

A CONTINUOUS SEISMIC PROFILING SURVEY OF
THE COAST OF LEBANON

by

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ABSTRACT

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The bathymetric results from a geophysical reconnaissance survey off Lebanon show that the continental shelf of Lebanon is generally narrow, with broadenings off Damour and between Tyr and Saida. The dip of the slope increases northward from 6 degrees at Tyr to 30 degrees at Beirut. South of Beirut, and possibly north of it, the slope is incised with canyons. Seismic profiling results show that a deep, ubiquitous, possibly Upper Cretaceous reflector forms the surface of an old slope off Lebanon and extends into the Eastern Mediterranean as far west as Cyprus and as far south as Port Said. On the outer shelf, this surface is overlain by a layered sequence of sediments as thick as 0.83 seconds and by an upper veneer of sediments as thick as 0.008 second. The continental rise is composed of mostly inhomogeneous sediments south of Beirut and a thick sequence of layered sediments north of Beirut. The area is surrounded by layered, mostly Nile-derived sediments.

It is suggested that the present shelf was formed by deposition of sediment on the ancient slope, and was later eroded. The eroded material, along with land-derived material, now constitutes the sediments of the rise.

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	2
LIST OF FIGURES	4
CHAPTER I. INTRODUCTION	7
CHAPTER II. METHODS OF OBSERVATION AND ANALYSIS	8
CHAPTER III. PRESENTATION AND DESCRIPTION OF RESULTS	25
CHAPTER IV. DISCUSSION OF RESULTS	67
CHAPTER V. SUMMARY AND CONCLUSIONS	90
APPENDIX A. GEOLOGY OF LEBANON AND ITS RELATIONSHIP TO SURROUNDING AREAS	94
APPENDIX B. TABLE 1	124
ACKNOWLEDGEMENTS	129
REFERENCES	131

LIST OF FIGURES

Text

<u>Figures</u>	<u>Page</u>
Figure 1. Schematic of profiling electronics.	9
Figure 2. Arrangement of ship, source, and receiver for seismic profiling.	9
Figure 3. Correction curve used in obtaining true water depths from seismic profiling records.	17
Figure 4. Corrected ship's tracks of echo-sounding survey.	18
Figure 5. Effect of varying velocities of sound in overlying sediment on position and attitude of reflector.	22
Figure 6. Offshore topography of Lebanon.	26
Figure 7. Seismic reflection profiling lines made in survey area.	30
Figure 8. Seismic reflection profiling lines made outside survey area.	31
Figure 9. Profile A_1A_5 .	39
Figure 10. Profile BB_2 .	39
Figure 11. Profile EC.	40
Figure 12. Profile FF_1 .	40
Figure 13. Profile GG_1 .	40
Figure 14. Profile A_6A_4 .	40

	<u>Text</u>	<u>Page</u>
Figure 15.	Profile H ₁ G.	41
Figure 16.	Profile HG ₁ .	41
Figure 17.	Veneer of sediments on shelf of Tyr-Saida Bank seen with short-pulse echo-sounder.	42
Figure 18.	Profile J ₂ JJ ₁ .	41
Figure 19.	Profile HD.	41
Figure 20.	Profile CC ₁ .	43
Figure 21.	Profile DD ₁ .	43
Figure 22.	Profile A ₄ A ₃ .	43
Figure 23.	Profile LC.	44
Figure 24.	Profile JH ₁ .	44
Figure 25.	Profile KK ₁ .	46
Figure 26.	Profile RR ₂ .	45
Figure 27.	Profile Q ₃ Q ₁ .	45
Figure 28.	Profile SM ₁ .	46
Figure 29.	Profile M ₁ MJ ₂ .	47
Figure 30.	Profile PF.	47
Figure 31.	Profile Q ₂ Q.	48
Figure 32.	Profile R ₁ R ₃ S.	48
Figure 33.	Contour map of deep reflector between Tyr and Saida.	69

<u>Text</u>	<u>Page</u>
Figure 34. Main structural units of Lebanon.	95
Figure 35. Main structural units of Levantine coast between Israel and Turkey.	99
Figure 36. Tectonic map of Lebanon.	99
Figure 37. Stratigraphic columns for Lebanon.	105
Figure 38. Regional structures surrounding Lebanon.	116

Plates

Plate 1. Geological map of Lebanon.	(envelope in back of thesis)
Plate 2. View of model showing adjacent geology of Lebanon.	33
Plate 3. View of model showing adjacent structures of Lebanon.	34
Plate 4. View of survey area south of Beirut.	35
Plate 5. Tyr-Saida Bank.	35
Plate 6. Detail of bedding on shelf and slope of Tyr-Saida Bank.	36
Plate 7. Detail of bedding on wide part of shelf opposite Damour.	36
Plate 8. Slope and rise at south end of survey area (opposite Damour).	37
Plate 9. Continental rise between Beirut and Tyr-Saida Bank.	37
Plate 10. Slope and rise between Beirut and Tripoli.	38
Plate 11. Three-dimensional view of sediment-filled depressions beneath continental rise, between Beirut and Batroun.	38

CHAPTER I

INTRODUCTION

In the summer of 1964, the R/V CHAIN (Cruise 43) conducted a two-day reconnaissance survey of the continental shelf, slope, and rise off Lebanon, making seismic profiling, bathymetric, gravitational, and magnetic measurements. One camera and two dredge stations were made. Except for a study of shelf sediments, no other work has been done offshore of Lebanon.

The object of this thesis is to present and interpret the seismic profiling and bathymetric data. The results of the lowerings will also be described. The gravitational and magnetic results have not been reduced by the writer, and therefore are not presented here, but they have been examined qualitatively during the analysis of the seismic profiling data.

CHAPTER II

METHODS OF OBSERVATION AND ANALYSIS

I. OBSERVATIONS

The Continuous Seismic Profiler

The Continuous Seismic Profiling system will be described here briefly. Complete descriptions of the theory, instruments and techniques employed can be found in J. Ewing (1963), Hersey (1963), Curry et al. (1964), Hoskins (1964a, 1965), Shor (1963), Caulfield (1962), and Caulfield et al. (1965).

The Continuous Seismic Profiler, used for mapping geologic structures under water-covered areas, produces a record displaying a profile of the sea floor and of acoustic discontinuities beneath the sea floor. If the discontinuities, which often appear as layers, represent lithological changes in sediments, (i. e. boundaries between different sediment layers), then the record is analogous to a geological cross section. The record is different from a geological cross section because it plots travel time against elapsed time, (corresponding to the distance the ship advances), rather than true depth against linear horizontal distance.

A. Design of Profiler:

The design of the profiling system used at the Woods Hole Oceanographic Institution is shown in the schematic diagram in Figure 1. The apparatus consists of a sound source and a receiver, both towed behind

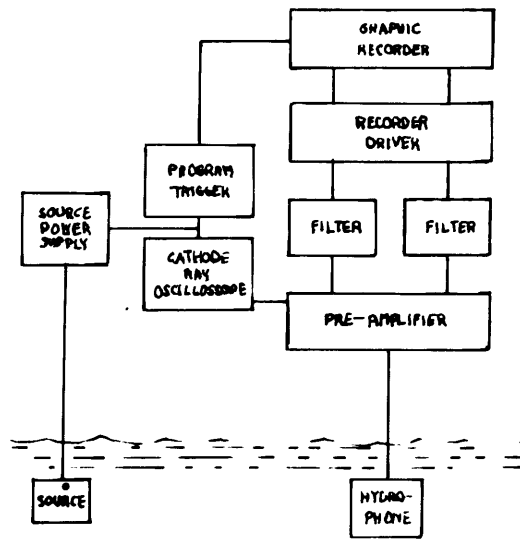


Figure 1. Schematic of profiling electronics.

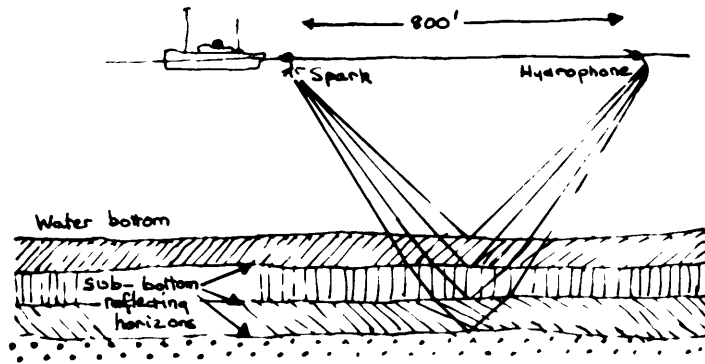


Figure 2. Arrangement of ship, source, and receiver for seismic profiling.

the ship, (see Figure 2), and a recorder for registering travel time. The source, triggered synchronously with the sweep of the recorder, generates a short pulse of high energy at regular intervals. The subsequent pulses and echo trains received from the sea floor, deeper interfaces, and other discontinuities are received by a hydrophone array and converted into electrical signals. These signals are passed through a broad-band amplifier, filtered for both a lower and a higher frequency presentation, and fed to two separate recorders.

The strengths of the signals are recorded as variations in the darkness of the line produced by the sweep-action of the recorder. Moreover, the recorder provides automatic correlation of trains of waves from successive sound pulses. As the ship moves over a continuous reflecting surface, the successive pulses reflected from that surface appear side by side along the length of the record, producing a line or curve as the paper advances through the recorder. A profile is thus built up as the ship proceeds.

Concurrent with these recordings, magnetic tape recordings of the unfiltered output of the preamplifier of the hydrophone are made. This combination of recording allows the data to be replayed and automatically correlated on other recorders at a later time (Bunce and Hersey, in preparation).

The components of the system are subject to some basic limitations. A high-energy source is required for penetration of the sound to deep reflectors. The sound pulse must be of short duration to obtain resolution between finely-spaced layers. The emitted sound pulse, moreover, must have most of its energy below 800 c. p. s. (Hersey and Ewing, 1949), preferably in the range of 10 to 150 c. p. s. (Hersey, 1963), because higher-frequency energy is preferentially absorbed by sediments. A compromise must thus be made between resolution and penetration in choosing the output wave form (Hoskins, 1965). The receiver must be pressure-sensitive and acceleration-insensitive, as well as having a linear response over a large dynamic range, and should have band-pass characteristics favorable to frequencies below 400 c. p. s. Finally, the recorder must have a precision time base keying the sparker and the recording sweep simultaneously on a repetitive basis. The accuracy of the recorder, and hence the straightness of the scale lines along the record, is determined by the consistency of its sweep rate over long periods of time.

Throughout this survey, the sparker was used as a source, (Caulfield, 1962; Caulfield et al. , 1965). The sparker produces a shock wave which decays exponentially, followed by several bubble pulses alternating 180° in phase. With a source depth of 12.5 feet, the total length of the pulse train, including a surface reflection, is about 33 milliseconds. The peak output pressure of the system, operating at 100,000 joules, (10 kilovolts

and 2000 μ farads), is 134 db. above 1 dyne/cm² at one yard. In this survey, the source was operated at 8.0 kilovolts and 2000 μ farads (64,000 joules), and was triggered once every 10 seconds.

