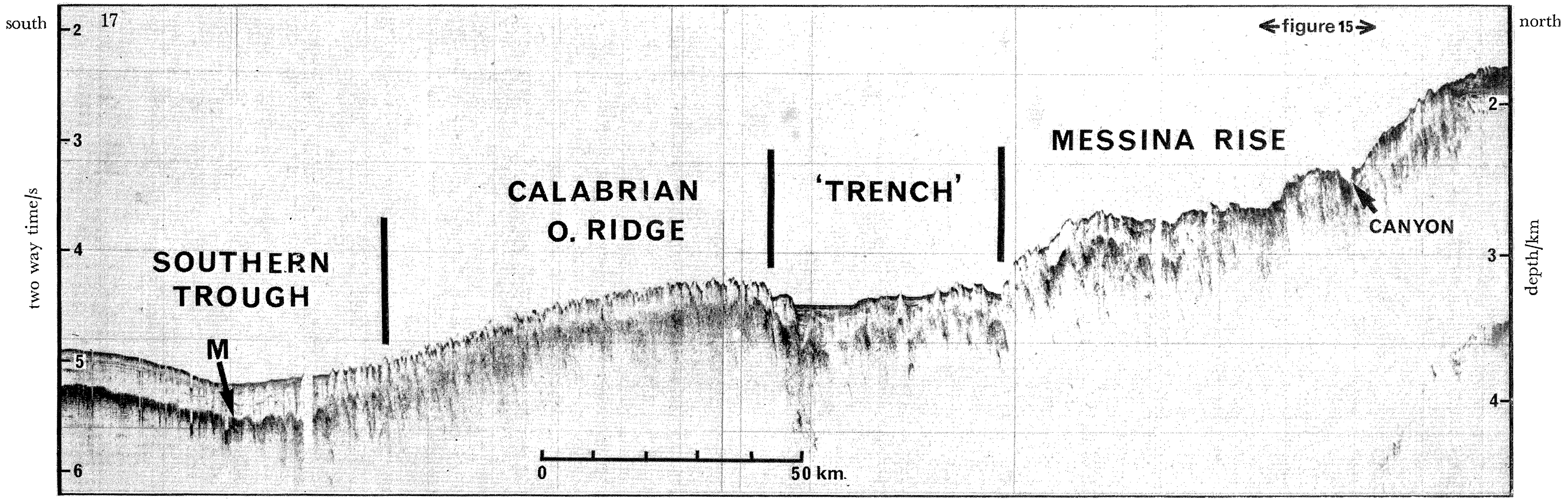


Figure 13. Sonograph (with profile along the same line as figure 12, plate 3) showing the Hellenic Outer Ridge abutting against the foot of the relatively smooth North African continental slope, broken only by two long faults. On this crossing of the southern edge of the Hellenic Outer Ridge the simple folds that are present further east and west, are here cut by strike faults and cross faults (structural style C).

Figure 14. Sonograph showing sinuosity in the folds (structural style A to B) on the southern side of the Hellenic Outer Ridge. The southernmost of these folds are bent around parallel with the foot of one of the Cyrenian Seamounts. The slope of the latter is rough and may be gullied and faulted.







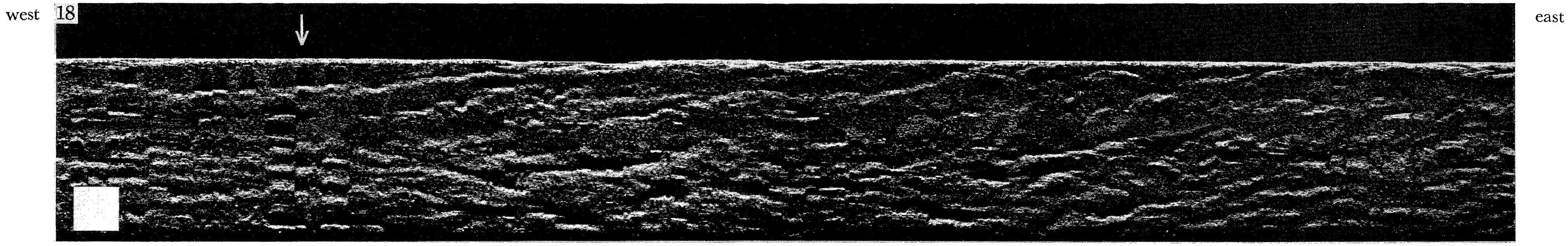


FIGURE 15. Sonograph showing an S shaped portion of a canyon about 1.5 km wide located on the upper part of the Messina Rise, along part of the profile of figeur 17. The wall more distant from the vessel is shown by a strong reflexion (white).

FIGURE 16. Sonograph showing curved features that extend along the contours on the upper part of the Messina Rise, and which are interpreted as due to gravity slides or thrusts.

FIGURE 17. Air-gun profile extending from the Messina Abyssal Plain to near the top of the Messina Rise and including the (asymmetrical) Calabrian Outer Ridge. The M horizon is shown.

FIGURE 18. Sonograph showing structural trends (style B of plate 2), along the central part of the Calabrian Outer Ridge. The effect of ship's yaw is to break up the continuity of some of these structural trends (e.g. below the arrow).

(iv) *The Calabrian Outer Ridge*

External to the Messina Rise and the trench along its foot there is a low swell, whose distinctive appearance both on an air-gun profile (figure 17) and on sonographs (figure 18, plate 6) shows its difference from the Messina Rise but its close similarity with the Hellenic Outer Ridge. It was initially named the 'Calabrian Ridge' (Belderson, Kenyon & Stride 1974*b*) but is better termed the 'Calabrian Outer Ridge'. Like the Hellenic Outer Ridge it is asymmetrical with a steeper inner (northern) slope. The elongation of the surface relief of the Calabrian Outer Ridge runs parallel to its curving axis (figure 4). Towards its western termination these features bend around parallel to the foot of the Malta Escarpment and die away. In its middle portion there is no well defined crest, but the trends curve around to run parallel with the Hellenic Outer Ridge until they reach the foot of the Escarpment bounding the Apulian Platform. Here the grain weakens and bends around to the north-west, so as to lie parallel to the Escarpment. These features are interpreted as faulted folds, giving way to more simple folds in the south, as in the case of the Hellenic Outer Ridge.

(v) *The Southern Trough*

South of the Calabrian Outer Ridge lies the Messina Abyssal Plain. Along its margins with the Calabrian Outer Ridge, and particularly in its northeast corner, rounded folds project above its surface (figure 19, plate 7) as in the case of the Herodotus Abyssal Plain. Hinz (1974) termed this the 'undulation zone'. The Southern Trough extends northwards from here as a narrow, partly flat-floored, strip of deeper ground (figure 20, plate 7) which reaches almost as far as the Apulian Escarpment. This line marks the 'suture' between the Calabrian and Hellenic Outer Ridges. Although this may superficially resemble a graben, it is more probably a 'ramp valley', bounded on either side by thrust (or incipient thrust) fronts. Along the base of the Apulian Escarpment a trough can be followed, both on the bathymetry and as an underlying series of sedimentary basins, up into the Gulf of Taranto and thence on shore into the Apennine Foredeep of southern Italy, where there is associated faulting (Structural Model of Italy, 1973, ed. L. Ogniben). Similarly, the western end of the Messina Abyssal Plain merges into a trough extending northwards along the base of the Malta Escarpment. It is probable that both escarpments are major faults, possibly with some strike-slip movement. An air-gun profile across the Apulian Escarpment (figure 21, plate 7) suggests some thrusting here, which may be related to such strike-slip faulting, while an air-gun profile across the base of the Malta Escarpment indicated more signs of tension than compression.

(*c*) *The modern Cyprus Arc System*

In comparison with the Hellenic and Calabrian Arc Systems the structural zones of the modern Cyprus Arc System are poorly developed at the present time. The relationship between the western end of the Cyprus Arc and the eastern end of the Hellenic Arc is also not clear.

(i) *The back-arc basin*

Although Upper Miocene–Pliocene andesitic flows are reported in the interior of the western Taurus (southern Turkey), there appears to be no present day andesitic activity. It must therefore be assumed that any manifestation of such activity is as yet confined beneath the surface. However, the central Turkish region to the rear of the Taurus has been characterized by Neogene extension and sedimentation in continental basins, together with associated Quaternary basaltic volcanism. This region is thus equivalent to the central Tyrrhenian and Aegean regions, except that it remains at a relatively higher level. Papazachos (1974) noted that southwest Turkey is characterized by normal faulting, and may be subdivided into a well-defined Taurus block and a less well defined Western Turkey block.

The Antalya Basin is seen as analogous to the Cretan Trough. Sonograph traverses do not show any consistent structural trends, except at the southern side of this Basin where there are a series of north-northeast trending structures. Ryan *et al.* (1971) suggested that these were due to décollement folding, but they are interpreted here as diapirs (figure 23*a*). Towards the Turkish side of the Basin a group of small depressions in the sea floor may represent hollows above diapirs, since probable diapiric instrusions of about the same width are seen nearby on the air-gun profile, and have also been postulated here by Lort & Gray (1974). The diapirism is probably associated with an extensional stress regime.

(ii) *The Cyprus Arc*

The Island of Cyprus is part of a submarine ridge which extends both eastwards to a structural continuation in the Misis Mountains of southeast Turkey, where there has been southeastwards thrusting during the late Pliocene to Pleistocene (Schiettecatte 1971) as well as a belt of modern seismicity, and westwards where it has been called the 'Florence Rise' by Biju-Duval *et al.* (1974). The arcuate Kyrenia Range in the north of the island was compressed into a tight anticline during late Miocene–Pliocene times, with late Pliocene epeirogenic uplift and cross-faulting. The Range was thrust against the Cretaceous ophiolites which extend outwards from the Troodos Massif (Dixey 1972; and unpublished manuscript) to form the basement of the whole island, and probably beyond. Earlier workers (Giermann 1969; Wong, Zarudzki, Phillips & Giermann 1971; Lort & Gray 1974) have postulated a large left-lateral transcurrent fault west of Cyprus, either across the Antalya Basin or along the line of the Florence Rise. We have no evidence for the existence of any such fault.

Magnetic anomalies suggest the presence of rocks of the ophiolitic suite beneath the Florence Rise, while two DSDP boreholes on the Rise showed a tentative correlation of Late Tertiary stratigraphy with Cyprus land sections, and also the presence of Late Miocene turbidites in this, now positive, relief element (*Geo Times* **20** (8), 16–19, 1975). Northwestwards the Rise structure probably extends onshore into the Antalya Nappes, which were thrust westward during Miocene times and are situated externally with respect to the Western Taurus (Brunn *et al.* 1971).

No predominant structural trend is distinguishable on sonographs of the Florence Rise. Several subcircular sunken features up to 2 km wide (figure 22, plate 8) with probable small-scale surface roughness may represent the surface expression of salt domes. An air-gun profile (figure 23*a*, plate 8) suggests that the tops of these reached the sea floor, possibly with consequent solution. There is also evidence of normal faulting (figure 23*b*) on the northeastern (Antalya Basin) side of the Florence Rise.

(iii) *The Cyprus Outer Ridge*

The structural trends on the Hellenic Outer Ridge follow the curve of the Hellenic Arc as far east as about 29° E (figure 4). Beyond again the trend becomes first easterly and then east-southeasterly, showing increasing control by the Cyprus Arc System. Dissension among previous workers as to the Ridge's relationship with Cyprus is now resolved, for it is apparent on sonographs that the structural grain on this Outer Ridge passes between the Cyprus block and Eratosthenes Seamount, bending around the seamount in much the same way as the Hellenic Outer Ridge bends around the bulge of Cyrenaica.

A series of four air-gun profiles (figure 23) show that this Cyprus Outer Ridge is best developed southwest of the Florence Rise. South of Cyprus the Ridge is less obvious and the small-scale relief shows a lower intensity of deformation. There is a relatively simple trough between the Cyprus Outer Ridge and the Florence Rise, while south of Cyprus the pattern is more complex with examples both of tilted and deformed trench fill and rigid blocks overlain by relatively undisturbed sediments, analogous to the Hellenic Trough Complex. It is possible that the presence of the large rigid block of Cyprus and its submarine extensions has disturbed the more simple tectonic pattern found west of the island. Any structural continuation east of Cyprus of the Cyprus Outer Ridge and associated troughs may be sought (probably buried) within the Iskenderun Neogene basin, situated external to the thrusts of the Misis Mountains in southeast Turkey.

The present survey was not carried far enough north on the sea floor to indicate the nature of the junction between the Cyprus and Hellenic Arcs. On land in the Lycian region of the Turkish mainland, the westwards thrust Antalya Nappes oppose the eastwards thrust Lycian Nappes (figure 2) across the domed Upper Mesozoic shallow marine carbonate platform of the 'Bey Daglari' (Brunn *et al.* 1971). Thus the Miocene Antalya Nappes may represent the extension of the Cyprus Arc, while the Miocene Lycian Nappes apparently connect with the eastern end of the Hellenic Arc. The Bey Daglari, and perhaps also the Anaximander Mountains on the nearby sea floor, would thus represent a resistant block wedged between the two Arcs. There is, however, a further possibility, that a fourth (minor) arc (which could be called the Lycian Arc) is centred on the Bey Daglari. The basin between here and the Anaximander Mountains would then be analogous to the Cretan Trough, while the Anaximander Mountains, which are fronted by a minor trough to the south and then by the Outer Ridge, would be the tectonic equivalent of Crete. Clearly there is a need for further study of this region.

(*d*) *The foreland*

The relatively stable foreland beyond the three compressional Outer Ridges seems to be characterized by tensional structures. On grounds of descriptive convenience it can be subdivided laterally into six provinces (figure 2).

(i) *The Nile Cone*

The northeastern segment of the Nile Cone (figure 4) has a northwest trending belt of grabens which themselves trend both northeast (alongslope) and northwest (downslope). Kenyon *et al.* (1975) surmised that these may have developed locally in the thick sediment wedge because of motion along an underlying offset prolongation of the northwest trending Gulf of Suez rift zone. The resulting tensional stress field would have facilitated both the intrusion of diapirs and downslope movement.

(ii) *The Cyrenaican continental slope*

The relatively smooth surface of the Cyrenaican continental slope contrasts strongly with the rough ground of the Hellenic Outer Ridge to the north of the intervening trench. The sonographs do show, however, a series of long, relatively straight east-northeast trending features (two of which are illustrated in figure 13, plate 5). These are probably faults related to the normal faults which have been mapped both offshore and parallel to the coast on the African mainland (Carte Géologique et Structurale des Bassins Tertiaires du Domaine Méditerranéen, I.F.P–C.N.E.X.O. 1974).

(iii) *The Gulf of Sirte and Strait of Sicily*

On the African mainland, south of the Gulf of Sirte, there is a system of tensional faults (including the Hon Graben), and associated Quaternary basaltic volcanism. Northwestwards in the Strait of Sicily, similar features are present in the form of three major grabens (Malta, Pantelleria and Linosa Troughs) which are also associated with Quaternary basaltic volcanism, some of it submarine.

The wide Gulf of Sirte has a continental slope and rise of low gradient underlain by thick Tertiary and probably also Mesozoic sediments which can be followed beneath the Ionian Sea (Finetti & Morelli 1973). These authors also note that, apart from local vertical faulting, the lower slopes are dominated by horsts and grabens.

New observations were only made on a single traverse along the lower slope of this Gulf, from south of the Cyrenian Seamounts to the Medina Seamounts (figure 4). South of the Cyrenian Seamounts the sonographs indicate a possible conjugate system of northeast and northwest trending faults. Further westwards the reflexion profile indicates normal faulting and grabens up to 150 m deep. Smaller features with a relief of about 20 m appear to be grabens or hollows situated above small diapirs, some of which may have undergone solution on reaching the sea floor. The associated sonograph indicates that some of the larger fault scarps have a general northerly trend. The smaller features, although apparently not steep or large enough to show up well on the sonographs, also follow the same northerly trend.

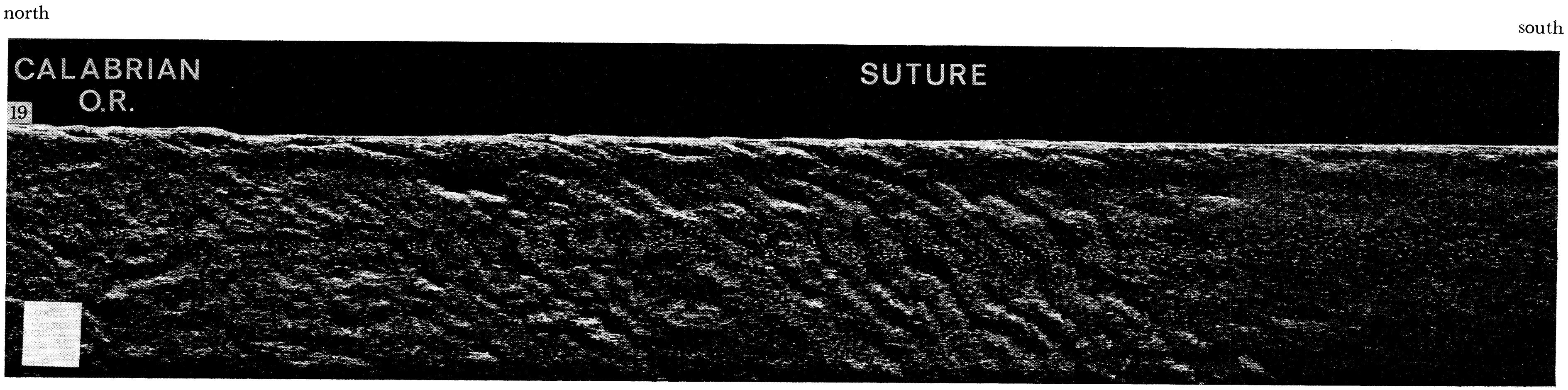
The available evidence therefore suggests that the Gulf of Sirte and neighbouring land is an area of tension at the present time. This is in marked contrast with the floor to the north of it. The change over from tensional to compressional deformation occurs in the vicinity of the narrow Sirte Abyssal Plain and the Cyrenian Seamounts, around which the Hellenic Outer Ridge folds are bent (figure 14, plate 5).

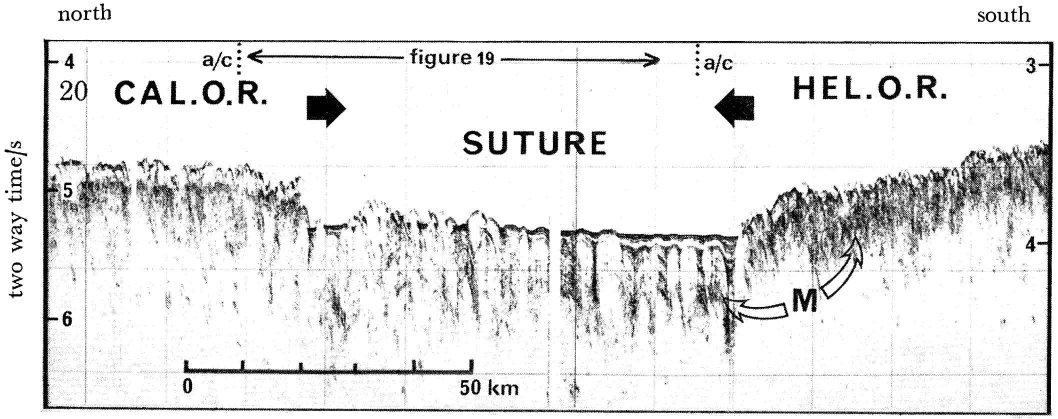
(iv) *The Ragusa Platform, Malta Escarpment and Medina Seamounts*

The Ragusa Platform of southeastern Sicily (together with its southwards submarine extension as the Malta Platform) consists largely of Mesozoic neritic limestones. On the north of this platform there are the extensive Neogene basalts of the Iblean Mountains.

The 3 km high Malta Escarpment is at its most precipitous off Sicily, while off the Malta shelf the lower half becomes less steep (figures 1 and 2). It is associated with strong magnetic anomalies (Finetti & Morelli 1973). The northernmost of two side-scan sonar crossings of this Escarpment (figure 4) viewed a spur of rough ground with stepped, alongslope-trending features that gave rise to strong reflexions. These may represent basic igneous rock outcrops as they are associated with a magnetic anomaly. They are crossed by weaker downslope trending relief features that may represent slump trails or turbidity current paths. More obvious downslope trending features were seen on the second crossing. These are slightly curved and at least 13 km long, extending well beyond the base of the Escarpment.

Magnetic anomalies are also associated with the Medina Seamounts. The northern and eastern slopes of these give rise to strong reflexions, as seen on sonographs. At the northeastern





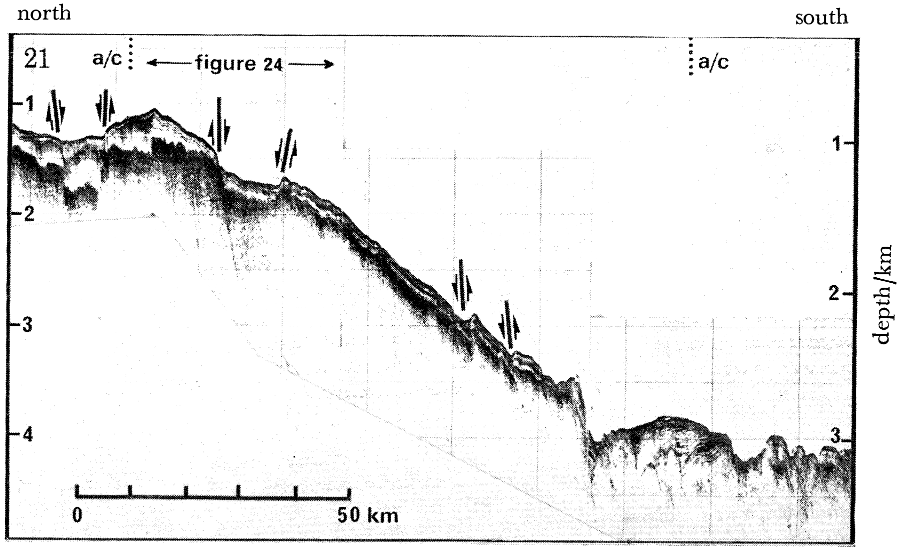
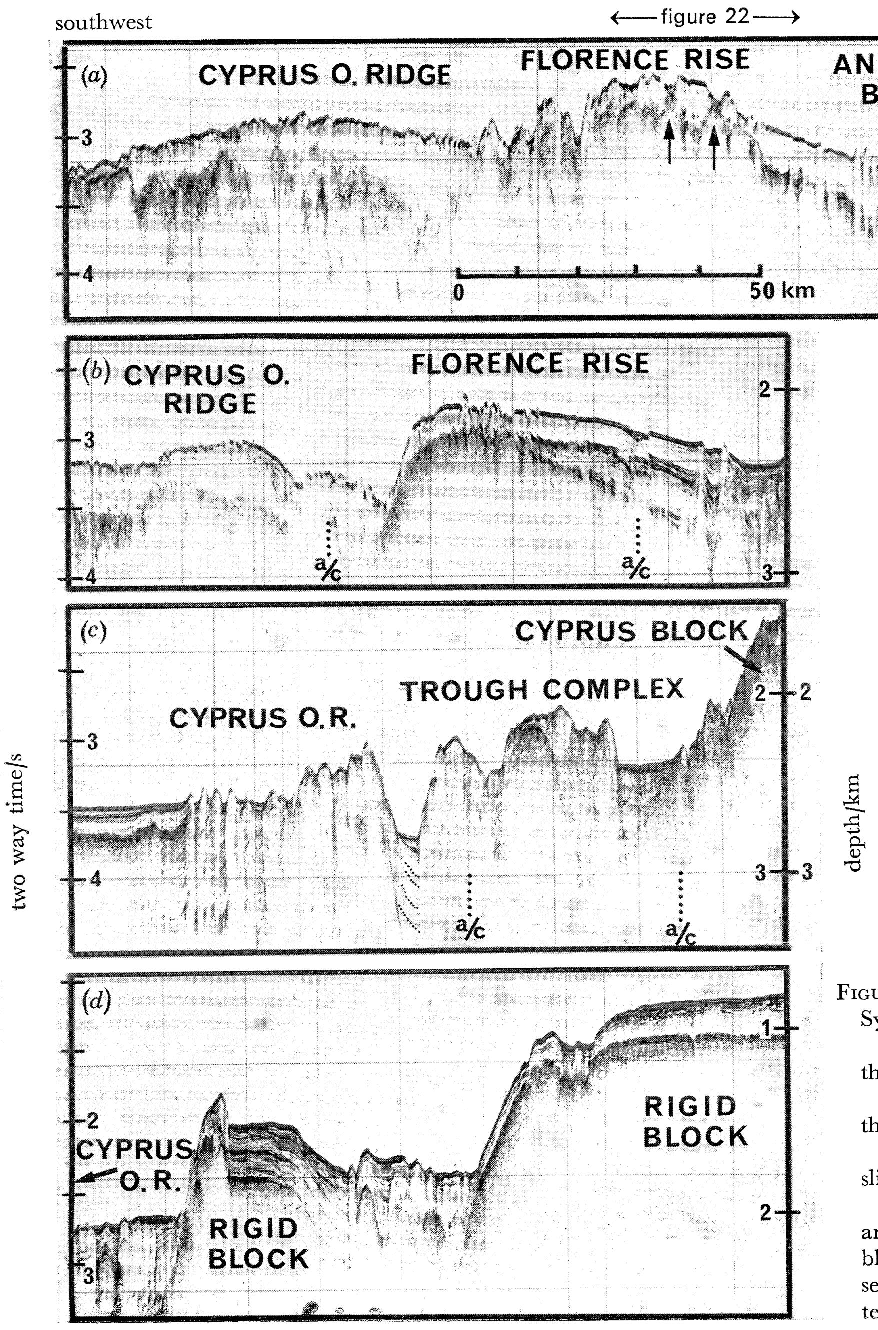


FIGURE 19. Sonograph showing sinuous folds (style A of plate 2) and flat floor in the suture between the Calabrian Outer Ridge (left) and the Hellenic Outer Ridge (shown in figure 20).

FIGURE 20. Air-gun profile showing the relatively steep sided suture between the Calabrian and Hellenic Outer Ridges at the northern apex of the Messina Abyssal Plain where it merges into the suture. This is interpreted as a thrust-bounded ramp valley. The black arrows represent the outward directions of advance of the Ridges. The M horizon is shown.

FIGURE 21. Air-gun profile across the Apulian Escarpment, with normal faulting at the top and possible thrusting (related to strike-slip motion) lower down. Note the disturbed and uplifted wedge of layered sediments in the trough at its base.



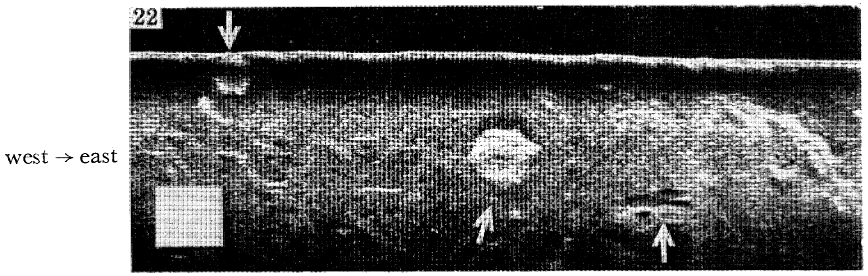


FIGURE 22. Sonograph showing rough surfaced, isolated, subcircular depressions (arrows) within the Florence Rise that may be the surface expressions of salt domes (see companion air-gun profile in figure 23 *a*).

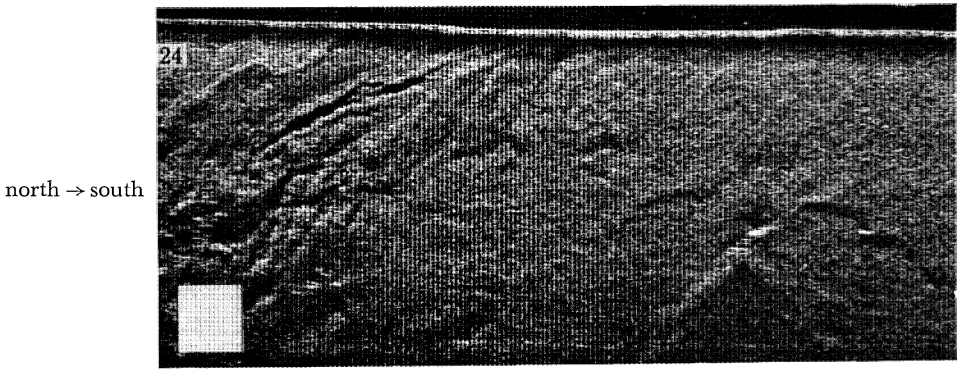


FIGURE 24. Sonograph showing northwesterly trending fault traces associated with grabens on top of the Apulian Plateau. These are shown in profile in figure 21.

FIGURE 23. Air-gun profiles across some submarine parts of the Cyprus Arc System.

Profile (*a*). Note the diapirs (arrows) that reach the sea floor on top of the Florence Rise.

Profile (*b*). Note that normal faulting and possible diapirs have affected the northern flank of the Florence Rise.

Profile (*c*). Note the trench with northerly tilted fill (its bedding has been slightly emphasized to make it more evident on this photograph).

Profile (*d*). The rigid blocks overlain by relatively undisturbed sediment are eastward extensions of the Hecateus Mountains (left) and the Cyprus block (right). The deformation of the sediments in the intervening trough seems to be compressional. The Cyprus Outer Ridge structures can be extended further south (left) as shown by Giermann (1966, profile K).

corner of the seamount chain (figure 4) there are features trending northeast–southwest along their length as well as other, more numerous features (probably faults) trending northwest–southeast. The lower flanks of these seamounts are mantled by partly slumped sediments up to 150 m thick. These pass laterally into the thicker (250 m), flat lying sequence (including turbidites) of the Messina Abyssal Plain and the downwarped sediments of the marginal trough at the base of the Malta Escarpment. As these deposits overlie the 'M' horizon, as well as the seamounts, the latter could be of Late Miocene age.

The Malta Escarpment and its probable associated basic igneous bodies is seen as originating as a tensional faulted flexure presumed to be coeval with the Neogene basaltic volcanism of the Iblean region of southeastern Sicily. Finetti & Morelli (1973) related this to a postulated Miocene collapse of the Ionian Basin. The substantial late Quaternary basaltic volcanism of Mt Etna implies continuing underlying tension in eastern Sicily. Grindley (1973) has drawn attention to the difficulty of associating this with its position directly in front of the compressional Calabrian Arc. As discussed earlier, there may now also be a dextral strike-slip component along the Malta Escarpment to accommodate the outward push of the modern Calabrian Arc System.

(v) *The Apulian Plateau*

The Apulian 'Plateau' is the ridge extending seaward of the Mesozoic–Palaeogene shelf-carbonate Apulian Platform which constitutes the 'heel' of Italy. In age, composition and location in relation to the Calabrian Arc the Apulian Platform is closely comparable with the Ragusa Platform of southeastern Sicily. Both are unaffected by Alpine folding. The escarpment and trough on the southern side of the Apulian Plateau is analogous to the Malta Escarpment and trough, and is probably also associated with strike-slip movement (in this case sinistral) together with possible associated thrusting as mentioned on page 267. The Apulian Platform is apposed on the west by the Calabrian Arc System and to the east by the western end of the Hellenic Arc System. Thus Aubouin (1965) described the Platform as an 'intermediate foreland' situated in the axial zone of a 'convergent bicouple'.

Our air-gun profile shows several instances of normal faulting and associated grabens on the top of the Plateau. The corresponding sonograph shows that the faults trend northwest along its axis (figure 24, plate 8). North of the Plateau, in a region of rapid deposition (the Kerkira Basin), a smooth, uniform-toned floor is seen, except along the axis of the trough between the Plateau and Greece, where a shallow but steep-edged, narrow, linear channel or fault is observed on the sonograph over a distance of 14 km. At the base of the continental slope off the northern end of the island of Corfu (Kerkira) there is also evidence on the air-gun profile of a local sedimentary fan (with complex proximal bedding) which is supplied along a canyon seen in the sonograph.