Recordings were obtained on the Precision Graphic Recorder (PGR), (Knott and Witzell, 1960; Knott and Hersey, 1956). The PGR was operated on the 1000 fathom scale, which has a sweep rate of 2.5 sec. , and was gated to record every fourth sweep. The resulting vertical-to-horizontal exaggeration of the record is about 20:1.

The signal recorded on the two PGR's was filtered in frequency bands of 15 to 50 cycles per second and 100 to 200 cycles per second respectively by means of Allison model 2AR passive filters.

The tape recorder used was a 4-track Crown recorder (model 800). On the first track, CSP data were recorded; on the second, voice announcements; on the third, scale lines; and on the fourth, the 60 cycle signal which formed the time basis of the PGR.

The receiving sensor consisted of a 15-foot, neutrally buoyant Alpine array, having five equally-spaced variable-reluctance hydrophones. The frequency response of this array is peaked at 120 c. p. s. (W. Dow, personal communication).

In some places, penetration of sediments to about 40 feet was achieved with a high-resolution, short-pulse echo-sounding technique employing a 12 K. C. pulse of 0.1 to 0.2 milliseconds duration. In these studies, a PGR sweep of 0.25 seconds was used.

B. Capabilities of Recorder

The capabilities of the seismic profiler can be demonstrated by considering the results of the theory of sound propagation. Sound propagation is governed by the Rayleigh wave equation. When the sound strikes a boundary, (i. e. water-air, water-sea floor, sediment, or rock boundaries), its reflection is governed by the corresponding boundary conditions. In the case of a plane wave striking a plane boundary separating two materials of constant density and sound velocity (Officer, 1958), the main conclusions of interest are:

- 1) A wavefront striking the air-water interface undergoes a 180° phase shift and almost total reflection.
- 2) Sound will not reflect from an interface unless there is a contrast in acoustic impedance between the materials on either side.

Given the right conditions, a geologic interface may not reflect sound at all; similarly, an acoustic reflection may not correspond to a lithologic change. It is generally found, however, that when an echo train has been compared with layering in cores, (Nafe and Drake, 1957; Shumway, 1960), the marked changes in porosity and lithification are evident on the reflection record.

In any case, a seismic profile will show only the presence of reflecting surfaces within the ocean floor; this information alone provides

inferences of a limited morphological type, such as

- 1) the lateral extent of layering and its relief,
- 2) the shapes of sediment bodies,
- 3) unconformable and conformable relationships between reflecting horizons,
- 4) the probable location of outcropping of layers,
- 5) the relationship of topography and structure; for example, whether topographic benches represent the outcropping of resistant layers.

No direct inferences can be made as to the composition of the layers.

The special capability of the seismic profiler is delineating the geometrical relations of reflecting interfaces (Hoskins, 1965).

C. Interpretation of Records:

The interpretation of CSP records in this paper is largely limited to the identification of reflecting surfaces by the correlation of individual echo sequences from successive pulses (a typical echo sequence is that formed by the succession of echoes reflected once by the sea floor) (Bunce and Hersey, in preparation).

It is necessary to identify false echo-sequences on the record which can not only be mistaken for real reflectors, but which can mask interfaces whose returns arrive concurrently with the interfering signals. Common among these signals are:

1) So-called multiple reflections from the sea floor and deeper layers, involving repeated transits of the water column by the sound pulse.

2) Side echoes from reflectors on or below the sea floor which are not directly below the line of the source and the receiver. Although these returns contain information about the topography or subbottom structure, they should not be interpreted as coming from a vertical reflection.

3) Noise generated outside the profiling system, such as power-line cross-feed, or ship-generated, water-bourne noise.

Multiple sea bottom reflections can easily be recognized. For instance, the first multiple bottom reflection will appear at twice the depth and have double the slope of the sea floor reflection. In shallow water, lines appearing after the first multiple bottom reflection were generally not trusted in this interpretation.

Topographic side echoes can be distinguished from subbottom reflectors by replaying the recordings through a filter which has a low frequency cut-off at 1000 c. p. s. or greater. Because of the preferential absorption of higher-frequency sound by sediment, the side echoes will be recorded but returns from true subbottom reflectors will not.

Noise generated outside the profiling system can often be recognized by examining the record at a time when the source was off or at

times between the initiation of the pulse and the sea floor reflection (Hersey, 1963).

After these unwanted signals are removed, it must be kept in mind that the resolution of individual layers on the recording is determined by the width of the band of parallel dark and light lines which represent a single reflecting surface. The width of this group of lines depends on:

- 1) The duration of the outgoing pulse.
- 2) The superposition of the pulses travelling along four separate source-reflector-receiver paths, which are determined by the relative positions of the source and receiver with respect to the sea surface and the sea floor. This process will not only widen the band of lines representing a single reflector but can also produce lines on the record which appear to represent additional reflectors. The resolution of individual reflecting surfaces has been estimated by Hoskins (1965) to be 50 milliseconds.
- 3) The width of the bandpass presented.
- 4) The recovery characteristics of the filters.

An examination of phase continuity and interference can be helpful in distinguishing individual reflectors in a series of layers which are spaced closer in time than the duration of the outgoing signal. The ability to correlate corresponding events on successive sweeps is determined by the

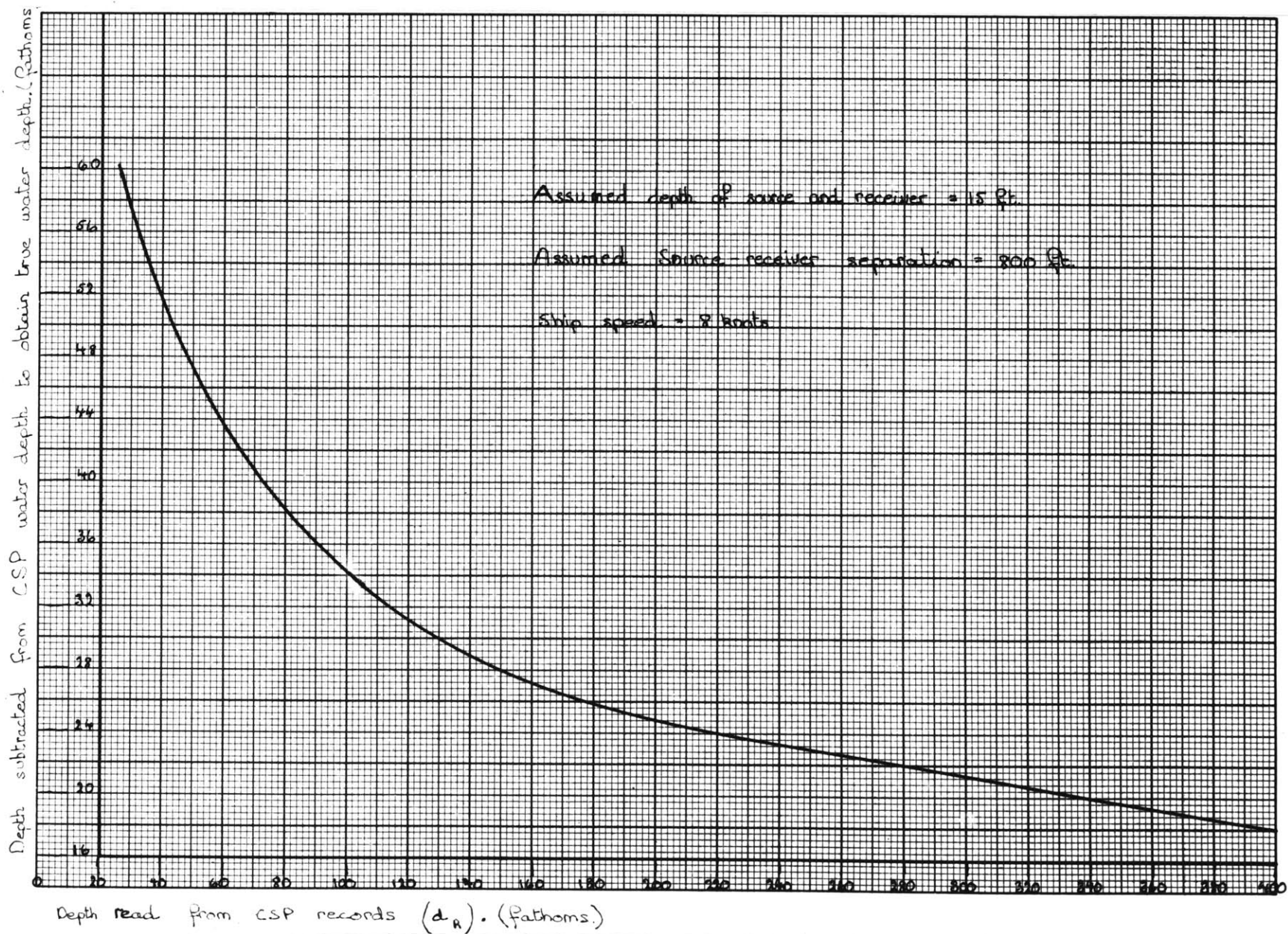


Figure 3. Correction curve used in obtaining true water depths from seismic profiling records.

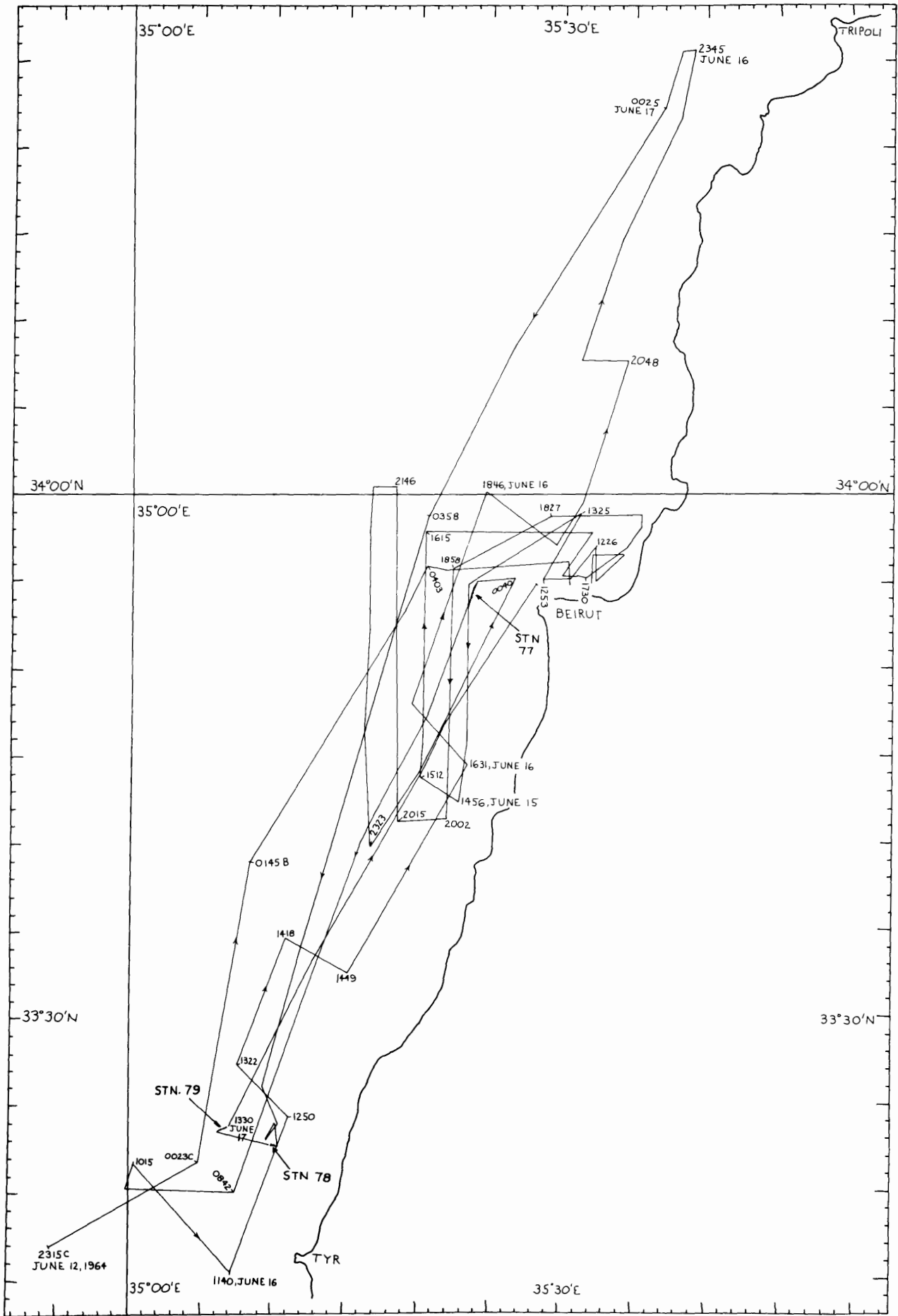


Figure 4. Corrected ship's tracks of echo-sounding survey.

ratio of the sweep-speed of the recorder to the wave period of the signal (Curry et al. , 1964).

II. METHODS OF ANALYSIS

The following steps were taken in the analysis of the data:

TOPOGRAPHIC DATA

A. Adjustment of ship's Tracks:

Track plots were prepared by the deck officers showing the position of the ship's tracks based on radar fixes. All the survey tracks were plotted on a grid which was 2.5 times larger than the original. The position of the time marks occurring between fixes was corrected to allow for variations in the ship's speed. The tracks were then adjusted, using the depths shown at each five-minute mark and the topographic maxima and minima which occurred between these marks, so that the depths at each intersection of the tracks agreed. Along some lines, the echo-sounder was not operational; in this case, depths were computed from the sea floor depths shown on the higher-frequency presentation of the seismic profiler using a hyperbolic curve (Figure 3). This curve compensates for the fact that the source-receiver travel path is not near-vertical in water shallower than 400 fathoms. The curve was calculated assuming a source and receiver depth of 15 feet, and a source-receiver separation of 800 feet. The correction curve was compiled so as to agree with other concurrent seismic profiling and shallow-water echo-soundings. At the time, the ship was maintaining a constant speed of eight knots; hence, the

variations in source and receiver depths should be small. The maximum disagreement between depths obtained by seismic profiling and echosounding, including the error of zero-registering the scale lines and reading the records, is estimated to be 15 fathoms.

Due to the large number of intersections, most of which occur at oblique angles, and the large changes of depth over a relatively short horizontal distance, the depths of the intersections agree on the average to within 20 fathoms. The maximum deviation of a track from its original position based on fixes, is about 0.75 miles.

B. Preparation of Topographic Map:

From the resulting track network (Figure 4), a topographic map of the sea floor was prepared (Figure 6). Since the ship was not allowed within the three-mile limit of Lebanon, most of the depths obtained are deeper than 200 fathoms. Topographic lines shallower than this are obtained from a chart by Boulos (1962), who shows in some detail individual soundings along the continental shelf and upper slopes. It is not known whether these soundings were obtained by echosounder or cable lowerings during dredge stations. Due to the detail of echosounding lines south of Beirut and their relative scarcity north of Beirut, the southern part of the topographic map is much more accurate than the northern.

The unit of depth used in the presentation and discussion of the topographic data is uncorrected fathoms.

SEISMIC PROFILING DATA

1. The chart of the echo-sounding tracks, along which the seismic profiling records were taken, was reduced to the same scale as the geological map of Lebanon (Plate 1).

2. Tracings were made from the records of the survey and from subsequent records, which were obtained by replaying magnetic tapes when details on the original records were not clear. These appear in Figures 9 to 32 .

3. The tracings were re-proportioned using a flow camera (Hoskins, 1964b) so that, while the vertical scale across the width of the records was constant between tracings, the horizontal scale, along the length of the record, was changed from a constant-time basis to a constant-distance basis. At the same time, by reducing the overall scale of the tracings, their horizontal length between successive fixes was made equal to the corresponding lengths of ship's track on the scale of the geological map of Lebanon (Plate 1).

4. A model using the re-proportioned tracings was made in three dimensions, as an aid to interpretation (Plates 2 to 11). This model,

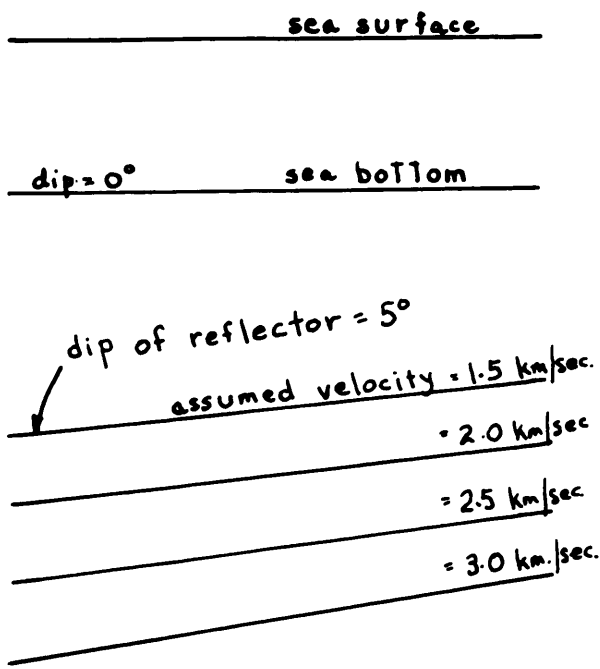


Fig. 5a

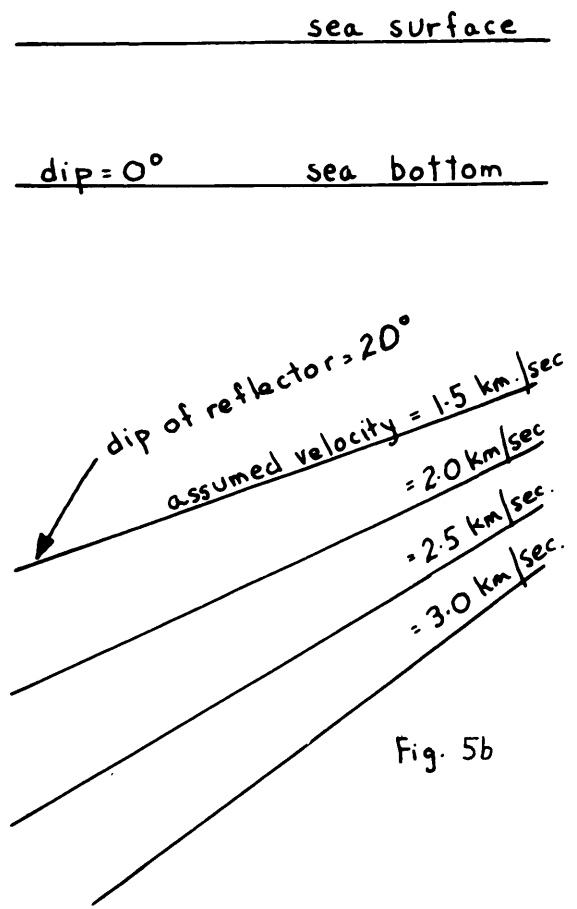


Fig. 5b

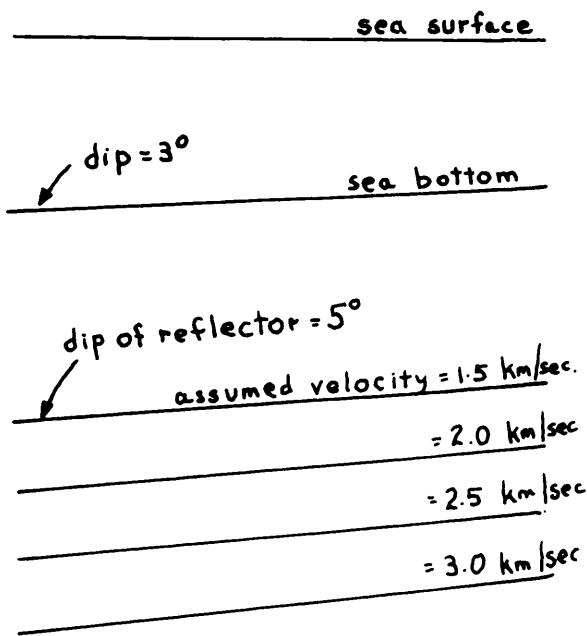


Fig. 5c

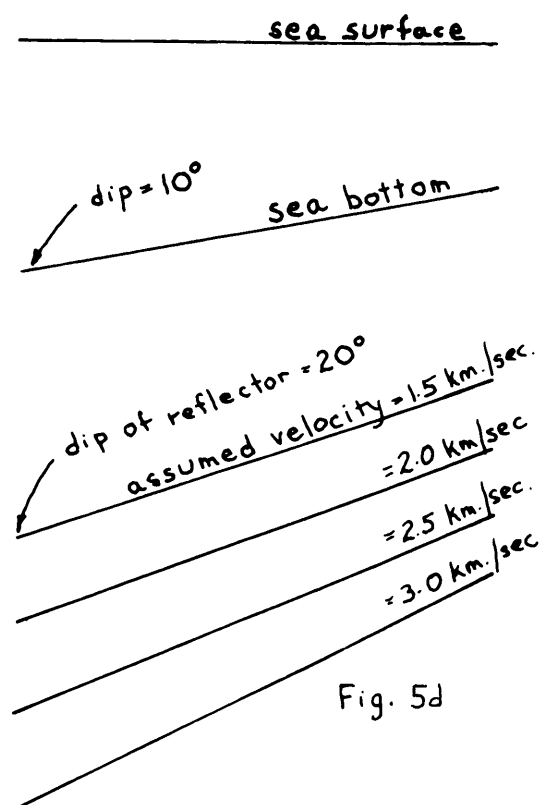


Fig. 5d

Fig. 5: Effect of varying velocities of sound in overlying sediment on position and attitude of reflector

constructed on the same lateral scale as the geologic map of Lebanon (Plate 1), allowed the writer to determine whether stratigraphic, topographic, or structural features seen on land could be extrapolated seaward to the area shown by the model.