(vi) *The Bey Daglari*

The Bey Daglari is another (mainly Mesozoic) shelf carbonate platform which, as with the Apulian Platform, is situated in an axial zone of convergence and thus may be considered to be an 'intermediate foreland'.

5. DEVELOPMENT OF THE OUTER RIDGES AND ASSOCIATED ARCS

It has generally been agreed that the gross structure of the Hellenic Outer Ridge is tectonic in origin, although the age and mechanism are in question. The choice offered by other workers is broadly (p. 256) between a Hellenic Outer Ridge that was associated with the Miocene formation of the Hellenides, and an Outer Ridge that developed as a result of Plio-Quaternary plate motion. A late Miocene or earlier initiation of uplift would seem to be supported by indications from sub-bottom reflexion profiles that the Messinian evaporites are thinner on the flanks of the Hellenic Outer Ridge and may even be absent from its crest (Finetti & Morelli 1973). The discovery of flysch-like sediments of Middle Miocene age in DSDP borehole 377 (*Geo Times* **20** (8), 16–19, 1975) situated near the middle of the Hellenic Outer Ridge suggests that the feature was then non-existent, at least at that locality. Furthermore there was no evidence in the pre-evaporite sediments to support the view that the Hellenic Outer Ridge is basically a giant olistostrome.

The smaller scale relief of the Hellenic Outer Ridge has generally been attributed to folding and faulting. Hieke *et al.* (1973) have suggested that tensional cracking on the crest of a compressional arch will induce a series of Ridge-parallel grabens. This latter possibility cannot be entirely discounted on available evidence, although no features resembling well formed grabens such as can be seen on the Nile Cone (Kenyon *et al.* 1975) have been recognized. Moreover, grabens would be out of keeping with the abundant cross faults. The Hellenic Outer Ridge relief has also been interpreted as karst topography (such as dolines) resulting from solution of Messinian evaporites (Ryan 1973) (or as relief due to diapirism associated with these same evaporites). Certainly there is some karstic relief associated with Miocene anhydrite in Sicily (Mascle & Mascle 1972), including dolines, but these authors make no mention of an ordered pattern of features, such as those which parallel the Outer Ridges. The main grain of the three Outer Ridges is also inconsistent with sub-aerial drainage patterns as it does not extend down the regional slopes. The only portion of the Outer Ridges where cursory examination of sonographs might suggest the presence of karstic depressions (Ryan 1973) is where the Hellenic Outer Ridge is much disturbed by cross fractures, such as north of Cyrenaica (Belderson, Kenyon, Stride & Stubbs 1973, Figure 109). A further argument against karst would be the progressively increasing degree of deformation northwards across the Outer Ridge which is clearly of tectonic origin.

The most satisfactory explanation for the existence of the broad swell of the Hellenic Outer Ridge, as well as for the small-scale structures affecting even Quaternary sediments, is that it is due to Plio-Quaternary tectonic deformation – associated with the *continuing* evolution of the compressional Cenozoic Hellenides fold belt. The sonograph data show unequivocably that the main structural grain is parallel to the length of the Hellenic Outer Ridge and also to the line of the Hellenides. The same correlation applies between the Calabrian Outer Ridge and the Calabrian Arc, and the Cyprus Outer Ridge and the Cyprus Arc. The present-day activity of these Arc Systems is evidenced by the modern andesitic vulcanicity of two of them, the strong seismicity (less active in relation to the Calabrian and Cyprus Arcs than to the Hellenic Arc), the recent tilting of young sedimentary fill in the deeps of the Hellenic Trough Complex and its equivalent south of Cyprus, and the rapid vertical movements inferred from the study of coastal archaeological sites and uplifted Quaternary terraces, as well as in more general terms by the extreme narrowness of the associated shelves in comparison to the broader more stable foreland shelves, such as the Libyan shelf to the south. The continuing uplift of the Hellenic Outer Ridge is shown by the presence of Quaternary turbidites, presumably originally deposited on abyssal plains but now found at various levels within this Outer Ridge (see, for example, Ryan *et al.* 1971; Ryan, Hsü *et al.* 1973, DSDP Site 130; Hieke, Melguen & Fabricius (in the press).

The gross profile and small-scale relief of the Hellenic Outer Ridge show that the portion with most tectonic disturbance (the 'Upper Plateau') is located south of Crete, in the narrowest part of the Eastern Mediterranean (figure 4). Here the Ridge is at its shallowest and narrowest as are also the adjacent parts of the Hellenic and Southern Troughs. Its southern slope has steps on it and is relatively steep: the southern edge wraps around the foot of the Cyrenaican continental slope such that the Southern Trough is at its narrowest and has no horizontal fill at present. Deep trenches of the Hellenic Trough Complex nose towards this highest part of the Outer Ridge, which is associated with some seismic activity (Papazachos 1974). The tentative conclusion is that this middle portion of the Outer Ridge is at a more advanced evolutionary stage, where the crust has been thickened by thrusting (associated with transcurrent faults) but not yet converted into the tectonic style seen in the Hellenic Trough Complex.

The 90 km wide 'Lower Plateau' between the shallowest part of the Hellenic Outer Ridge and the Hellenic Trough Complex is seen as a relatively little deformed block, in spite of the intense disturbance around and presumably even beneath it. If so it may be analogous to the many unfolded plateaus and basins within the Jura fold belt which have been translated along with the rest of the sedimentary cover above the basal thrust (Laubscher 1972).

The structural continuation of the Hellenic Outer Ridge (and the associated portions of the Hellenic Trough Complex and Southern Trough) into the region of the Ionian Islands is accompanied by narrowing of the structural zones due to severe constriction against the Apulian Plateau (figure 1). This foreshortening may be partly accommodated by the series of dextral transcurrent faults already known in western Greece (B.P. 1971).

In the case of the Calabrian Arc System petrological and isotopic data (Barberi *et al.* 1974) indicate that the Aeolian Island volcanoes probably have an upper mantle source (which they related to a supposed down-going 'oceanic' slab), and that the arc has now reached a senile stage of evolution. This is in keeping with the more advanced stage of collapse that has been reached in the Tyrrhenian Basin compared with the partial collapse of the Aegean floor.

Ritsema (1970, 1972) concluded that it is Calabria that is actively overriding the Ionian Basin, rather than the latter actively subducting beneath the former. He pointed out the structural and geometrical impossibility for the Ionian block to be 'subducting' to both WNW (beneath the Calabrian Arc) and ENE (beneath the Hellenic Arc) at the same time, especially as there are few earthquakes occurring within the middle of this basin. It seems, therefore, that a tongue, bounded to either side by faults along the Apulian and Malta Escarpments, has moved out into the Ionian Basin, raising ahead of it the compressional Calabrian Outer Ridge. Any lateral but foreshortened structural equivalents of the Calabrian Outer Ridge should be sought westwards in the Caltanisetta region of Sicily, and to the north in the Appennine Foredeep where a possible equivalent structure has been described (Jacobacci 1962, Figure 1). Geological, seismic and palaeomagnetic data suggest that the Ragusa (Iblean) Platform of southeastern Sicily and the Apulian Platform of southeastern Italy are both parts of the African block (Channell & Tarling 1975). Furthermore, palaeomagnetic data (J. E. T. Channell, private communication) suggest that the Sicilian allochthons have been systematically rotated in a *clockwise* direction relative to the autochthonous Iblean region, while the southern Apennine allochthons show systematic *anticlockwise* rotations relative to the Apulian region. These rotations are in the correct sense to suggest substantial bending on either flank of the central Calabrian Arc as it has pushed outwards. Thus, Carey's (1958) concept of a 'Sicilian Orocline' may be correct, in so far as its curvature is interpreted as having been impressed rather than pre-existing.

The western part of the Cyprus Outer Ridge is less deformed than much of the Hellenic Outer Ridge and the degree of development decreases eastwards. The Cyprus Arc System is also at present less associated with seismicity. This implies that the Cyprus Arc System is now less active than the Hellenic Arc System. The anticlockwise post-Cretaceous rotation of Cyprus (Moores & Vine 1971) is in the correct sense to suggest bending here, as with the Calabrian Arc (except that the 90° rotation would seem to be rather too large). Cyprus would thus seem to have behaved as a large raft rather than a rigidly rooted block.

A notable feature of the Calabrian and Hellenic Arc Systems (and probably the Cyprus Arc System as well) is that their evolution in plan view seems to have been accomplished by a combination of strike-slip faulting with a process of flexure. The faulting is predominantly right and left lateral on the right and left sides of the arc, respectively (looking outwards). The outwards flexure involves rotation of the two limbs of the arc, such that the right side rotates clockwise and the left side anticlockwise, so as to increase the overall curvature.

6. Analogues of the outer ridges

We suggest that a well developed Outer Ridge can be recognized to the east of the Barbados Ridge at the southeastern part of the Antilles Arc System, and that a similar Outer Ridge may be present in the external part of the Indonesian Arc System. These will be described more fully elsewhere (Belderson & Kenyon 1977).

Giermann (1966, 1969) was the first to liken the 1300 km long Hellenic Outer Ridge to the 'foreland' fold belt of the Jura. Such a comparison might be useful, bearing in mind that with a length of 300 km and width of 80 km the Jura is more nearly comparable with the Calabrian Outer Ridge. The Jura mountains are an arcuate belt of folds which may be considered the most external and youngest of the décollement sheets of the Alps (Laubscher 1972). Rocks outcropping there are entirely sedimentary, with about 200 m of Tertiary 'molasse' overlying about 1500 m of Mesozoic limestones and shales, as well as Middle Triassic evaporites. The outer margin of the Jura varies from being sharply defined by thrusts to narrowly gradational, where 'foreland' folds occur (Bernoulli, Laubscher, Trümpy & Wenk 1974). Subordinate to the thrusting and folding there are many minor transverse strike-slip faults showing displacements of up to about 300 m, with predominantly sinistral movement on the left and dextral on the right of the Arc (facing outwards). The folds have an average amplitude of 1000 m and wavelength of 2500 m, with vergence vertical or directed northwest (outwards). There appear therefore to be similarities in structural style between the Jura and the Hellenic Outer Ridge, except that thrusting and strike-slip faulting, although strongly suspected, remain to be proven for the latter.

7. MODERN MIOGEANTICLINES† OF THE EASTERN MEDITERRANEAN

Aubouin (1965) stressed that in an elementary 'geosyncline' the geanticlinal ridges are as important as the geosynclinal furrows. He further felt 'compelled to suppose' that a 'wave of intumescence' was propagated from the interior towards the exterior of the system. Indeed, he provided good documentation (Aubouin 1965, Figure 51) for an outward migration of orogenesis in time for the Hellenides, and such appears to be typical of the fold belt extending from the Zagros (see, for example, Falcon 1974, Figure 2) through the Taurids, Hellenides, Carpathians, Alps and Apennines. In the case of the Hellenides, which developed progressively in successive tectonic zones during the Cretaceous and Tertiary, Aubouin concluded that their geosynclinal evolution had been completed and that they (including both the Aegean and Ionian Basins) were now in a 'post-geosynclinal' period of extension, normal faulting and subsidence. The subsequent discovery of the Hellenic Outer Ridge even further to the south, when considered in conjunction with the continuing and vigorous earthquake activity along the Hellenic Arc suggests, however, that the orogeny is far from complete, and that compression and consequent outward migration still continue with the development of a new miogeanticlinal ridge, which itself is already in an advanced stage of evolution in the segment between Cyrenaica and Crete. Thus, if the mio-eugeosynclinal scheme of the Mesozoic–Tertiary Hellenides of Aubouin (1965) is applied to the modern Hellenic Arc System, the following sequence from north (internal zones) to south (external zones) is recognized (figure 25): the Aegean Sea with its andesitic volcanoes – the inner (tensional) marine basin; the Hellenic Arc – the eugeanticlinal ridge (massive overthrusting); the Hellenic Trough Complex – the eugeosynclinal furrow (outcrop of major thrust planes); the Hellenic Outer Ridge – the miogeanticlinal ridge (compressional uparching); the Southern Trough (the trench and abyssal plain zone south of the Ridge) – the miogeosynclinal furrow (incipient compression). This arc system of ridges and troughs fronts on to Africa – the modern, broadly tensional foreland. The same sequence can be recognized for the Calabrian and Cyprus Arc Systems, but is not so well developed. The Apulian Platform and perhaps the Bey Daglari are 'intermediate forelands' situated between converging arc systems. The relationship of the three Arc Systems to the various major graben systems situated within the foreland (Malta, Pantelleria, Linosa, Hon and Gulf of Suez grabens) remains enigmatic.

8. INDICATIONS OF THE DRIVING FORCE

It is apparent that simple collision between the African and Eurasian plates with associated subduction (see, for example, Ryan *et al.* 1971), which by great coincidence has only now finally consumed any former oceanic crust, does not seem to account for such facts as the apposition of the Calabrian and Hellenic Arcs across the Ionian Basin, or the radial polarity of the Arc Systems. The more complex hypothesis of McKenzie (1972) faces the same problem. Furthermore, if the supposed Aegean and Turkish rigid 'micro-plates' are being pushed aside by the Arabian plate, it is difficult to explain the distortion and stretching along the Hellenic Arc and the normal faulting in the Aegean and western Turkey suggested by that author. We therefore incline to the view of Van Bemmelen (1972), who invoked an orogenic wave directed outwards

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† These miogeanticlines and miogeosynclines are evolving within an *active* orogenic setting. They must not be confused with the fundamentally different features of the *passive* Atlantic continental margin of eastern U.S.A., in spite of the somewhat similar terminology used by certain workers.

from a 'mushrooming' mantle diapir or 'geotumour'. Such a mantle diapir located beneath the Tyrrhenian is thought to be in a dying phase of development, with the sea floor now subsided to great depths and intruded and covered in parts by basaltic outpourings, while the Aegean floor is at a relatively more youthful stage of subsidence, with a far greater degree of seismicity along its southwards thrusting perimeter. Further mantle diapirs, 'still in a tumescent state', are suggested by Van Bemmelen to be situated beneath Turkey, which would account for the Cyprus Arc System. Thus, rather than there being a series of subduction zones resulting from world-wide plate motion, with *underthrusting* from the south (Ionian–Levantine Basin) side of the Arcs, there should be *overthrusting* emanating from a series of local outwards pushing mantle diapirs located to the north, with perhaps only minor anticlockwise rotation of Africa. The preferential outward push on one flank of such a diapir has been accounted for by the supposed diapirs having inclined axes (Krebs 1975). Further east, however, modern compression along the Zagros fold belt is more readily explained by the relatively rapid northeastward movement of the Arabian Plate away from the active Red Sea spreading axis.