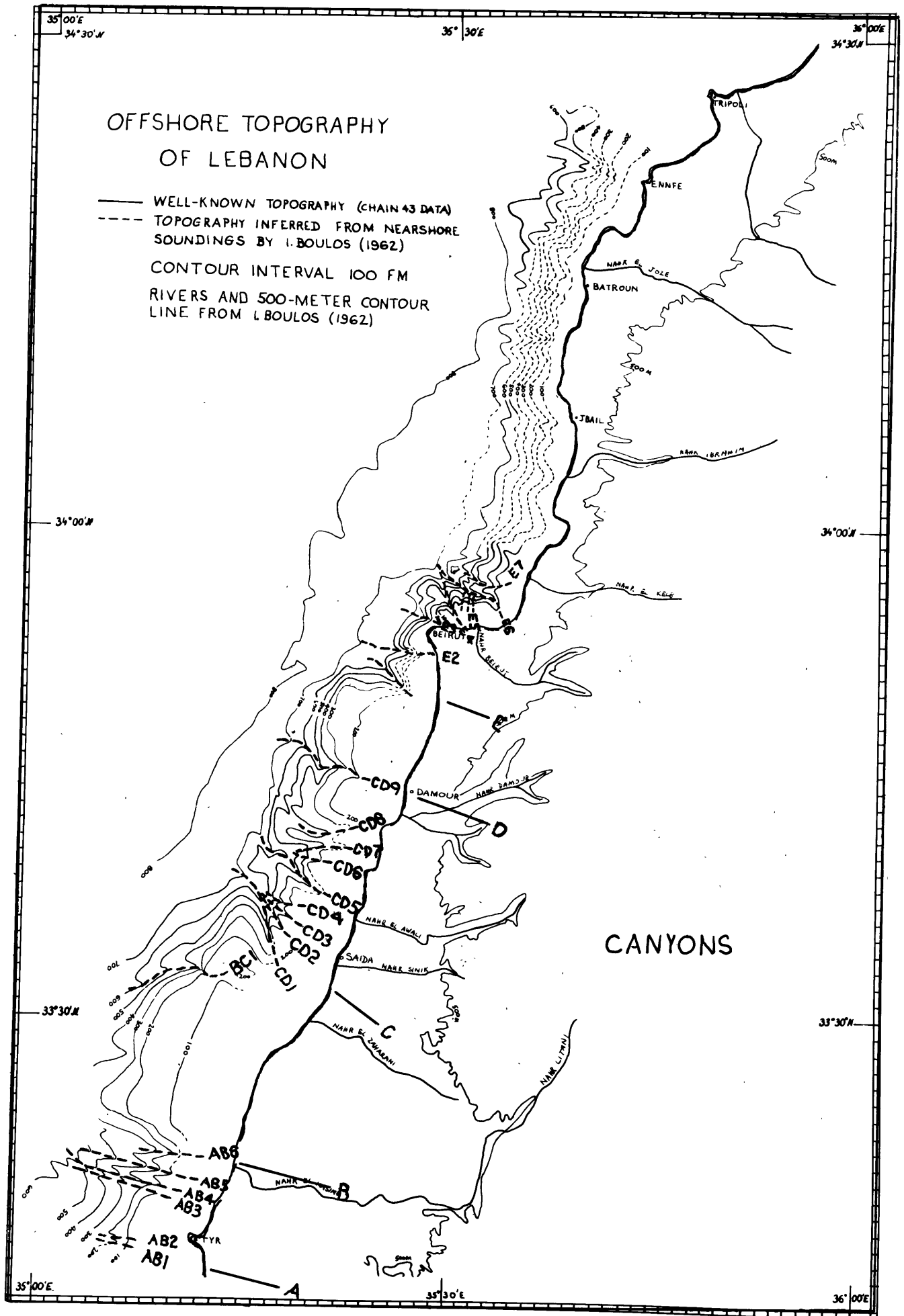
5) The seismic profiling results presented here are the repropor-tioned tracings. Several photographs of the model are included to assist the reader in following the description of the results. A solid line represents an easily recognized succession of echoes. A dashed line represents successions which are less conspicuous. A dashed line with a question mark suggests the continuation of a layer between two points where it can be seen.

In these tracings, the attitude of the reflectors is based on the assumption that the velocity of the seismic pulse is always the same as the velocity of sound in water (i. e. 1500 meters/second); but the pulse travels through sediments in which the velocity of sound is greater than that in water. No correction is made for the greater velocity of sound in sediments, since no information is available on this point in the area surveyed. The effect of such a correction on the dip of an interface is shown in Figure 5 . As a result, the dips of buried interfaces on the reflection recordings are reduced on the shelf and exaggerated on the slope. (Hoskins, 1965). If a layer crops out in a canyon, the velocity difference

between water and sediment can be used to calculate either the dip of the layer or the velocity of sound in the overlying material (Hoskins, 1964; Roberson, 1964); the calculation of one quantity assumes a value for the other. Such calculations were tried assuming horizontal layering. These results will be indicated in the discussion of the profiling data.

Arc-swinging to determine the true position of the layers (Hoskins, 1964) was considered unnecessary. To be of value, the arc-swinging must take into account the velocity of sound in sediment, and this quantity is unknown.

In the discussion of the geological interpretation of the results, layer thicknesses will be reported as the difference in total travel time between echoes below and above the layer, and similarly, depths below the sea floor. The context will indicate whether layer thickness or depth is intended (as in Bunce and Hersey, in preparation).



CHAPTER III

PRESENTATION AND DESCRIPTION OF RESULTS

I. TOPOGRAPHIC RESULTS

The topographic contour map (Figure 6) describes the continental shelf, slope, and rise off Lebanon. On this map, solid contours, mostly south of Beirut and outside the three-mile limit, indicate where the topography has been well-established by echo-sounding lines. Dotted contours, mostly north of Beirut and inside the three-mile limit, indicate where the topography has been inferred from available echo-soundings and soundings given by Boulos (1962) to 200 fathoms.

The nearshore information given by Boulos indicates that except where broadenings of the shelf occur (these features will be discussed in the following paragraphs), the shelf is generally 3 to 7 km. wide, with a shelf break at a depth of about 50 fathoms.

A detailed description of the topography south of Beirut will now be given. In this area, much of the continental slope is incised by canyons, and relevant information on them is given in Table I. The seaward extension of lines A to E on the contour map are good reference points for a detailed discussion of the topography because they roughly define the areas containing interesting topographic features.

Between lines A and B off Tyr, the shelf break appears to be about 25 fathoms deep, approximately 4.5 kilometers off shore. The continental slope between the 100-fathom and 500-fathom contour lines has an average

declivity of 6° . In the north half of the area, three canyons are recognized between the 200-fathom and 600-fathom contour lines.

Between lines B and C, a feature exists which will be called the Tyr-Saida Bank. The shelf of this bank extends farther seaward than the adjacent shelves, and has an average slope of 2.5° between the 100-fathom and 200-fathom contour lines. The shelf break occurs at a depth greater than 200 fathoms, approximately 14 kilometers from shore. The slope fronting the bank has an approximate declivity of 12° between the 200-fathom and 600-fathom contour lines. Only one canyon cuts across the slope. Near the edge of the shelf, the canyon is represented by a 30-fathom depression, but is cut much deeper farther down the slope. From the shelf break down to 400 fathoms, the canyon is sinuous; deeper than 400 fathoms, it curves slightly in a WSW direction.

In the area between lines C and D the slope to the north at the Tyr-Saida Bank is deeply incised by canyons. Four systems of canyons are recognized: the southern one has four tributaries; the next northward has three; the other two are single canyons. All but the northernmost of these canyons appear to stop at the base of the continental slope.

Opposite Damour (between lines D and E), as in area B to C, the shelf is again wider than in the adjacent areas. Its average slope is 3.5° between the 100 and 200-fathom contour lines. The shelf break occurs at

a depth of 220 fathoms (410 meters), approximately 10 kilometers from shore. The average declivity of the slope steepens from 9° in the south to 13° in the north. Although this feature is bounded to the north and south by canyons, none cut across the embankment.

North of line E, near the Beirut peninsula, a marked increase in the declivity of the continental slope is seen; it increases to 20° on the west side of the peninsula, and to 30° on the north. Several canyons are seen near the peninsula; a major one, named Beirut Canyon by Emery et al. (in press), is fed by several tributaries from the south. These canyons all extend to the continental rise.

South of Beirut, the base of the continental slope, following approximately the 700-fathom line, is marked by hills typically 20 meters high, which extend perhaps a kilometer seaward to the 750-fathom contour line. Between the 750 and 800-fathom contour lines, the upper continental rise is characterized by long rolling hills and a smooth sea floor. Outside the 800-fathom line, variations in topography become slight and the sea floor descends westward in a long concave arc (Emery et al., in press).

North of Beirut, only two sounding lines across the rise and lower slope define the topography. The available information suggests that the slope is steep (on the order of 15°), and variations in both the shallow-water and the deep-water soundings indicate that the slope is incised by canyons.

II. SEISMIC PROFILING RESULTS

When a seismic profiling survey along the edge of a continental margin is laid out so that the survey lines are at right-angles to the shore, the change in the configuration and sequence of sediments can be traced from the continental rise to the continental shelf. The data can often then be grouped into the physiographic divisions of continental shelf, slope, and rise. This reconnaissance survey, however, was run mostly parallel to the shore, with the result that many of the north-south profile lines cross the continental margin obliquely. Moreover, along the coast of Lebanon, a number of structural or topographic units extending seaward from the shelf to the rise complicate the organization of the data into divisions of shelf, slope, and rise. Nevertheless, for purposes of comparison, this classification has been used. Fortunately, most of the structural and topographic units can be discussed satisfactorily within this framework. In many cases, the profiles will be grouped to illustrate a structural or topographic feature. Consequently, the profiles illustrating one type of structure will often be chosen to overlap the profiles illustrating the neighboring structure in order to point out the relation between the two. The profiles will be referred to by upper case letters; particular points of interest will be indicated by Greek lower case letters. Photographs of the model constructed from the reflection profiles will assist the reader in identifying profile lines and will show the various structures in three dimensions.