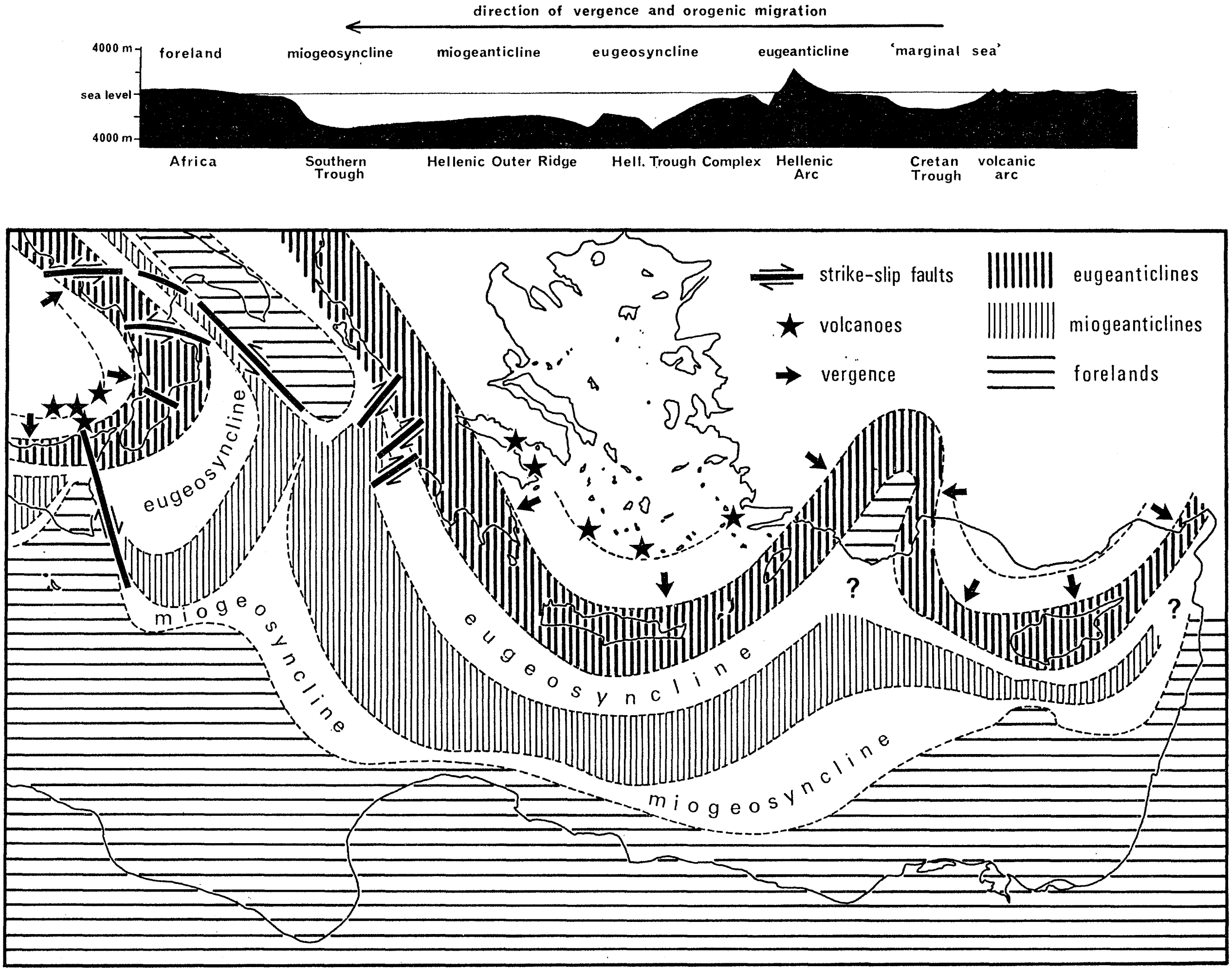

FIGURE 25. The on-going geosynclinal systems of the Eastern Mediterranean (volcanoes which are dominantly basaltic are not shown). The north–south profile of the modern Hellenic Arc System is drawn through the longitude of eastern Crete.

If the existence of a series of mantle diapirs is accepted, then the question why they occur there needs to be posed. It has been suggested that the north–south closure between Africa and Eurasia across the Tethys, starting in the Upper Jurassic in the west and proceeding eastwards in time, as indicated by a belt of Jurassic–Cretaceous ophiolites younging eastwards through the region (Moores 1970), overrode an actively spreading mid-ocean ridge (Dewey, Pitman, Ryan & Bonnin 1973). Is it possible that mantle plumes associated with this former spreading axis have remained active enough in the post-collision period to produce the orogenic belts which have dominated the post-Cretaceous evolution of the region?

Finally, it is worth looking a little more closely at the contrast between orogeny produced by subduction associated with world wide ocean floor spreading, and orogeny associated with the Arc Systems of the Eastern Mediterranean (and perhaps some other arc systems as well). Ocean floor spreading, as visualized by Morgan (1972) is driven by a relatively small number of mantle plumes, or 'hot spots', which are *coupled* to the base of 'lithospheric plates', with only passive upwelling of basaltic material along much of the resulting mid-ocean ridge system. In contrast to this, it has been proposed (in relation to the Western Mediterranean) by Alvarez (1972) that a mantle plume *uncoupled* from the base of the lithosphere explains the basic tectonic features. This would involve erosion and deposition on the underside of the crust in the form of an inverted 'subcrustal ripple pattern' of large ridges and troughs concentric about the rising mantle column. Such a pattern would seem to be worth considering as being applicable to the three Arc Systems in the vicinity of the Eastern Mediterranean. If this suggestion is correct it may be relevant that Alvarez argued that subcrustal erosion beneath the eugeosyncline would eventually weaken the crust to such an extent that it would be shortened by crushing. In the case of the Hellenic Trough this would mean that the Hellenic Arc and Hellenic Outer Ridge would be thrust together (as already partly achieved south of Crete). However, the greater outwards growth of the Ridge to the east and west of the 'Upper Plateau' would suggest that the outwards migration of the Arc System is accomplished by a more steady advance rather than by means of a series of 'jumps'.

9. Main conclusions

Relatively small-scale relief, seen in plan view by means of long range side-scan sonar, has provided widespread evidence of distinctive structural trends on the floor of the eastern half of the Mediterranean Sea.

The main structural trends (folds and strike faults) recognized on sonographs follow the curve of the Hellenic Outer Ridge (previously known as Mediterranean Ridge, Mediterranean Outer Ridge or Mediterranean Rise). They also suggest a structural prolongation of the Ridge into the Ionian Islands west of Greece.

Similarly, a ridge located outside the Calabrian Arc is shown to exist in the west (Calabrian Outer Ridge). This is partly welded to the Hellenic Outer Ridge across a narrow suture zone, and may extend from there into the Appennine Foredeep of Italy.

The eastern end of the Hellenic Outer Ridge merges with a less well developed ridge (Cyprus Outer Ridge) that is situated external to the Cyprus Arc.

Cross-faults (possibly strike-slip) are abundant in a zone along the northern side of the Hellenic Outer Ridge. They are also well developed north of Cyrenaica, where the Outer Ridge is both highest and narrowest, and where the intensity of deformation is greatest and is thought to be accompanied by thrusting. Elsewhere the deformation decreases in intensity southwards across the Outer Ridge.

Slumping seems to be responsible for a progressive reduction in the height of the relief produced by folding and faulting.

The Hellenic Outer Ridge is interpreted as a miogeanticline belonging to the Plio-Quaternary phase of the continuing southwards migration of the Hellenic Arc System. Likewise the Calabrian and Cyprus Outer Ridges are seen as Plio-Quaternary miogeanticlines relating to the Calabrian and Cyprus Arc Systems, respectively. These three miogeanticlines are of particular interest because they reveal some early evolutionary stages of a compressional mountain range, which could never be observed unaltered above sea level.

The overall curvature of the Arc Systems seems to have been accomplished by both strike-slip faulting and flexure. The former is right and left-lateral on the right and left sides of the Arc, respectively (looking outwards). The latter involves rotation of the outer limbs of the Arc in a clockwise direction on the right side, and anticlockwise on the left side of the Arc.

The driving force of the orogeny is seen as resulting from mantle diapirs spreading *outwards* from the Tyrrhenian, Aegean and Turkish regions, rather than from closure of the Eastern Mediterranean due to a supposed plate convergence of Eurasia and Africa.

A deformed sedimentary ridge, external to the Barbados Ridge of the Antilles Arc, is thought to be analogous to the young miogeanticlines of the Eastern Mediterranean described in this paper.

The successful evolution and operation of the Institute of Oceanographic Sciences' prototype long range side-scan sonar (GLORIA) has called for the cooperation of many people, although space only allows a few to be acknowledged by name. The authors are especially grateful to Dr J. S. M. Rusby, and Mr M. L. Somers, successive leaders of the GLORIA team, and Mr J. Revie for his care with the production of sonographs and for their subsequent treatment, in conjunction with Mr C. D. Pelton. It is a pleasure too, to acknowledge the work done by the diving team led by Mr S. K. Willis, and to thank Messrs A. R. Stubbs and C. Flewellen for their setting up and operation of narrow beam sounder and air-gun systems respectively. Grateful thanks must also be offered to Captain G. F. Howe and his officers and men on R.R.S. *Discovery*, especially for their careful work during launch and recovery of the GLORIA vehicle.

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Appendix. The side-scan sonar system

By M. L. SOMERS

(a) *Acoustic considerations applicable to side-scan sonar*

In acoustic terms the function of side-scan sonar is to map the acoustic backscattering from the sea-floor on to a suitable recording medium, which it does by successively scanning each point on the sea-floor in a series of lines perpendicular to the survey track and extending to the extreme range. The lines are occupied successively by moving the sonar transducer along the survey track. In order to carry out this task the sonar must receive enough energy from each point to detect it above ambient noise, and this involves both geometrical and physical limits. The geometrical limits arise from the variation from place to place of the velocity of acoustic propagation. The physical limits arise from a number of causes among them being spherical spreading, attenuation, peak power limits, angular variation of backscattering and ambient noise level.

(b) *Variations in the velocity of propagation*

The velocity of sound propagation in the sea has a marked variation with depth. Broadly speaking in the first few hundred metres the drop in temperature causes a fairly rapid fall in velocity. At about 1000 m there is a velocity minimum but at greater depths this is compensated by a rise due to increasing pressure. Below about 1300 m the water is nearly isothermal and the velocity rises steadily thereafter. In high latitudes where the surface temperature is much lower the minimum is less pronounced or absent altogether. The steadily rising velocity at great depths gives the sound rays an upward curvature such that a ray launched at a shallow angle becomes horizontal before it reaches the bottom. This gives rise to the so called Deep Shadow Zone and limits the range, at any depth, at which side-scan sonar remains effective, and it is in fact seldom reasonable to strive for ranges in excess of 28 km. Of course greater ranges can be obtained if the ground slopes upwards towards the extreme range, but the survey cannot always be carried out in this way.

(c) *The shape of the sonar beam*

In side-scan sonar the angular shape of the beam is of paramount importance. In the horizontal plane the beam should be as narrow as possible so as to obtain the maximum cross-range resolution at extreme range. On the other hand there is a limit to the size of array which can be handled and to the frequency which may be transmitted without unacceptable propagation losses. These two effects conspire to limit the horizontal beam width to about 2°. It is then fairly simple to stabilise the receiver beam during the inter-pulse period. The vertical beam is made wide enough to allow proper illumination of the bottom out to extreme ranges. The GLORIA array was designed for a 10° vertical beam, but this has proved to be too narrow, and in 1973 a 30° vertical beam was used with great success, though the optimum would appear to be somewhere between 20° and 30°.

(d) *Transmitted power and noise*

Peak transmitted power is limited by cavitation at the transducer face. The permissible level rises very slowly with frequency in the low kilohertz region applicable to long range side-scan sonar, and higher power levels can be tolerated only by increasing the operating depth of the array. The GLORIA array was designed to handle 60 kW at a depth of 150 m, and this was the output of the largest amplifier available in the country at the time outside the field of radio transmitters.

The ambient noise is invariably dominated by the self noise of the survey vessel, and cavitation at the screw can be particularly troublesome. The noise level itself falls at about 10–15 dB per decade of frequency in this frequency range, and as far as the array is concerned it is directional and so is reduced by the directivity of the array. This again slightly favours high frequencies.

(*e*) *Attenuation*

All these effects, however, are completely eclipsed by attenuation, which increases as the square of the frequency and for any range imposes absolute upper limits to the frequency of operation. The GLORIA system was designed to operate at 7 khz where the round trip attenuation over a 22 km range would be 18 dB, which is still manageable. At 10 kHz an extra 20 dB attenuation would be incurred. As it happened the design frequency was fixed at 6.4 kHz for other reasons and the attenuation loss is only 15 dB.

Having taken the decision to deploy the transducer array at depth so as to increase the transmission power capability and to ease propagation problems a further benefit accrues in that the array is removed from the major source of ambient noise.

(*f*) *The bottom backscattering process*

The major unknown in the equation is the strength of backscattering from the bottom, and since the survey is concerned with mapping this over unknown terrain this is hardly surprising. On the other hand it is possible to put bounds on the backscattering strength at the design stage of the sonar, the lower bound being set by the sonar design parameters discussed in previous paragraphs. And if the noise level is set at the threshold of the display, the upper bound determines the required dynamic range of the display. In order to maximize the displayed dynamic range of the backscattering function, the backscattered energy is normalized by time varied gain to eliminate the effect of spreading and attenuation. At angles of incidence nearer the vertical than about 45° the situation is complicated by a number of factors. First the backscattering function increases quite sharply towards normal incidence, secondly the area of the bottom illuminated by the pulse increases towards the vertical and lastly, associated with this, if recorded on a linear recorder (i.e. with a constant velocity stylus), the scale becomes distorted towards the vertical. Various schemes have been evolved for eliminating this distortion but none has gained wide acceptance, mainly because the change in scattering geometry ensures that one is no longer comparing like with like.

In order to estimate the acoustic pressure at the transducer due to the wave backscattering from the sea floor one computes from classical scattering theory the echo from a perfectly reflecting spherical target of cross-section A and one then multiplies this area A by a non-dimensional scattering function $S_{\text{h.f.}}$. The reason for the suffix h.f. is that, in side-scan sonar, conditions approximate to the high-frequency limit of the sea-floor model used. So far the description is elementary and takes the form

$$\langle s^2 \rangle = \frac{p_0}{4\pi} \rho c D F \frac{A}{R^4} \mathrm{e}^{-2\alpha R} S_{\text{h.f.}},$$

where $\langle s^2 \rangle$ is the mean square echo pressure amplitude. In the more usual decibel notation this reads

$$20 \lg \tilde{s} = 71.6 + 10 \lg P_0 + \text{D.I.} - 40 \lg R - 2\alpha R + 10 \lg A + 10 \lg S_{\text{h.f.}},$$

where $\tilde{s}$ is now the r.m.s. pressure in microbars, 71.6 allows P_0 to be expressed in dB relative to 1 W, R is in yards, α is in decibels per yard, A in square yards and D.I. is the directivity index. At near grazing incidence A is given by

$$A = \tfrac{1}{2}R\theta_{\mathrm{h}}c\tau,$$

where θ_{h} is the effective horizontal beam angle, c is the velocity of propagation and τ the pulse length, or more generally the effective width of the transmitted pulse auto-correlation function. τ is expressed as a statistical quantity, since the bottom model on which the calculation of $S_{\mathrm{h.f.}}$ is based is essentially statistical in the absence of knowledge of the detailed bottom topography.

A model for backscattering purposes presents great difficulty for angles near grazing incidence. Essentially one can either model the bottom as a random collection of reflecting facets and postulate physically reasonable distributions for facet sizes and slopes, or one can attempt to evaluate the Helmholtz integral for the known illumination distribution and physically reason able bottom slopes or elevations. Both models make the Kirchhoff approximation, which assumes that the local radius of curvature of the boundary is everywhere greater than the wavelength, and both models assume an absence of shadowing. This latter assumption is clearly incorrect in side-scan sonar conditions, and the former is to say the least questionable over most of the ocean floor.

(*g*) *The sonar equation*

By inserting the known factors for the GLORIA system into the sonar equation and equating the echo level so obtained to the known noise level one can arrive at a figure which the backscattering function must exceed. The calculation goes (in decibel notation) as follows

power level, P_0 = 10 kW = +40 dB
directivity index = +32 dB
processing gain = 23 dB
conversion (W → μbar)† = 71.6 dB

total source level = 166.6 dB rel. 1 μbar at 1 m

† 1 bar = 10^5Pa.

Since $A = \frac{1}{2}\theta_{\mathrm{h}}c\tau \times R$, we can incorporate the range dependence in the spreading term

$10 \lg (\frac{1}{2}\theta_{\mathrm{h}}c\tau)$ = -1.5
$-30 \lg R$ = -130.2 dB
$-2\alpha R$ = -22 dB

153.7 dB total.

Thus $\tilde{s} = 12.9 + S_{\mathrm{h.f.}}$ dB, and with the operating noise level of about -40 dB, corrected for directivity and receiver bandwidth we have the result that

$$S_{\mathrm{h.f.}} \geqslant -53 \text{ dB}.$$

In fact models of the sea-floor based on a Gaussian distribution of bottom slopes predict that $S_{\mathrm{h.f.}}$ falls below this value at angles of incidence around 45°, well before grazing incidence except for extremely rough floors. However since side-scan sonar demonstrably works at the GLORIA frequency, the violation of the Kirchhoff approximation and assumption of no shadowing must have a profound effect on the backscattering. On the other hand over an abyssal plain area the records show that $S_{\mathrm{h.f.}}$ in accordance with the model, falls well below -53 dB. One can conclude that even at these frequencies side-scan sonar is capable of distinguishing textural differences on the sea floor, and this conclusion is borne out by recent evidence.