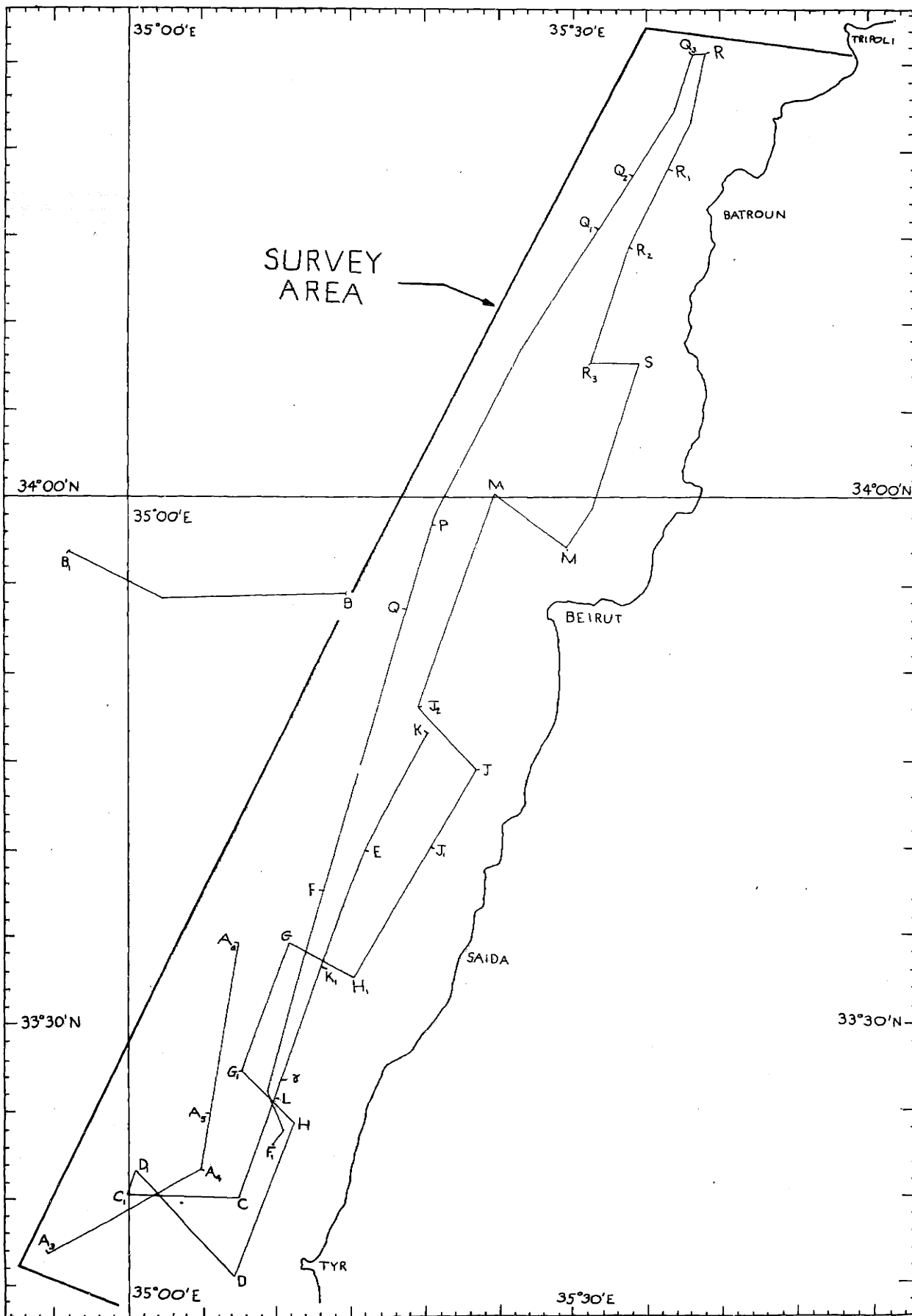


Figure 7. Seismic reflection profiling lines made in survey area.

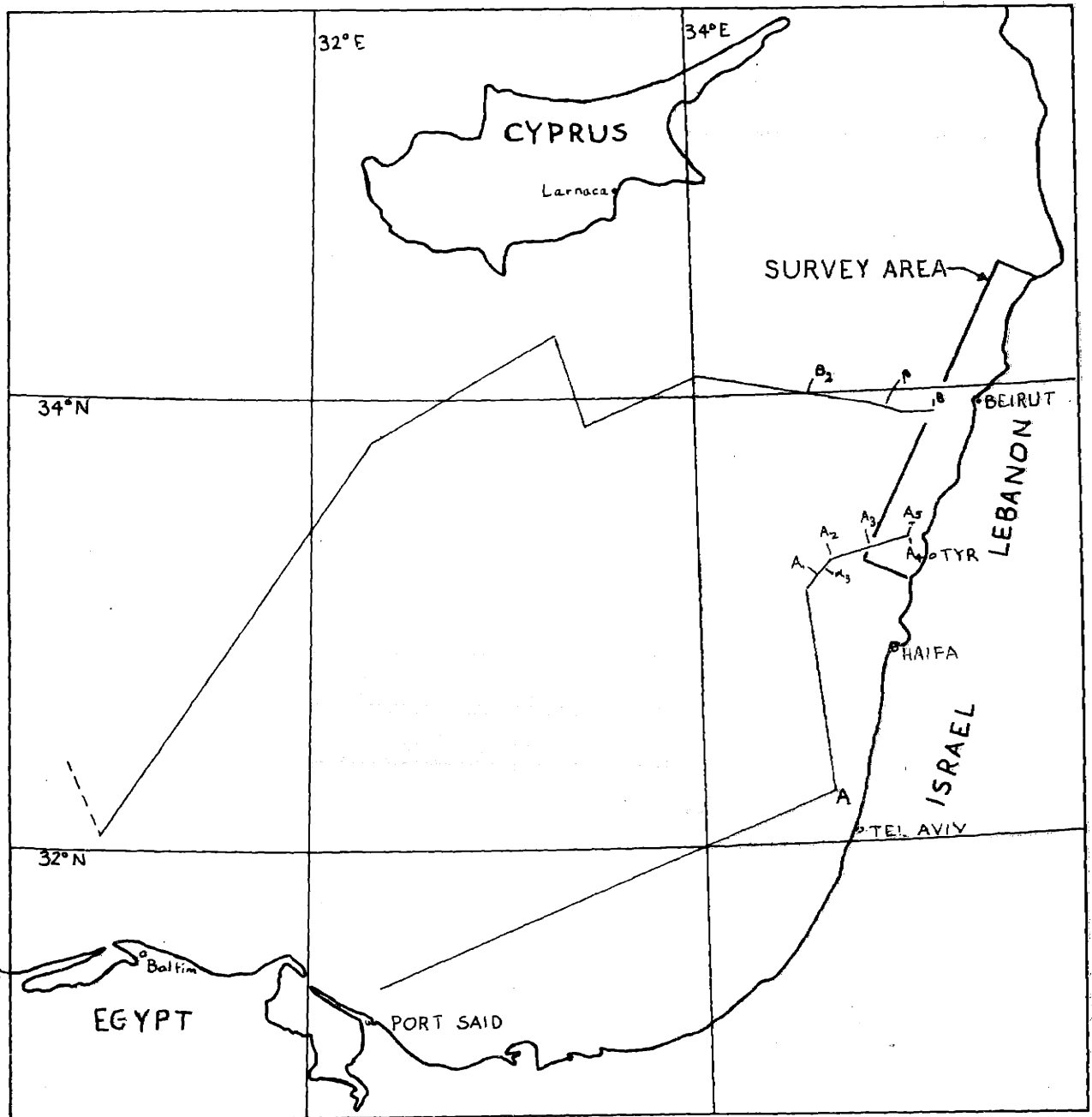


Figure 8. Seismic reflection profiling lines made outside survey area.

GEOLOGICAL MAP OF LEBANON




Adapted from M. Louis Dubertret.

1

2

3

CONVENTIONAL SIGNS.

-  Geological contours
-  Apparent faults
-  Hidden faults

LEGEND.

I VOLCANIC ROCKS.



A. BASALTS.




-  jurassic
-  lower cretaceous
-  miocene
-  pliocene
-  quaternary
-  scoria cones
-  volcanic ash

II SEDIMENTS.







A. SECONDARY.

1. Jurassic.



-  green marls and black dolomite (LIAS?)
-  black dolomite (BAJOCIAN)

-  yellow limestone (BAJOCIAN?)
-  light-grey limestone (BATHONIAN-CALLOVIAN)
-  terminal jurassic (SAFORDIAN-PORTLANDIAN)



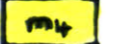
2. Cretaceous.



-  grés de base
-  APTIAN
-  ALBIAN
-  white marls (TERMINAL CENOMANIAN)
-  CENOMANIAN-TURONIAN
-  SENONIAN

B. TERTIARY.





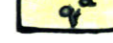



- 1.  EOCENE
- 2.  MIOCENE (marine)

3. NEOGENE (continental)

-  lacustrine deposits. (miocene)
-  massive limestones of Mt. Tirbol (HELVETIAN)
-  lacustrine marls and conglomerates
of River Barid (Pontian)

-  torrential deposits (miocene or pliocene)
-  soft sandstone (PLAISANCIAN)