(*h*) *Vehicle design*

The Gloria array, 3 m long by 1.6 m high, had to be towed horizontally on a stable heading at a depth of about 130 m, and the array tilt about the long (fore and aft) axis had to be remotely adjustable over an angular range of greater than 180°, so that the survey could proceed looking either to port or starboard. Various services are incorporated in the vehicle and these have been described in outline elsewhere (Rusby 1971). From the engineering viewpoint the major auxiliary service is the compressed-air storage and control for launch and recovery of the vehicle. From the acoustic point of view the measures to control the vehicle's performance in yaw are most important and are the subject of the next section.

(*i*) *Yaw performance*

Taken over a period of time the vehicle must follow the same track over the ground as the ship. On the other hand both the ship and the vehicle suffer fluctuations in heading, and the vehicle may have a permanent offset to port or starboard due to a number of factors like current shear, hydrodynamic characteristics of the vehicle, etc. The vehicle is equipped with an aircraft-type directional gyro, but only recently has a flux gate been fitted to compensate for earth rate precession. In the early years this was not considered important because it was thought that yaw periods longer than about 2 min would not affect the sonar performance and the high frequency components were damped by an active rudder system. In addition to this there is a steering system which stabilizes the received beam, by electronic means, to the direction of transmission. These two precautions ensure that there is no loss of acoustic performance. With experience it began to appear that the vehicle might have larger towing offsets than was realized and that these and longer yaw periods could be producing curious artefacts on the record. Evidence from a recent cruise with the flux gate in operation have indeed revealed aspects of vehicle behaviour only suspected previously. The results are not yet analysed but the first indications are that, as suspected, current shear and leeway will cause a heading offset, but the vehicle seems to have quasi-stable towing configurations with several degrees of offset, and that these states can change for no apparent reason after up to half an hour of stable operation.

(*j*) *The correlator*

The importance of a high signal-to-noise ratio has already been pointed out. The correlator is a device for increasing this ratio while paying the minimum price in range resolution, and finds its usefulness because of the peak power limitations of sonar transducers. It can be shown that the parameter of the pulse which determines the signal to noise ratio is its energy, and with a peak power limit the energy can only be increased by using longer pulses. On the other hand the range resolution (or temporal resolving power) of a pulse can be shown to depend only on its bandwidth. Hence the best pulse in a power limited situation is the longest possible pulse with frequency components distributed over a bandwidth sufficient to give the resolution. From the conceptual point of view the simplest such pulse is the linear frequency modulated (f.m.) pulse, and it happens that this is also a pulse form of wide practical use. As the name implies the carrier frequency is varied linearly with time over the required band. To gain the temporal resolution of which the pulse is capable it has to be processed in such a way that at the output of the processor the energy associated with all frequency components coincides in time. This is known as matched filtering and it is easy to see that for a linear f.m. pulse the matched filter is a delay line of which the delay varies linearly with frequency over the bandwidth of the pulse. The differential delay, or dispersion, has to match the pulse length. A mathematically equivalent process is cross-correlation of the echo with a delayed replica of the transmitted pulse.

There are of course other classes of pulse with different frequency time distributions and the choice of pulse depends upon the sonar environment. For side-scan sonar the linear f.m. pulse is ideal except for the existence of sidelobes at the processor output, which result from the finite bandwidth of the sonar pulse and this must be considered when designing the pulse.

In practical terms the correlator is usually more difficult to implement because a reference pulse has to be provided for every range cell of interest, whereas a matched filter makes use of the continuum of ranges. The Gloria correlator consists essentially of a magnetic coating on a uniformly rotating drum. Outside the drum is a magnetic write head which continuously records the reverberation, followed by a flexible distributed read head. Neither of these heads is actually in contact with the drum. The pattern of conductors on the read head is a time reversed version of the f.m. pulse waveform. According to one's point of view this arrangement may be regarded as a correlator with continuous reference delay variation, a matched filter in that each frequency component is read by its corresponding read head component after a delay which varies with frequency, or a transversal filter with a very large number of taps. The transmitted pulse is generated on another portion of the drum. So far use has been made of pulses of 2 s or 4 s duration, each with a linear frequency spread of 100 Hz.

(*k*) *Recording and display*

The processed output of the receiver is displayed on a dry paper facsimile type recorder, and is also tape-recorded for subsequent replay. The facsimile recorder provides an immediate demonstration that the system is working correctly, and its data serves to control the conduct of the survey. Its main advantage is immediate visibility, but some quality is sacrificed to this end. There are two processing channels one of which has automatic gain control and the other fixed gain, and both are displayed and recorded on tape. The tape recordings are used off-line to produce records of greater tonal range for analysis and publication. The heart of the system is a line picture receiver normally used over telephone lines, but specially adapted for this purpose. This machine records directly on to photographic paper, and will comfortably handle the full dynamic range of the tape recorder. The output of this machine is not directly usable because the various geometrical scales combine to produce a distortion which exaggerates down range distances by 3 or 4 to 1, and it is not satisfactory to increase the line-width to compensate. This distortion is removed by a special anamorphic camera in which the moving record is photographed through a stationary slit on to a moving film. If the relative speed of film and object are correct and everything is carefully aligned, the camera produces a 35 mm negative in true scale. This negative can then be printed at any enlargement desired. Of course the records still contain the close range non-linear distortion but this can be minimized by manual plotting of the data.

During a survey a speed-up in tape replay makes it possible to produce prints from both channels, within 24 h, even when using the full process of tape replay, anamorphic photography and printing.

REFERENCE

Rusby, J. S. M. 1970 A long range side-scan sonar for use in the deep sea. *Int. hydrogr. Rev.* **47** (2), 25–39.

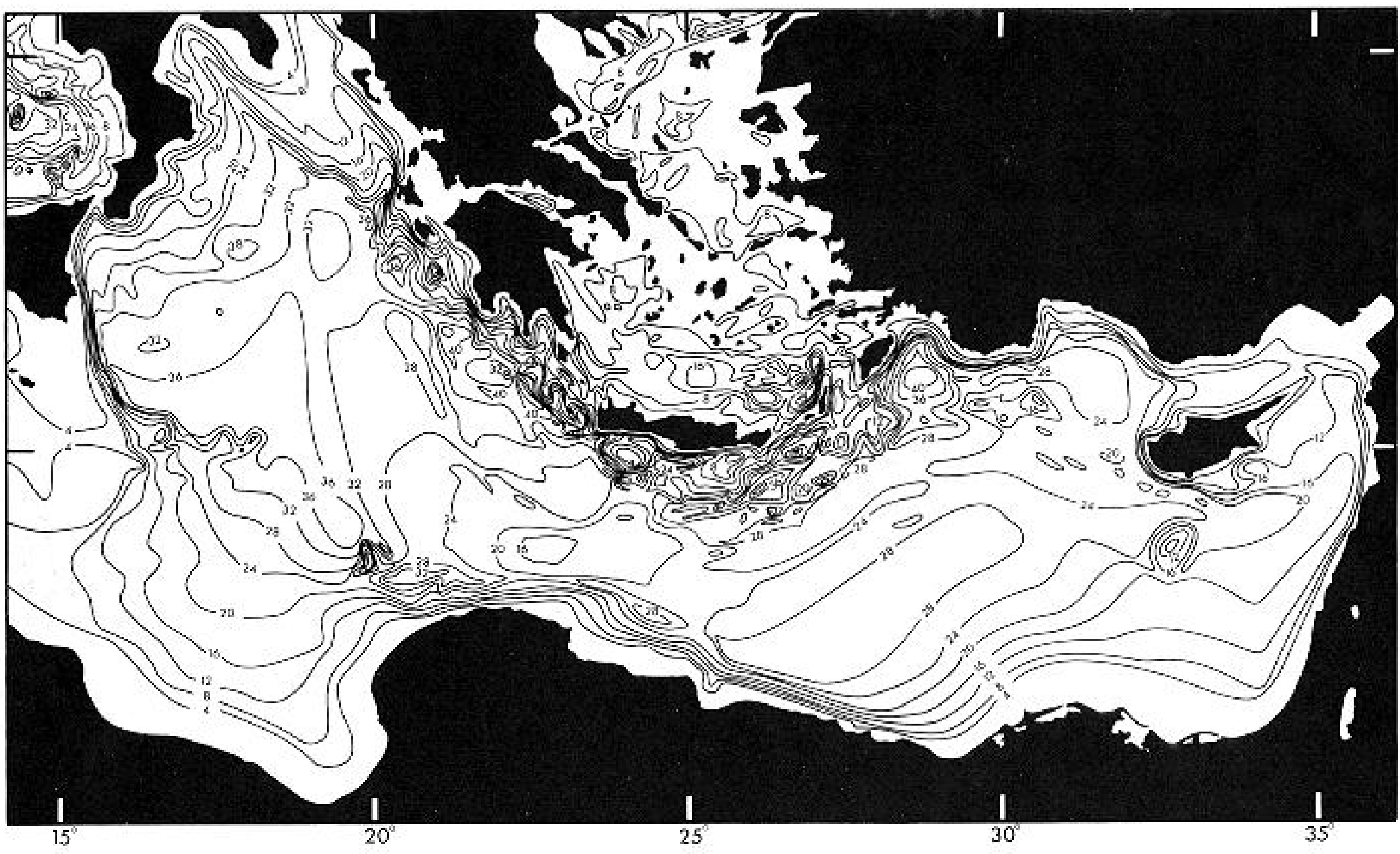


FIGURE 1. Generalized depth contours, at 400 m intervals, show the gross relief of the Eastern Mediterranean sea floor. Based mainly on bathymetric charts; U.S. N.O. 310 (Defence Mapping Agency Hydrographic Center 1972) and on Wright *et al.* (1975).

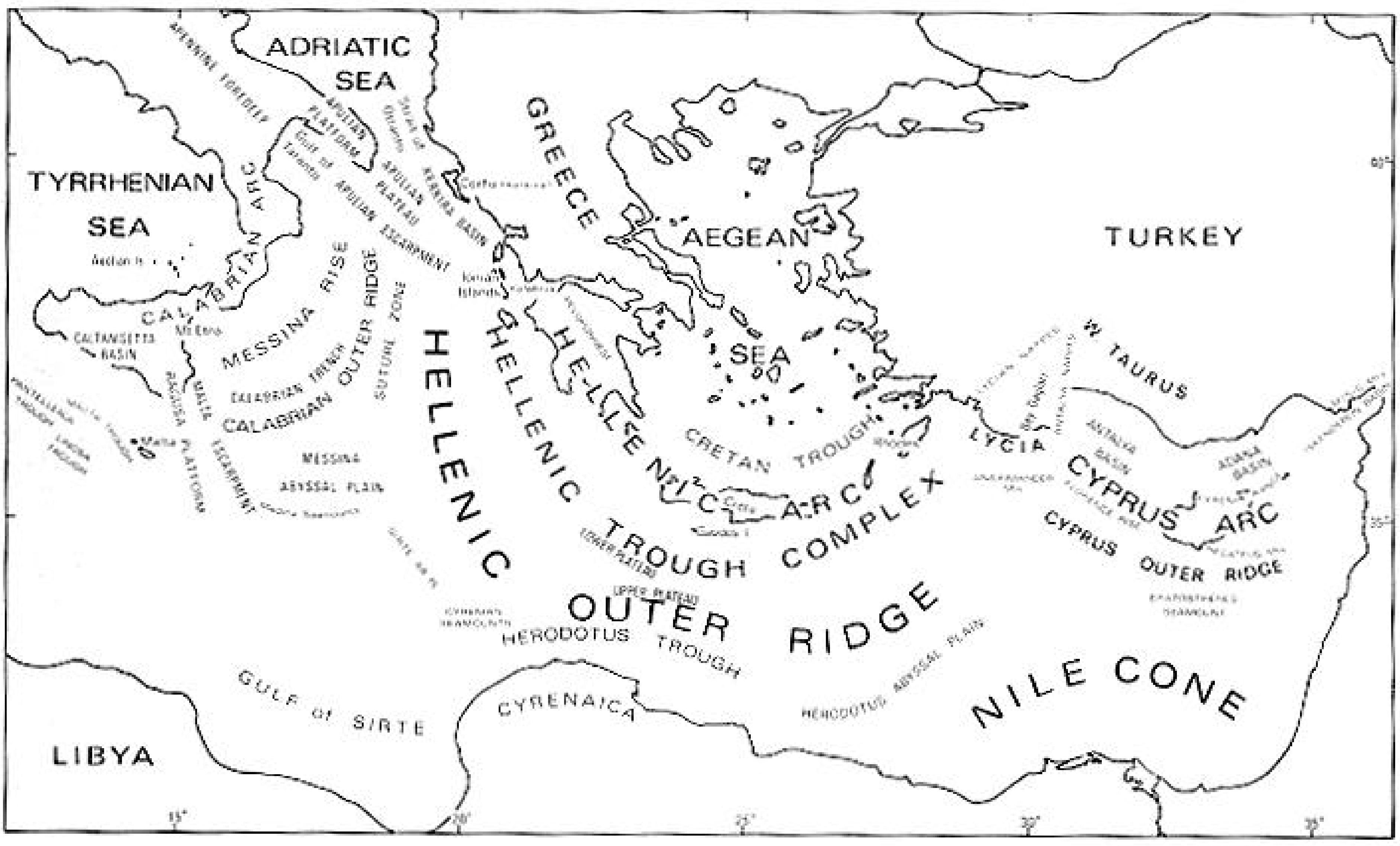


FIGURE 2. Location map for the Eastern Mediterranean showing the geographical names used in this paper. The Messina and Sirte Abyssal Plains, the Herodotus Trough and the Herodotus Abyssal Plain are all part of the Southern Trough.

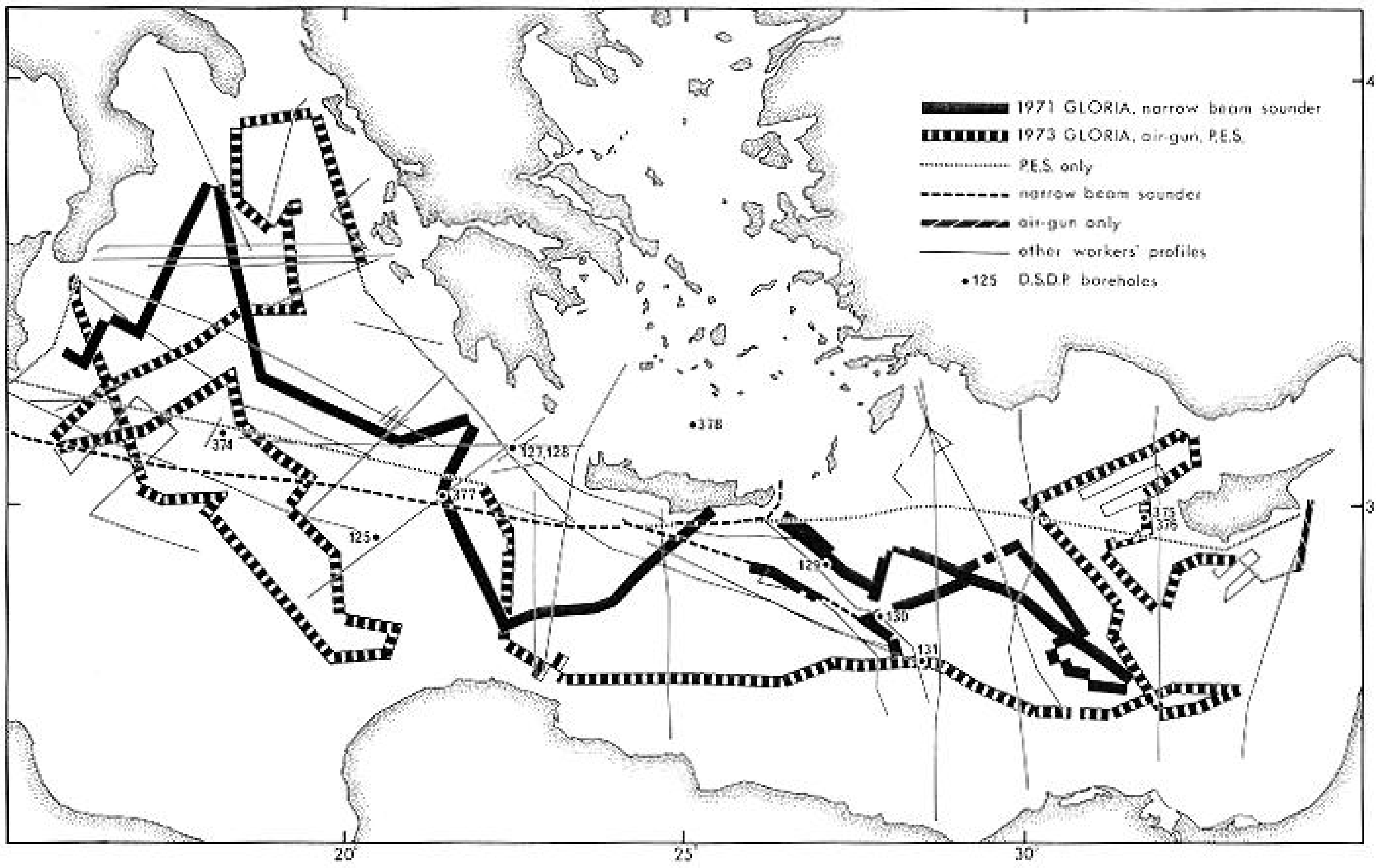


FIGURE 3. Data coverage for the Eastern Mediterranean, mostly from cruises of R.R.S. *Discovery*. In the case of the long range side-scan sonar (GLORIA) the thickness of the line shows the width of ground actually examined. Survey tracks by other workers using echo-sounder or sub-bottom profilers were taken from Emery, Heezen & Allan 1966; Giermann 1966, 1969; Ryan *et al.* 1971; Sancho *et al.* 1973; Wong *et al.* 1971; Zarudzki & Phillips 1971; Hieke *et al.* 1973; Hinz 1974; Lort & Gray 1974.

Figure 4. Simplified trends of structural relief shown on sonographs of the Eastern Mediterranean, together with the trends of gross relief derived from published bathymetric data. The boundary between the Hellenic Trough Complex and the Hellenic Outer Ridge is difficult to define. The southern boundary of the Outer Ridges is placed at the outer limit of the smaller-scale structures. The inset figure shows the positions of sonographs, air-gun profiles and narrow beam echo-sounder profiles that are figured in this paper.

Figure 5. Sonograph showing the smooth surface of a relatively rigid block (Ptolemy Mountains) within the Hellenic Trough Complex. This contrasts with the rough slopes of the two trenches bounding the block and with the small-scale tectonic relief on the northern flank of the Hellenic Outer Ridge. Note the southerly tilted floors of the trenches. In this sonograph (in contrast to all the others) shadows or smooth floors appear as light tones and strong reflexions from steep surfaces appear as dark tones, and there is also a range distortion of about 2.5:1 (as shown by the black rectangle with each side equivalent to 2 km). The area shown is 140 km × 13 km. 'P' is the profile of the floor.

Figure 6. The relatively low relief of the 'Lower Plateau' contrasts with the rougher, more tectonically disturbed 'Upper Plateau'. A ridge of rough ground (left) which fingers into the 'Lower Plateau' is considered to be due either to local buckling along a zone of weakness, or else may result from thrusting. This sonograph, and all subsequent ones are true plan views (except for a narrow zone near to the profile 'P'), and strong echoes appear white and shadows black. The sides of the white square represent 2 km.

Figure 7. Sonograph showing the west facing fault scarp bounding the 'Lower Plateau' (L.P.), which is a relatively undeformed block within the Hellenic Outer Ridge. Large faults (f–f) cut across both provinces but probably do not extend far into the 'Lower Plateau' beyond the area shown by this sonograph. For the location of these and other sonographs see figure 4.

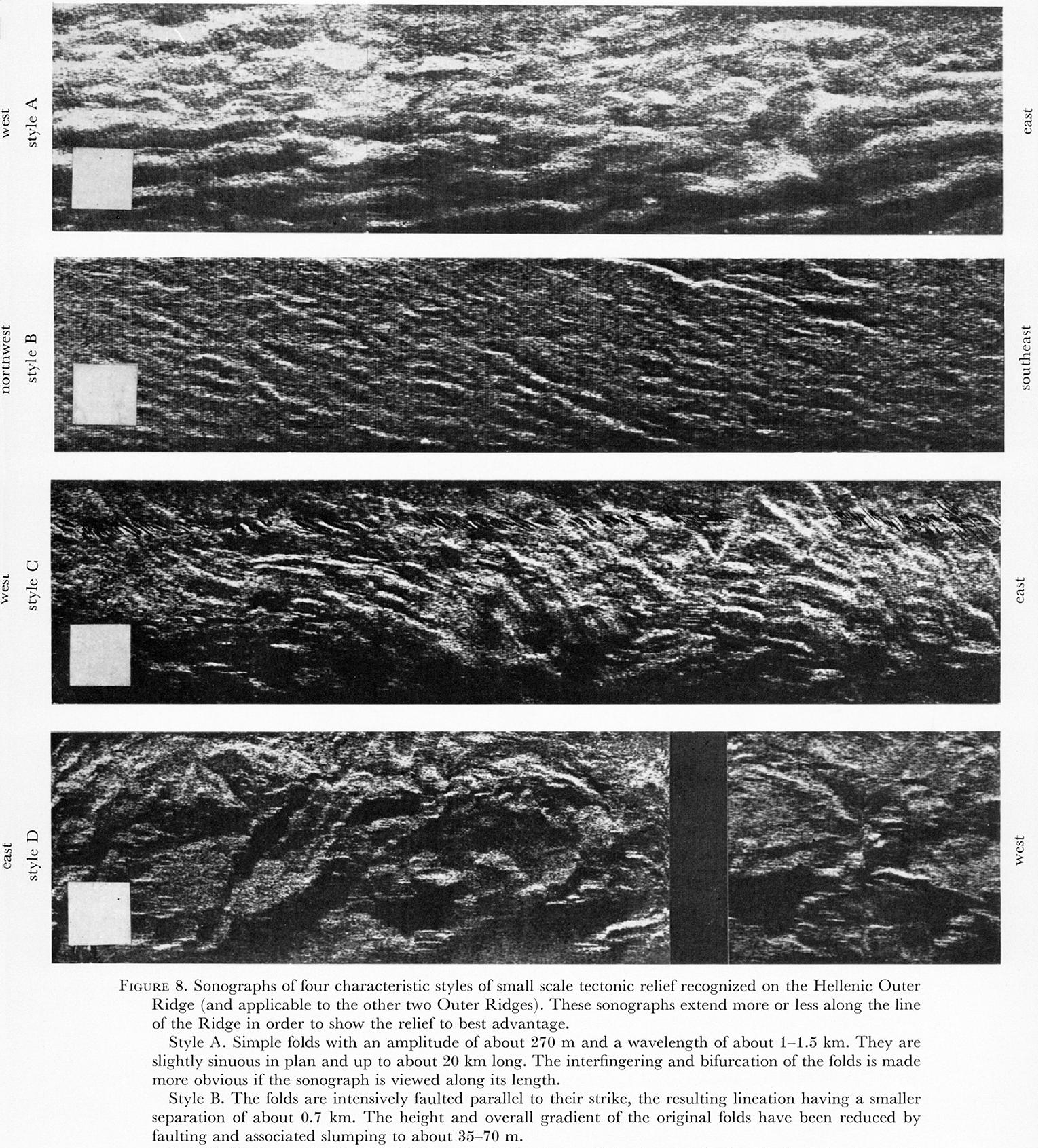


Figure 8. Sonographs of four characteristic styles of small scale tectonic relief recognized on the Hellenic Outer Ridge (and applicable to the other two Outer Ridges). These sonographs extend more or less along the line of the Ridge in order to show the relief to best advantage.

Style A. Simple folds with an amplitude of about 270 m and a wavelength of about 1–1.5 km. They are slightly sinuous in plan and up to about 20 km long. The interfingering and bifurcation of the folds is made more obvious if the sonograph is viewed along its length.

Style B. The folds are intensively faulted parallel to their strike, the resulting lineation having a smaller separation of about 0.7 km. The height and overall gradient of the original folds have been reduced by faulting and associated slumping to about 35–70 m.

Style C. On the north side of the Ridge cross faulting is as well developed as the longitudinal structures, but no sonograph of suitable quality is available to show this. The present sonograph illustrates a transition between tectonic styles B and C, in which Ridge-parallel structures are kinked and interrupted by incipient cross faults and relief is reduced by slumping to about 35–70 m.

Style D. The Ridge-parallel structural trends are dissected by cross faults of various trends. Thrusting and strike-slip faulting are suspected. The relief is about 35–55 m but shows up well because this ground, the 'Upper Plateau', is in relatively shallow water so that the shadows are correspondingly long.

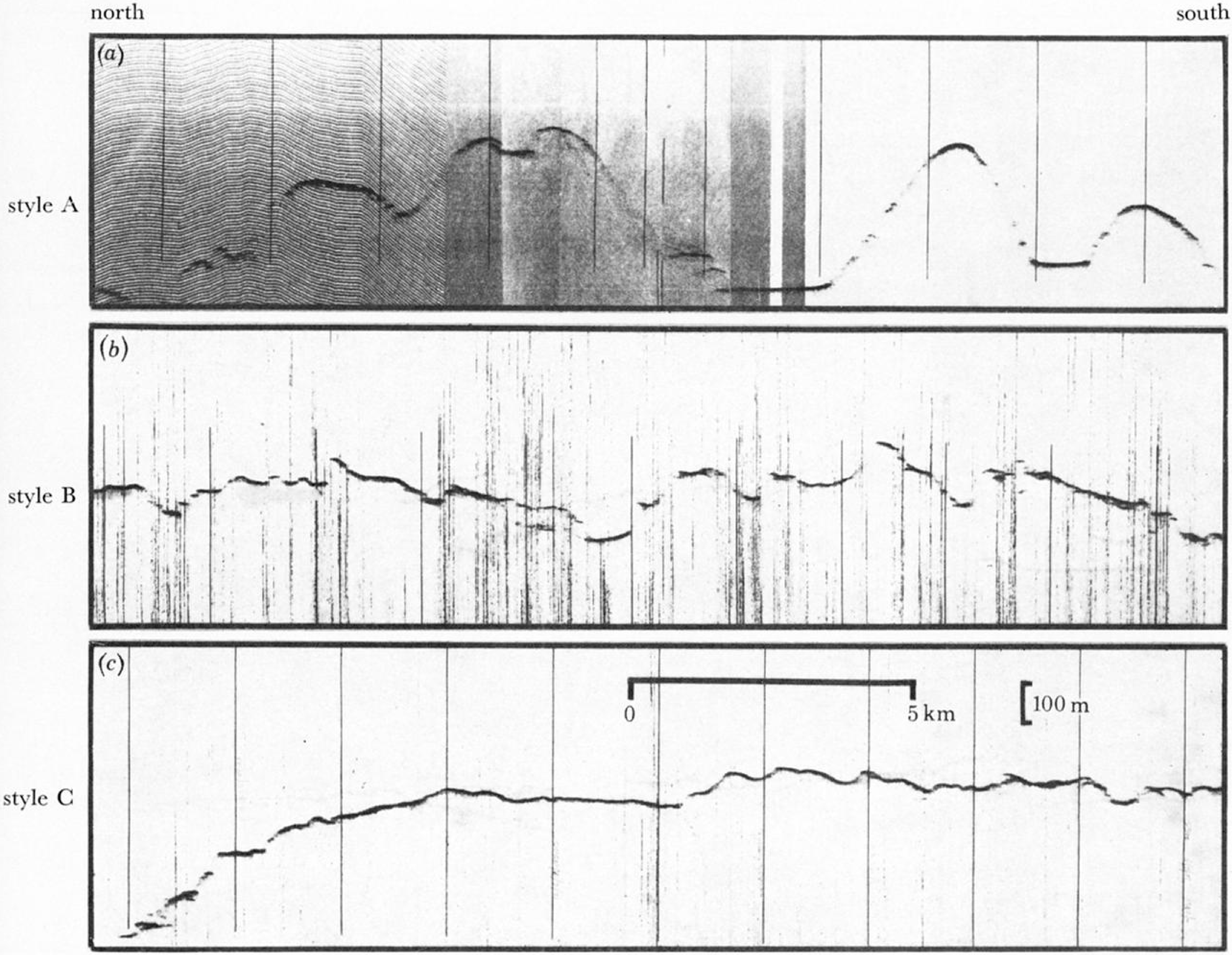


Figure 10. Narrow-beam echo-sounder profiles of the small-scale relief styles of the Hellenic Outer Ridge (the profiles, at about right angles to the Ridge, are located in figure 4).

Style A. The right hand side shows two gentle folds at the outer (southern) edge of the Ridge. The small steps are interpreted as slumps. The troughs have a flat fill of young sediment. To the left the folds become more broken by faulting and gravity slides. Note the crestal graben.

Style B. Irregular, lower amplitude relief which characterizes much of the middle part of the Ridge.

Style C. Relatively low relief of the northern part of the Ridge. The steps on the relatively steep northern slope are due either to faulting or possibly renewed slumping. The relief of Style D is similar, and is therefore not shown.

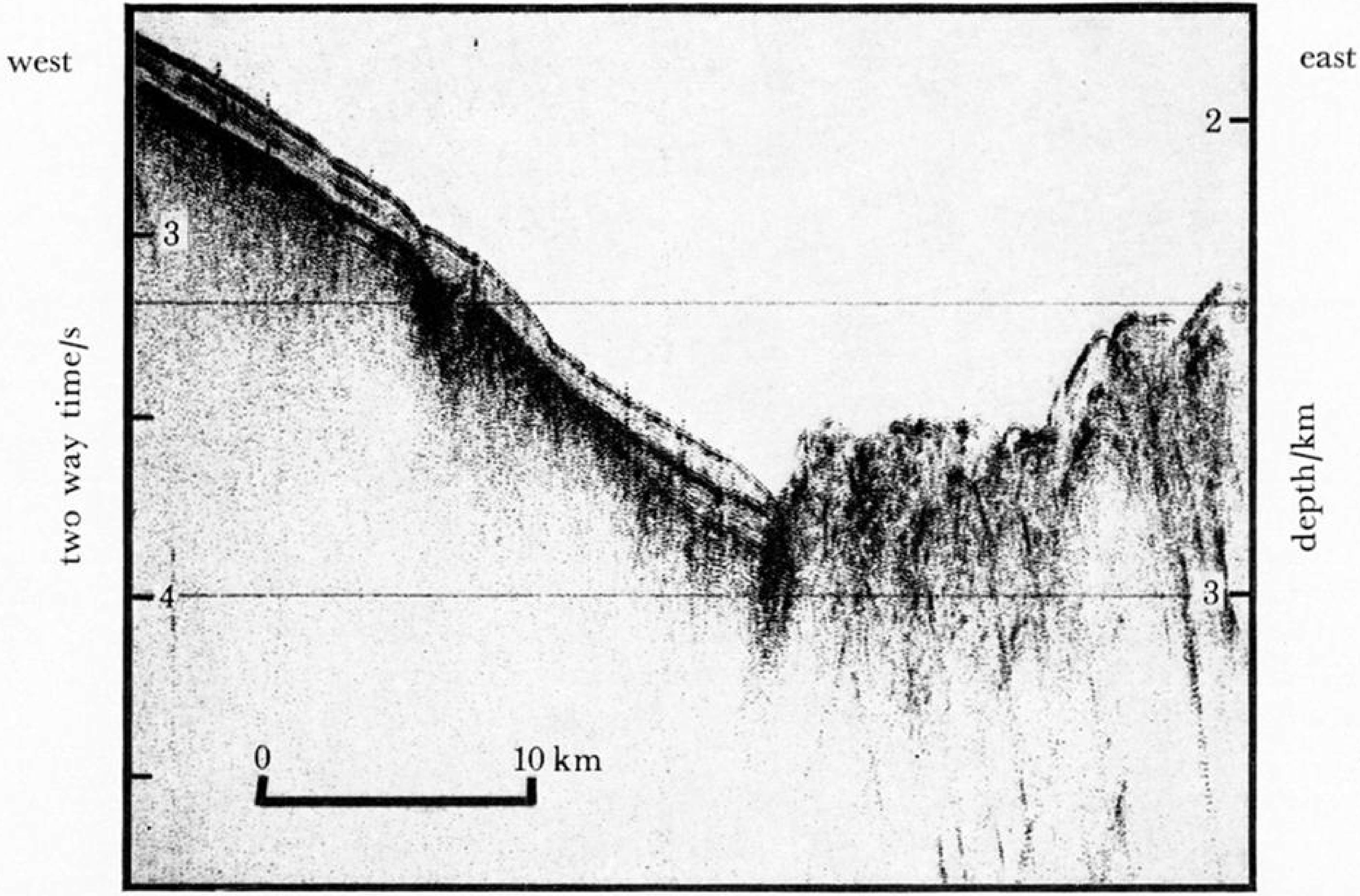


FIGURE 12. Air-gun profile showing the abrupt transition from the rough surfaced Hellenic Outer Ridge (right) to the relatively smooth North African continental slope. Note the absence of any flat lying fill in the bottom of the intervening Southern Trough.