C. QUATERNARY.

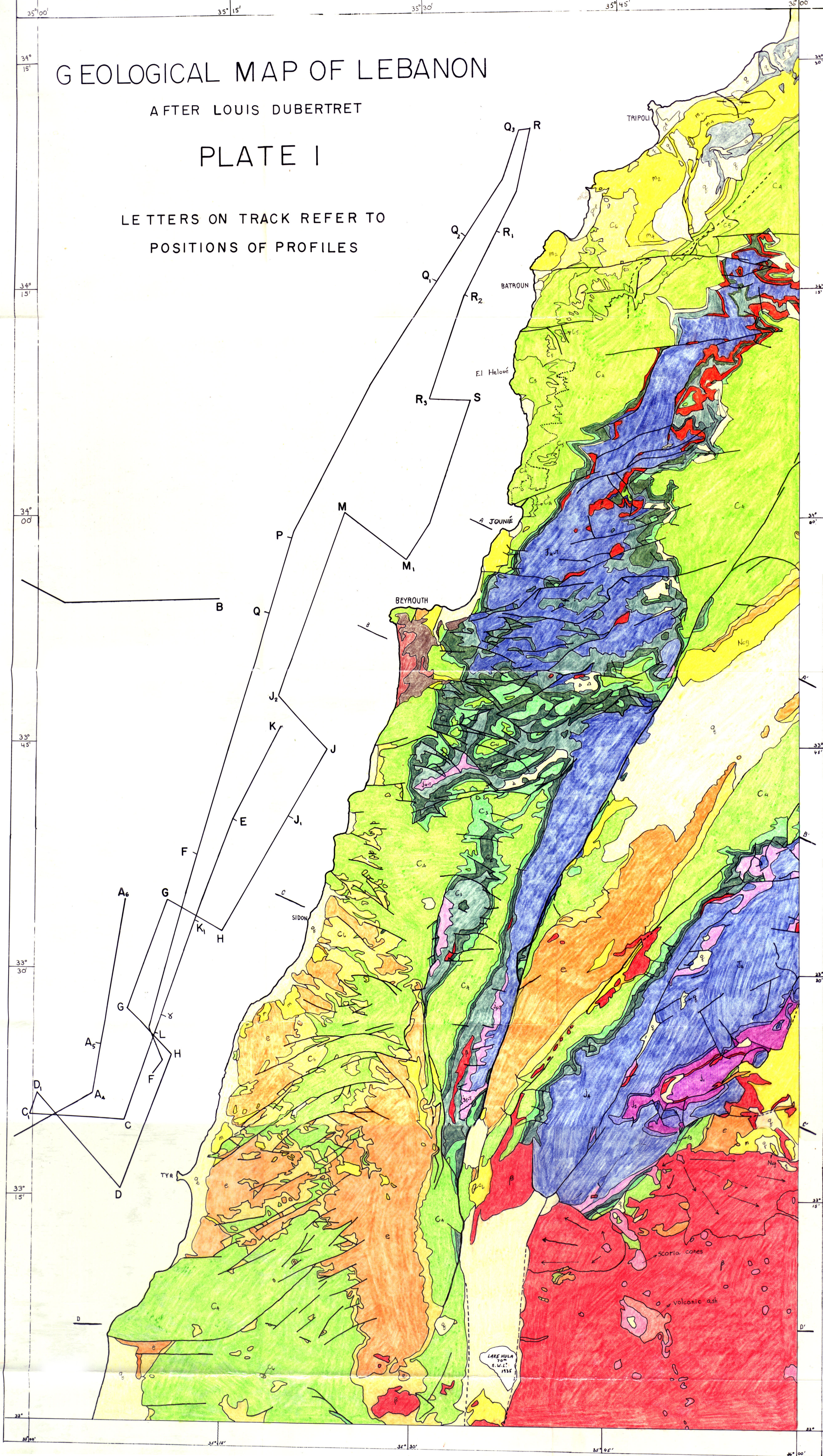
-  sandstone and littoral sand
-  soils resulting from decalcification of
littoral sandstone
-  arable land
-  loose material
-  sand dunes
-  moving dunes
-  broken flint
-  fluvatile conglomerates
-  alluvial mud

GEOLOGICAL MAP OF LEBANON

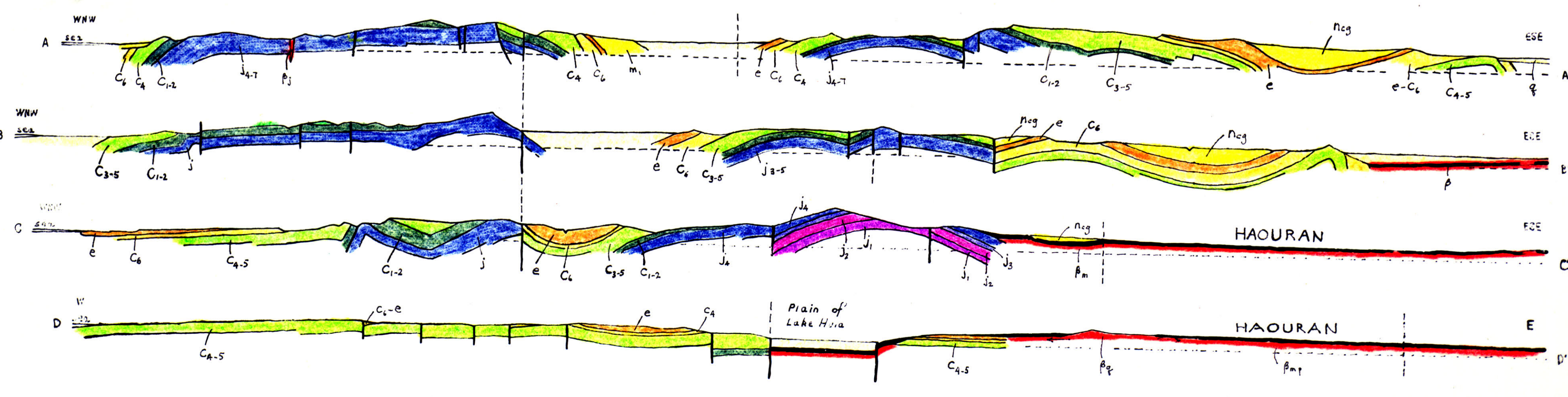
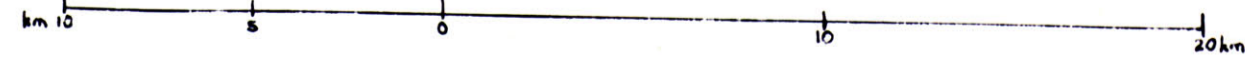
AFTER LOUIS DUBERTRET

PLATE I

LETTERS ON TRACK REFER TO POSITIONS OF PROFILES



Scale 1:200,000



KEY FOR PLATE 2



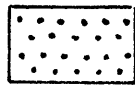
Jurassic



Cretaceous



Eocene



Quaternary



Volcanic Rock

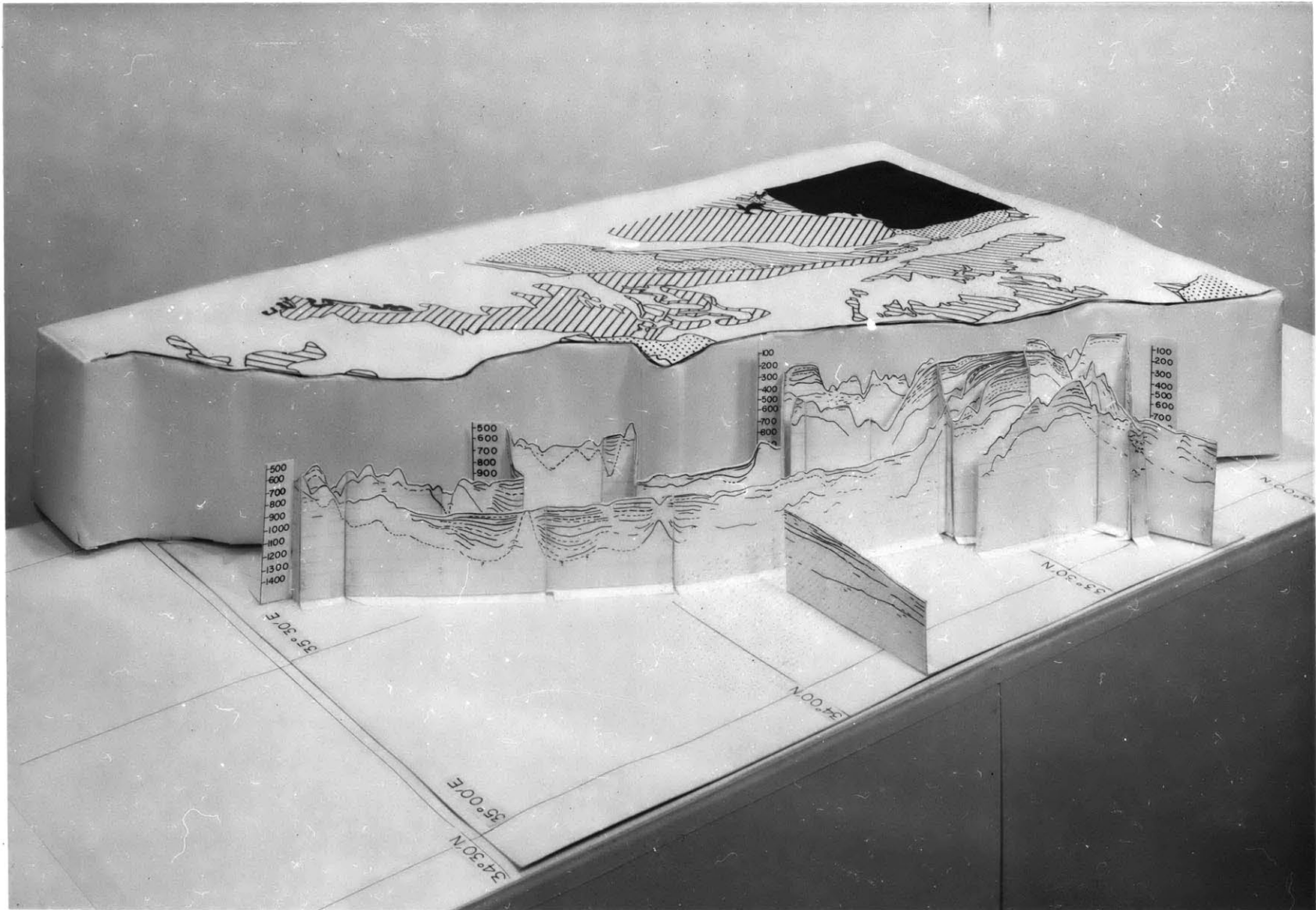


Plate 2. View of model showing adjacent geology of Lebanon.