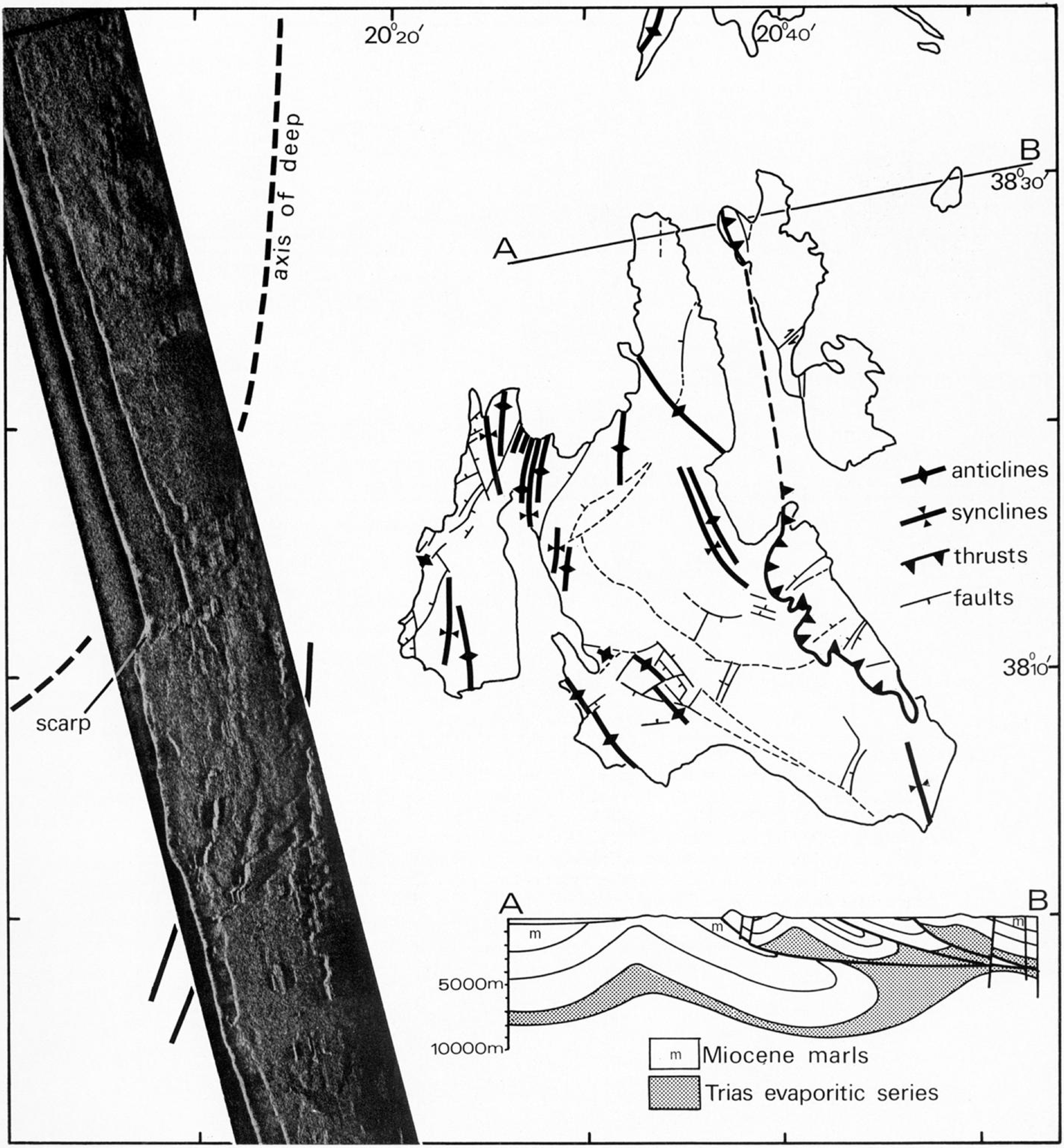


Figure 11. The island of Kefallinia is considered to be part of a narrow structural continuation of the Hellenic Outer Ridge. Fold and fault trends on the island are similar to the structures seen on the sonograph of the neighbouring sea floor. These are emphasized by short lines drawn alongside (*n.b.*: The apparent sinuosity of some of the features results from vehicle yaw). The deep is the structural equivalent of the Southern Trough. North of this (top left) the sonograph shows part of the almost undisturbed eastern slope of the Apulian Plateau. (The structural map and section of Kefallinia are based on B.P. 1971. Between the Trias and the Miocene there are Mesozoic to Eocene carbonates. The Miocene is overlain by Plio-Quaternary sediments.)

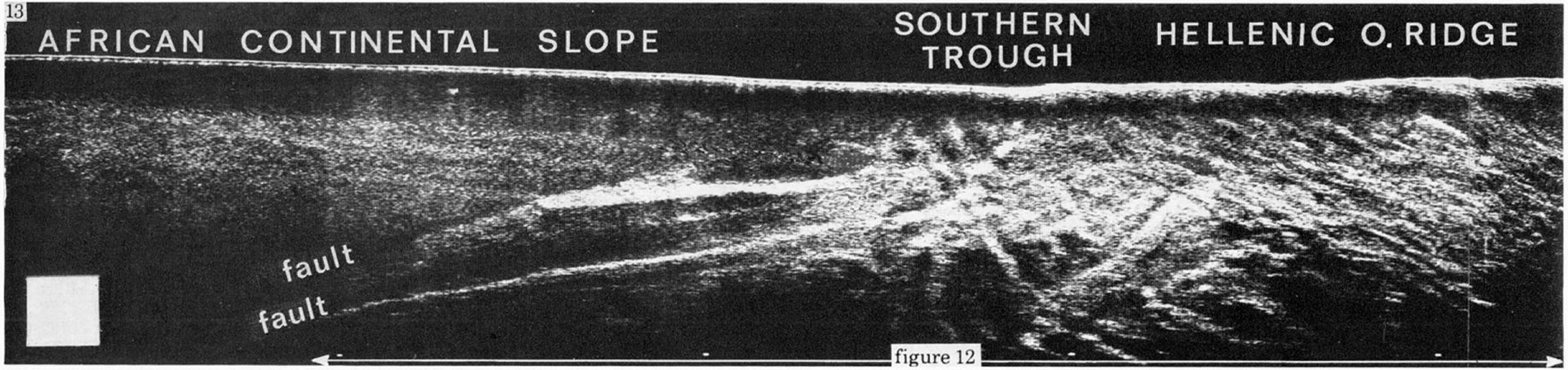
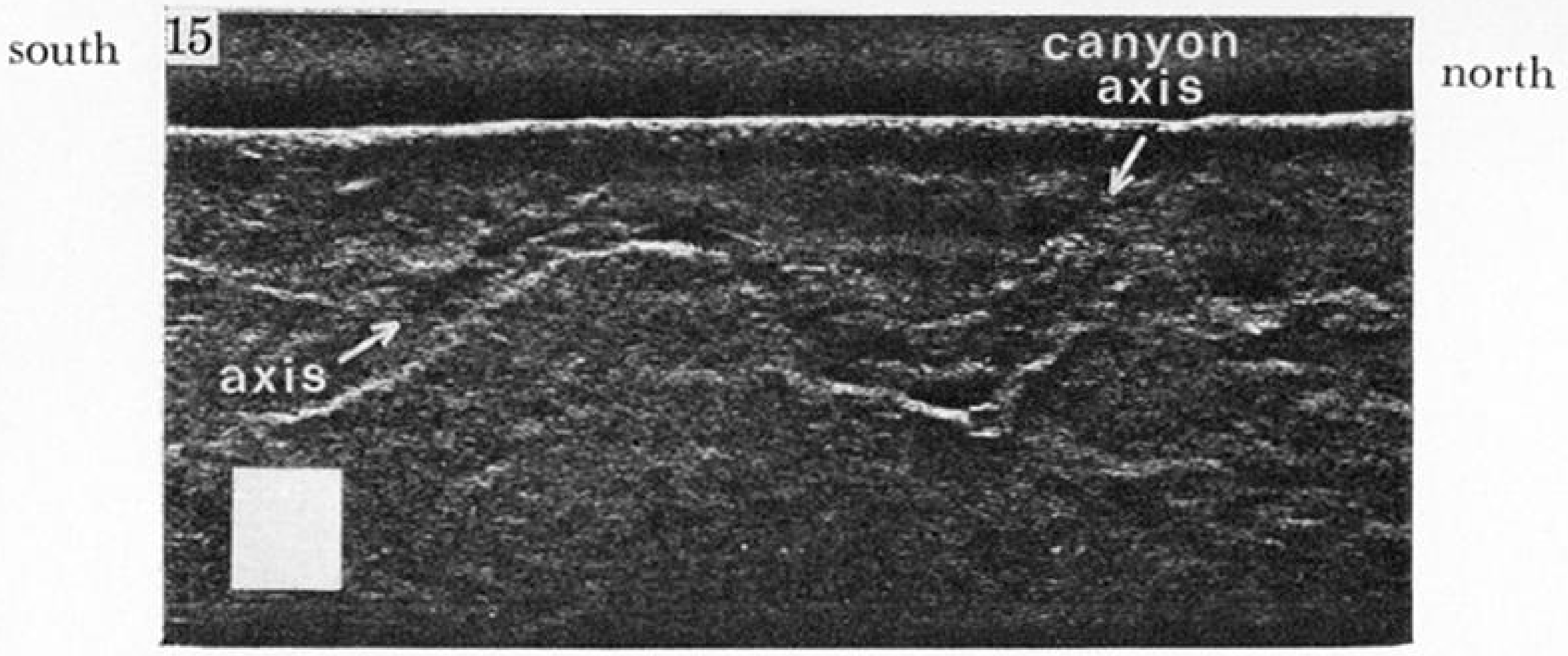


FIGURE 13. Sonograph (with profile along the same line as figure 12, plate 3) showing the Hellenic Outer Ridge abutting against the foot of the relatively smooth North African continental slope, broken only by two long faults. On this crossing of the southern edge of the Hellenic Outer Ridge the simple folds that are present further east and west, are here cut by strike faults and cross faults (structural style C).

FIGURE 14. Sonograph showing sinuosity in the folds (structural style A to B) on the southern side of the Hellenic Outer Ridge. The southernmost of these folds are bent around parallel with the foot of one of the Cyrenian Seamounts. The slope of the latter is rough and may be gullied and faulted.



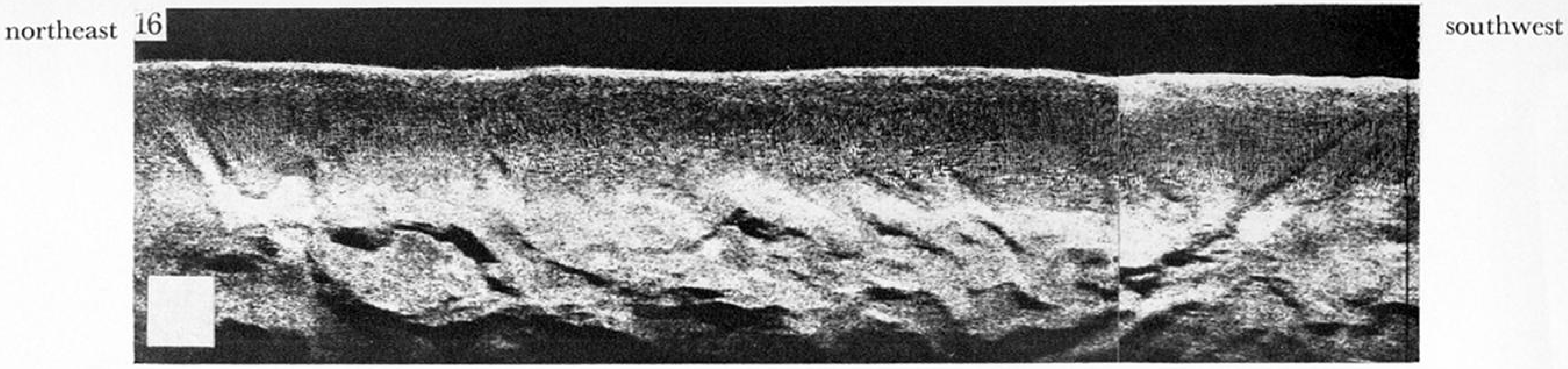
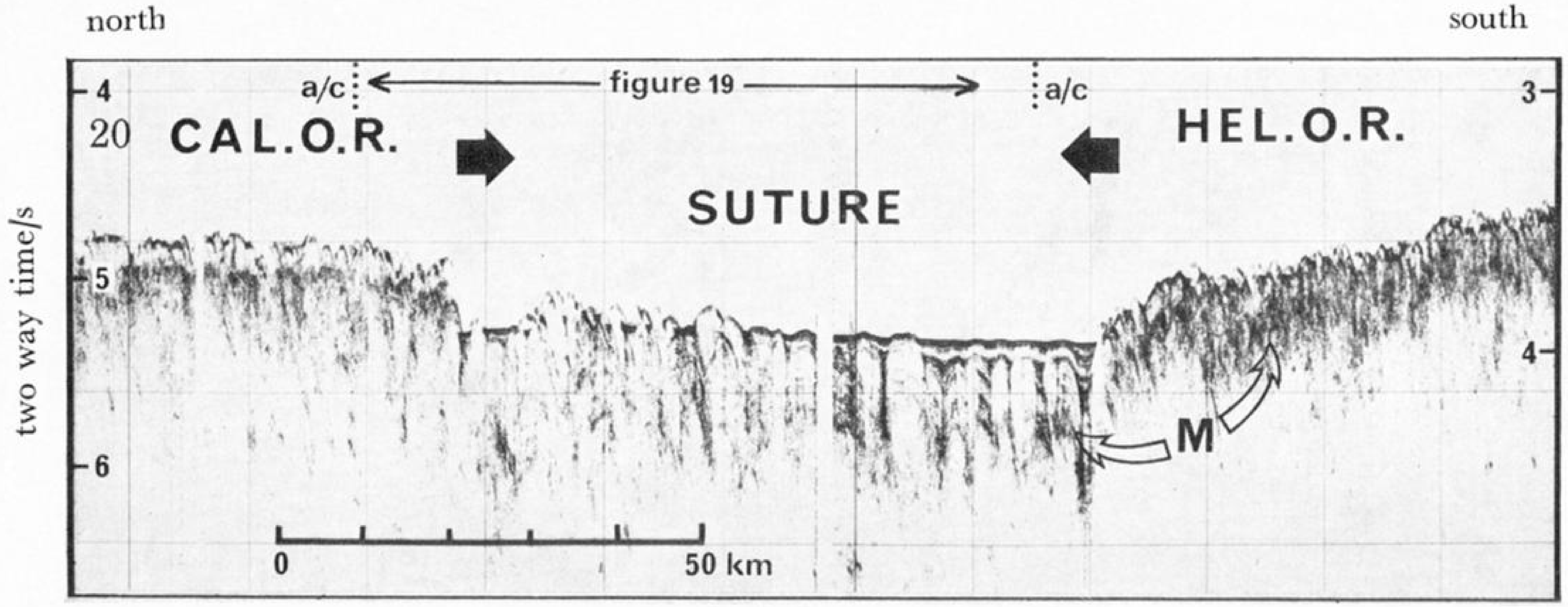


FIGURE 15. Sonograph showing an S shaped portion of a canyon about 1.5 km wide located on the upper part of the Messina Rise, along part of the profile of figeur 17. The wall more distant from the vessel is shown by a strong reflexion (white).