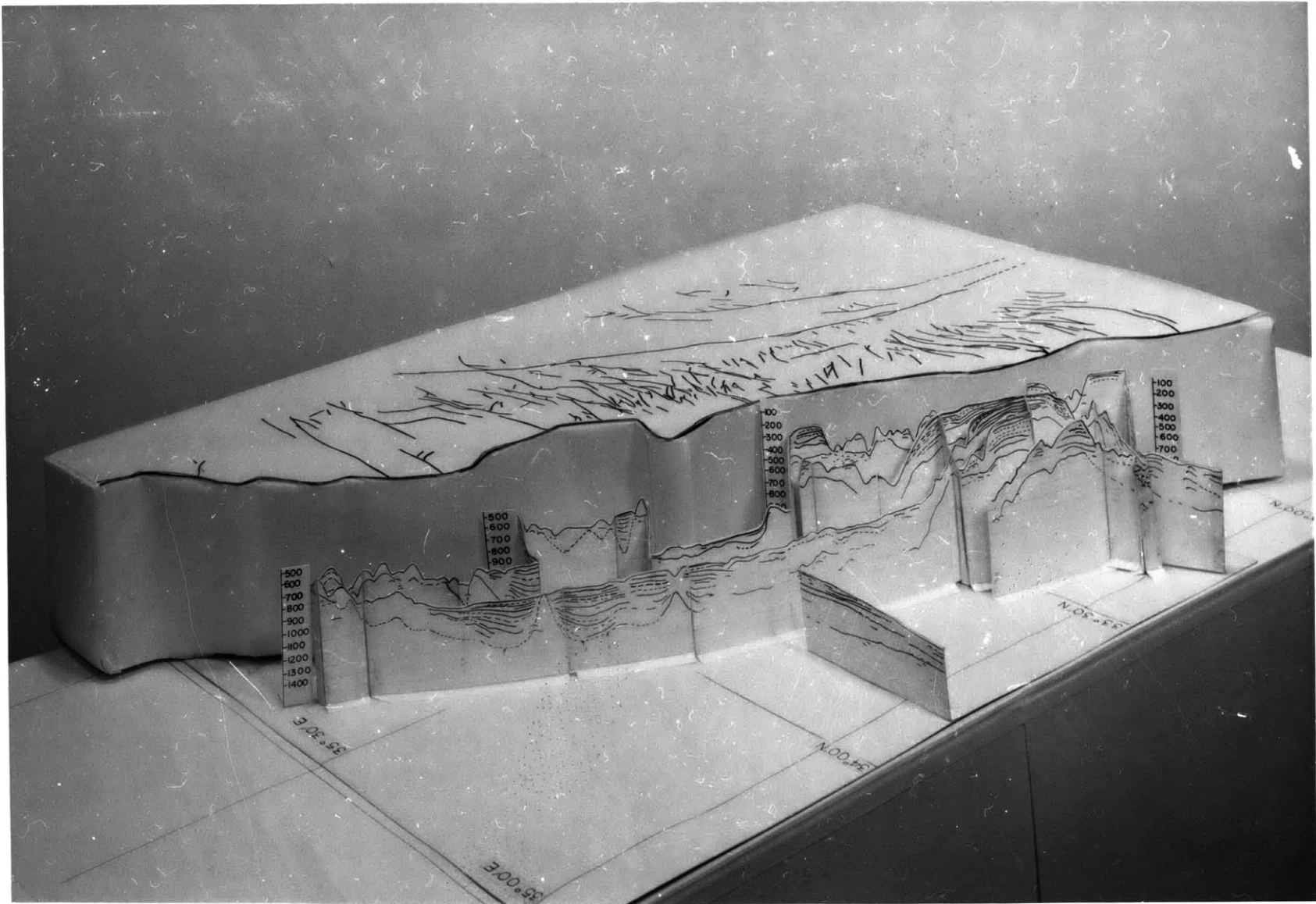


Plate 3. View of model showing adjacent structures of Lebanon.

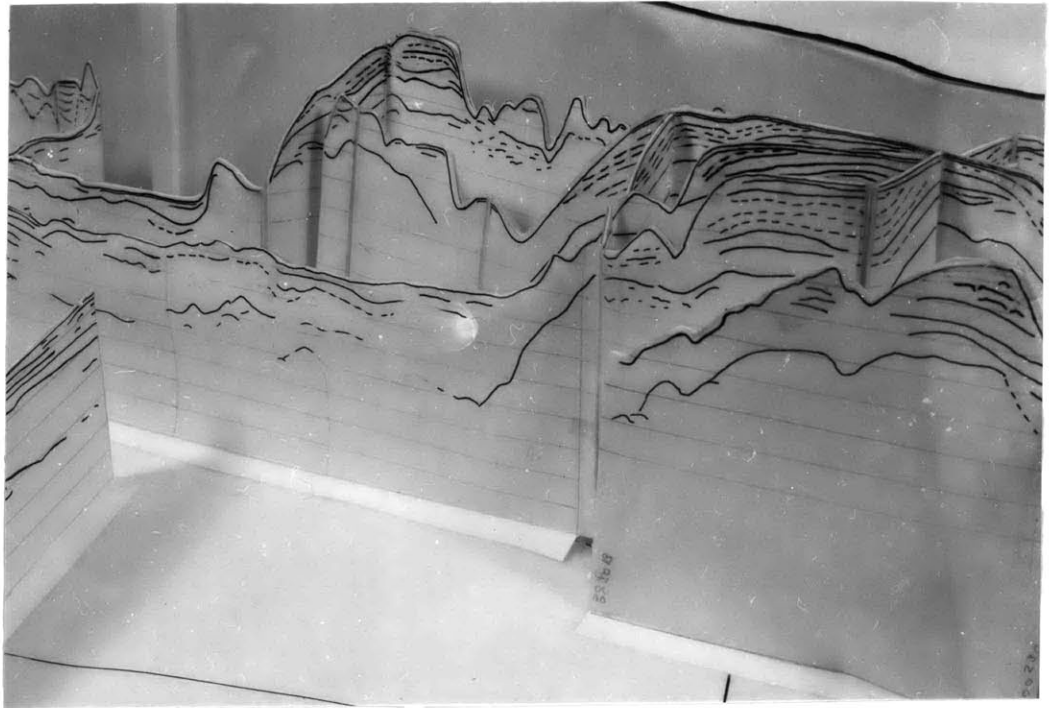


Plate 4. View of survey area south of Beirut.

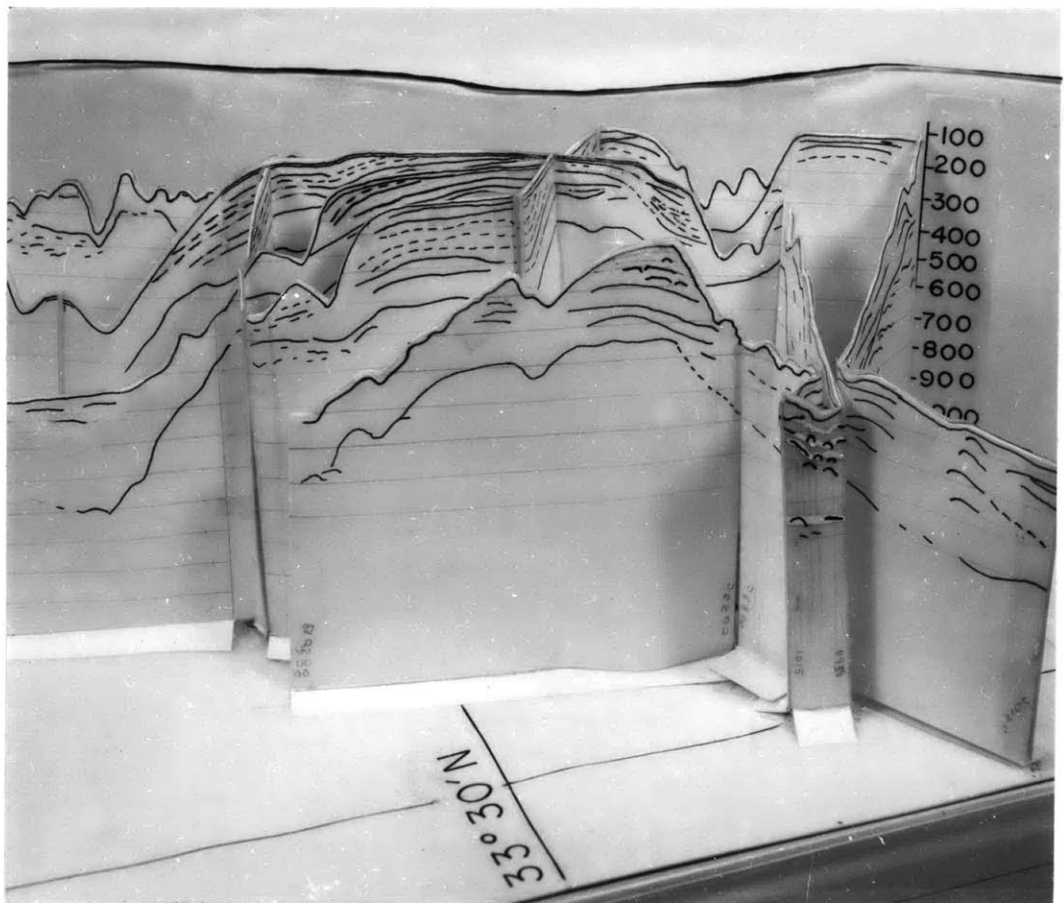


Plate 5. Tyr-Saida Bank.

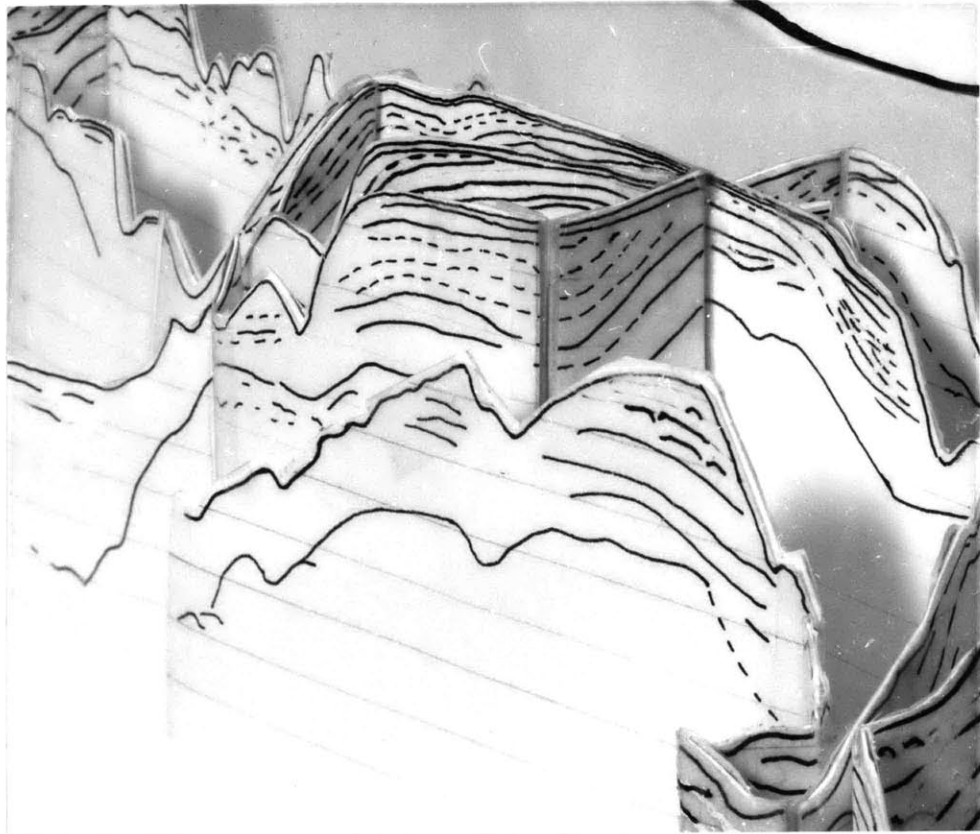


Plate 6. Detail of bedding on shelf and slope of Tyr-Saida Bank.