FIGURE 16. Sonograph showing curved features that extend along the contours on the upper part of the Messina Rise, and which are interpreted as due to gravity slides or thrusts.

FIGURE 17. Air-gun profile extending from the Messina Abyssal Plain to near the top of the Messina Rise and including the (asymmetrical) Calabrian Outer Ridge. The M horizon is shown.

FIGURE 18. Sonograph showing structural trends (style B of plate 2), along the central part of the Calabrian Outer Ridge. The effect of ship's yaw is to break up the continuity of some of these structural trends (e.g. below the arrow).



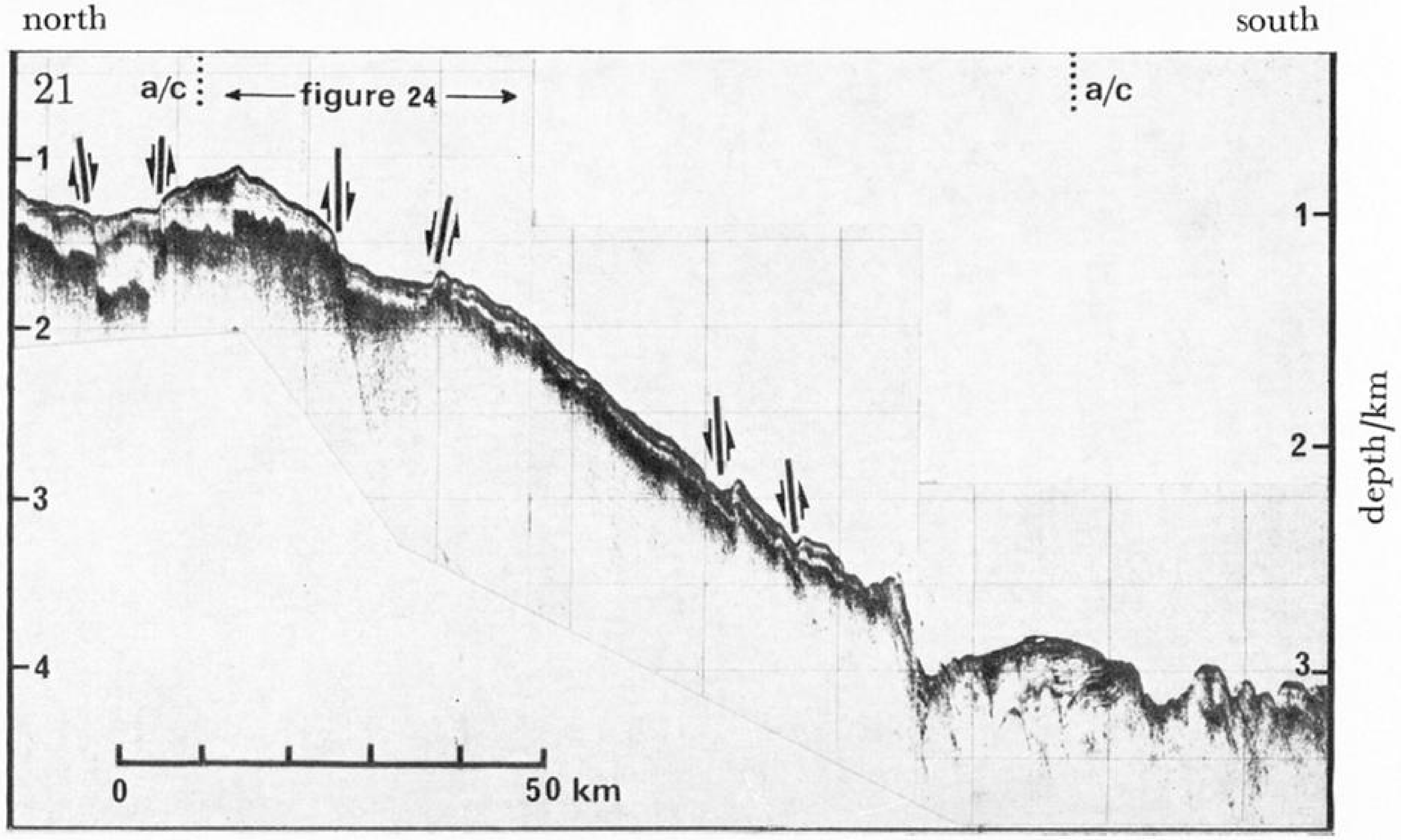


FIGURE 19. Sonograph showing sinuous folds (style A of plate 2) and flat floor in the suture between the Calabrian Outer Ridge (left) and the Hellenic Outer Ridge (shown in figure 20).

FIGURE 20. Air-gun profile showing the relatively steep sided suture between the Calabrian and Hellenic Outer Ridges at the northern apex of the Messina Abyssal Plain where it merges into the suture. This is interpreted as a thrust-bounded ramp valley. The black arrows represent the outward directions of advance of the Ridges. The M horizon is shown.

FIGURE 21. Air-gun profile across the Apulian Escarpment, with normal faulting at the top and possible thrusting (related to strike-slip motion) lower down. Note the disturbed and uplifted wedge of layered sediments in the trough at its base.

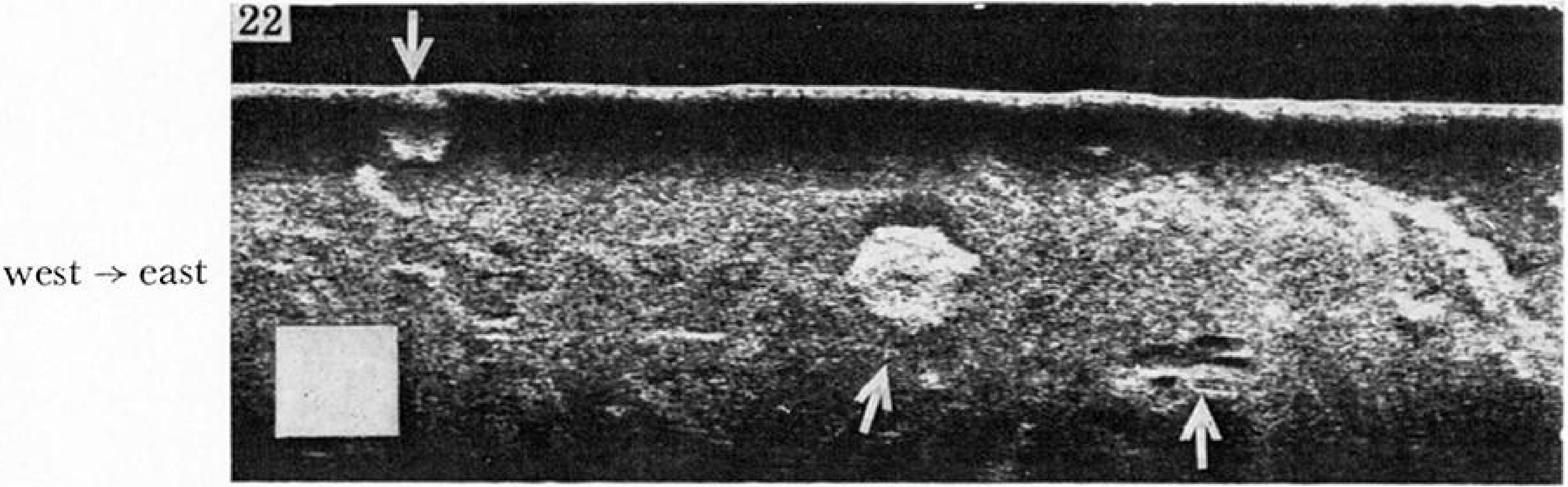


Figure 22. Sonograph showing rough surfaced, isolated, subcircular depressions (arrows) within the Florence Rise that may be the surface expressions of salt domes (see companion air-gun profile in figure 23 *a*).

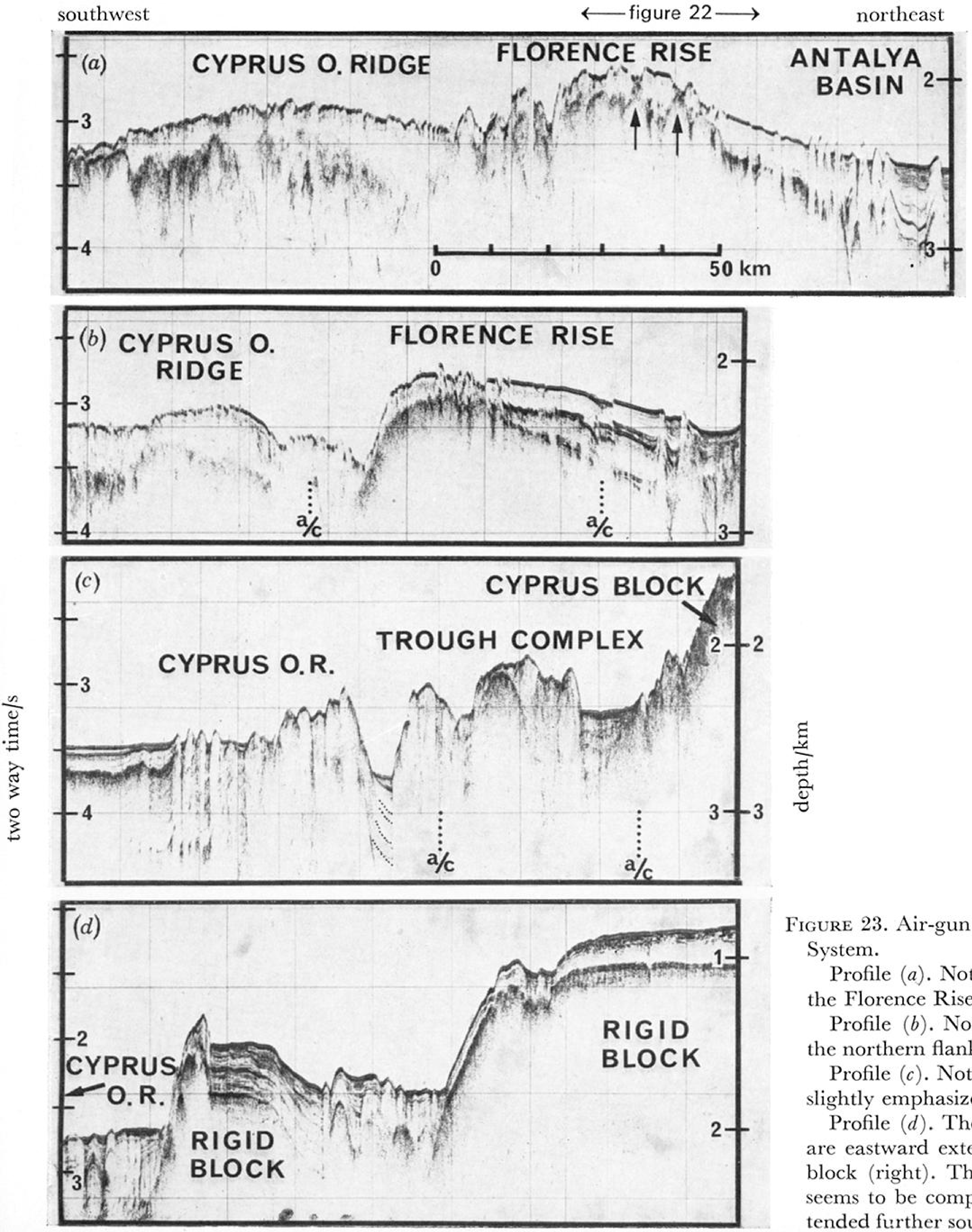


FIGURE 23. Air-gun profiles across some submarine parts of the Cyprus Arc System.

Profile (*a*). Note the diapirs (arrows) that reach the sea floor on top of the Florence Rise.

Profile (*b*). Note that normal faulting and possible diapirs have affected the northern flank of the Florence Rise.

Profile (*c*). Note the trench with northerly tilted fill (its bedding has been slightly emphasized to make it more evident on this photograph).

Profile (*d*). The rigid blocks overlain by relatively undisturbed sediment are eastward extensions of the Hecateus Mountains (left) and the Cyprus block (right). The deformation of the sediments in the intervening trough seems to be compressional. The Cyprus Outer Ridge structures can be extended further south (left) as shown by Giermann (1966, profile K).

north → south

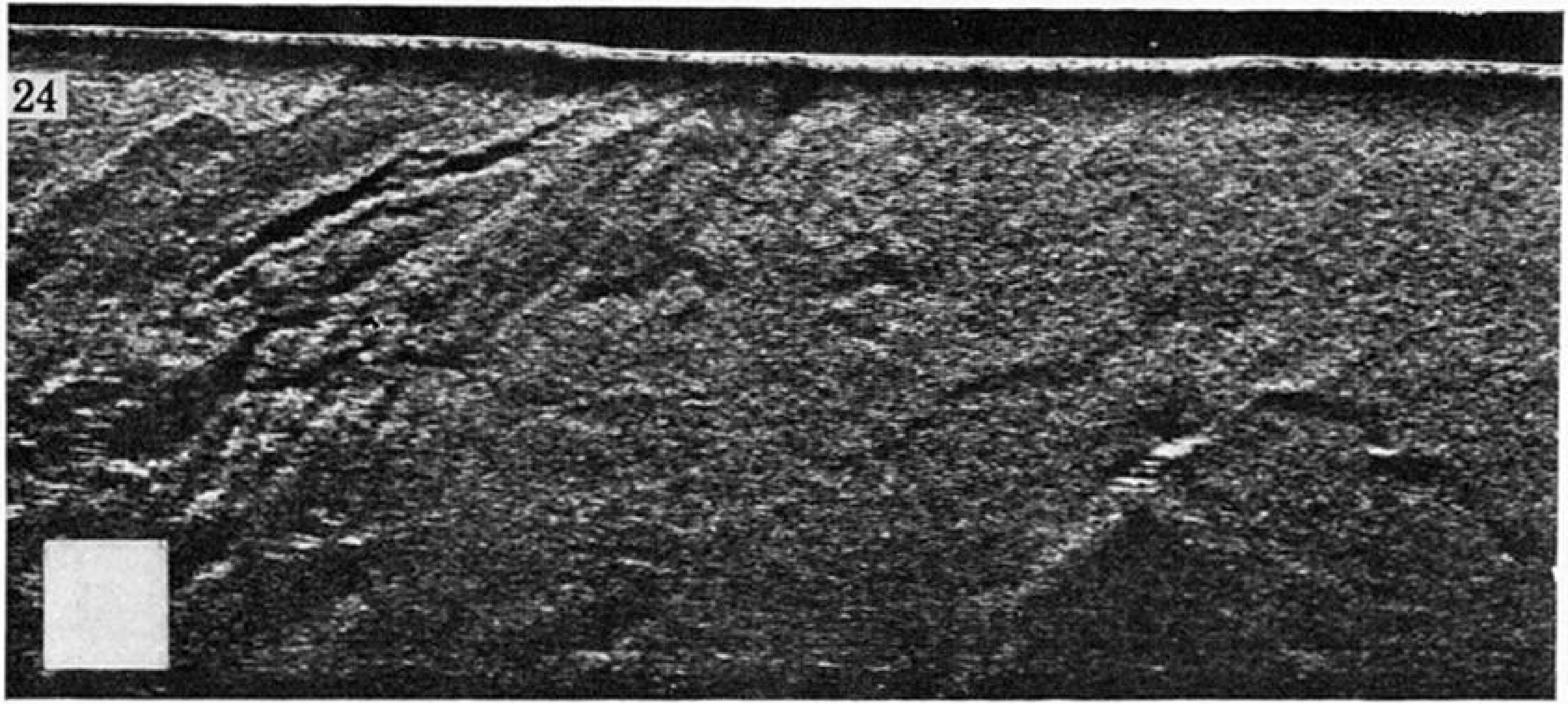


FIGURE 24. Sonograph showing northwesterly trending fault traces associated with grabens on top of the Apulian Plateau. These are shown in profile in figure 21.