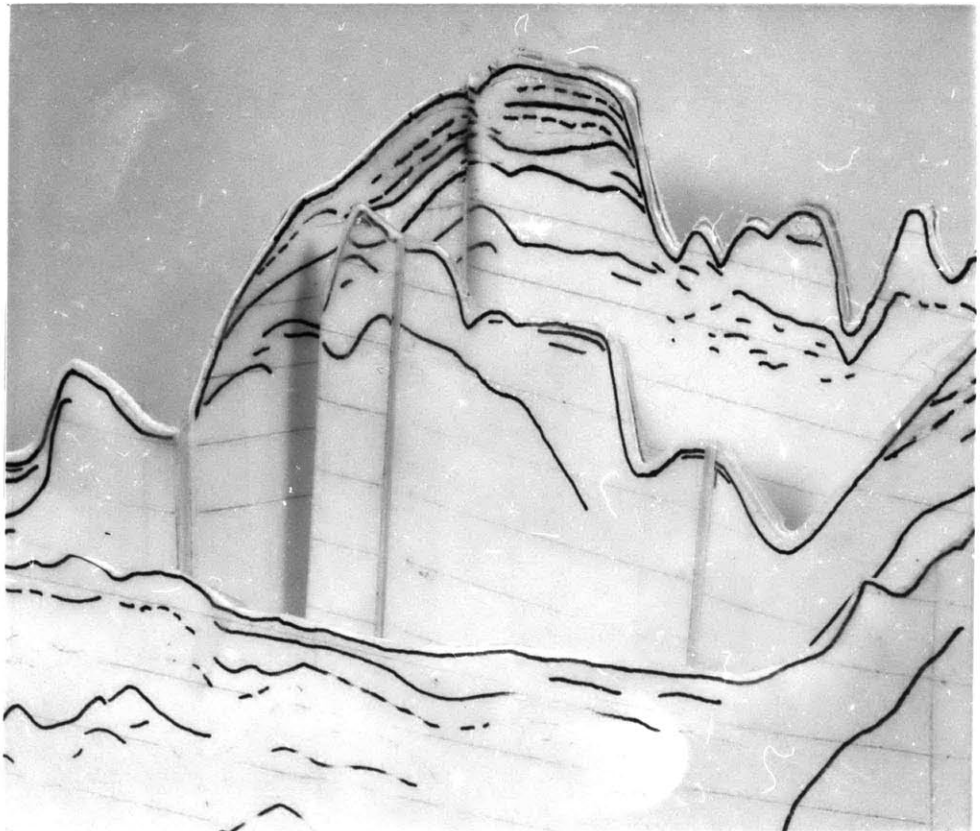


Plate 7. Detail of bedding on wide part of shelf opposite Damour.

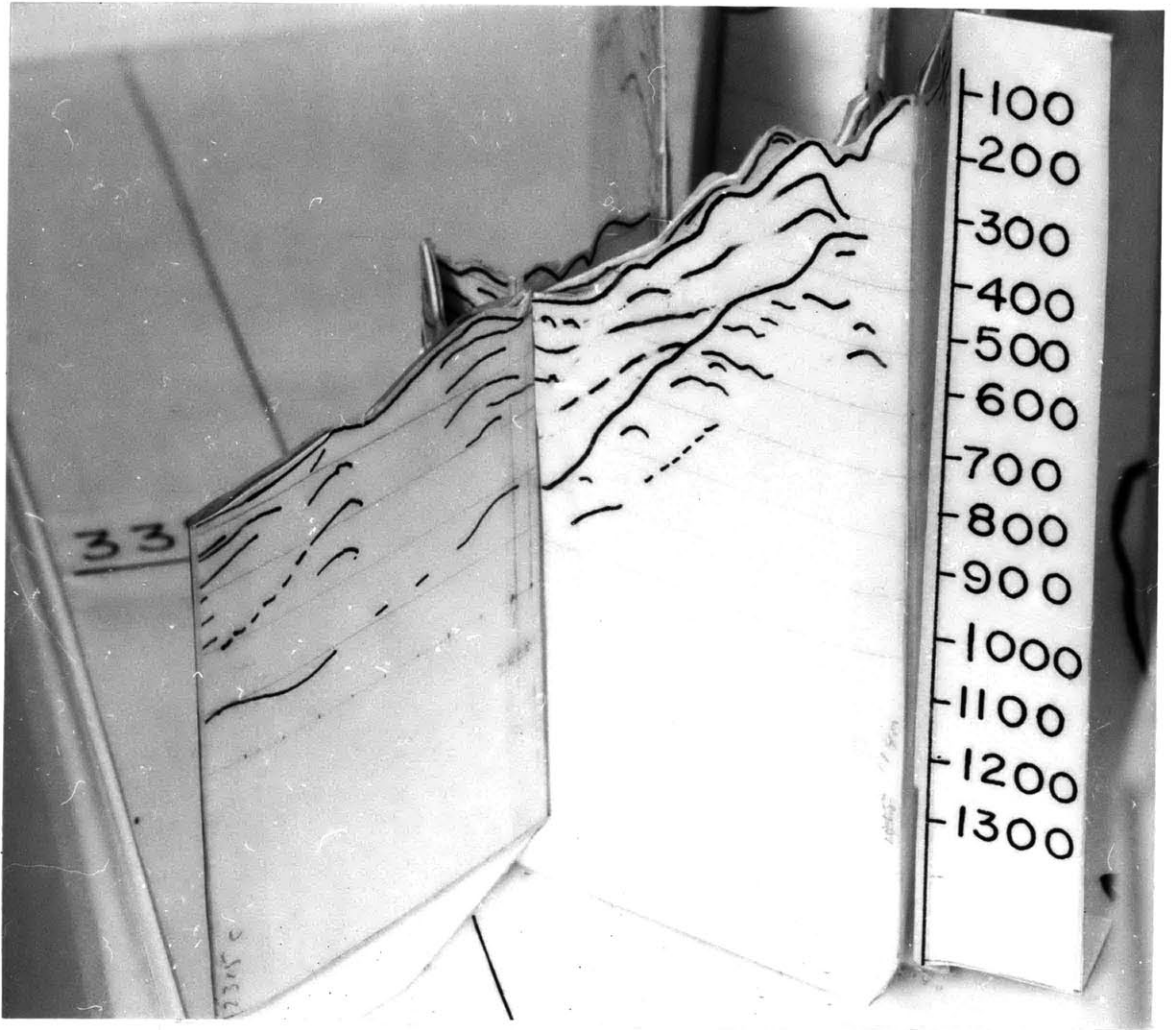


Plate 8. Slope and rise at south end of survey area.

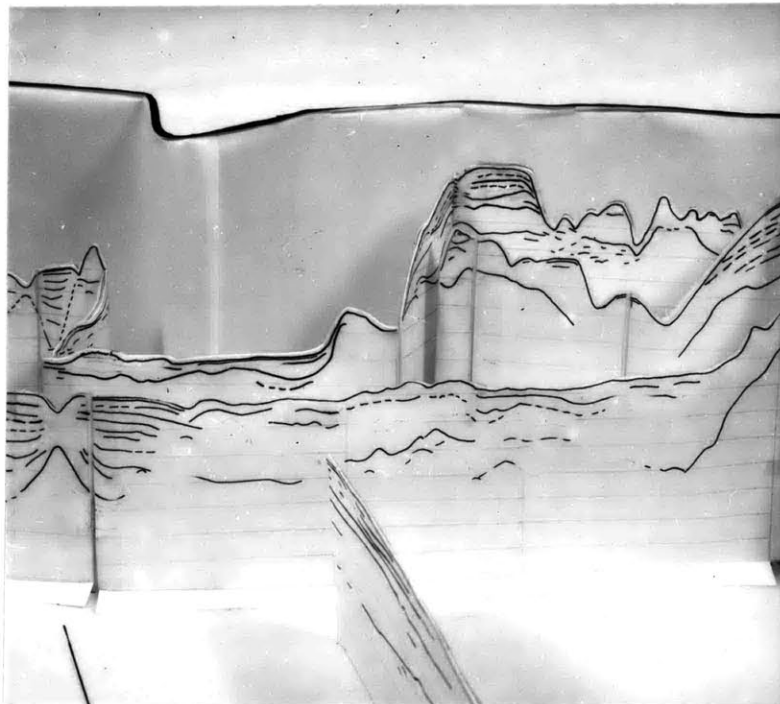


Plate 9. Continental rise between Beirut and Tyr-Saida Bank.

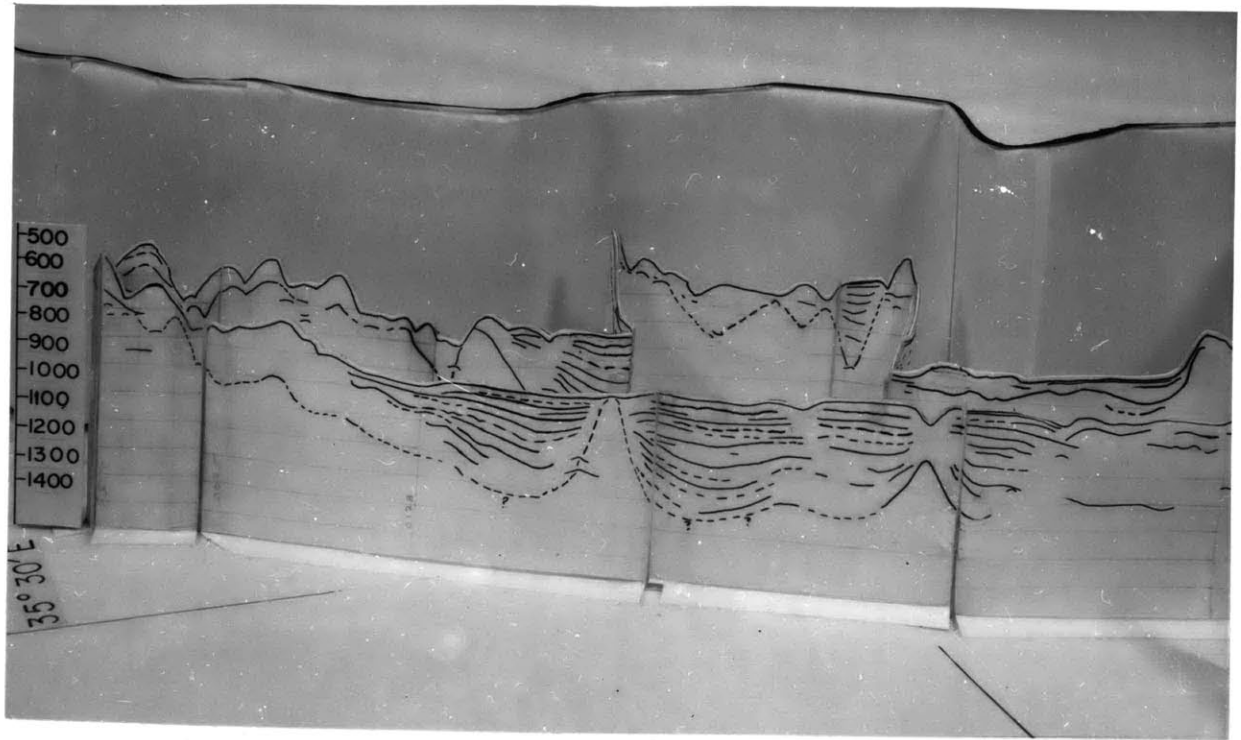


Plate 10. Slope and rise between Beirut and Tripoli.

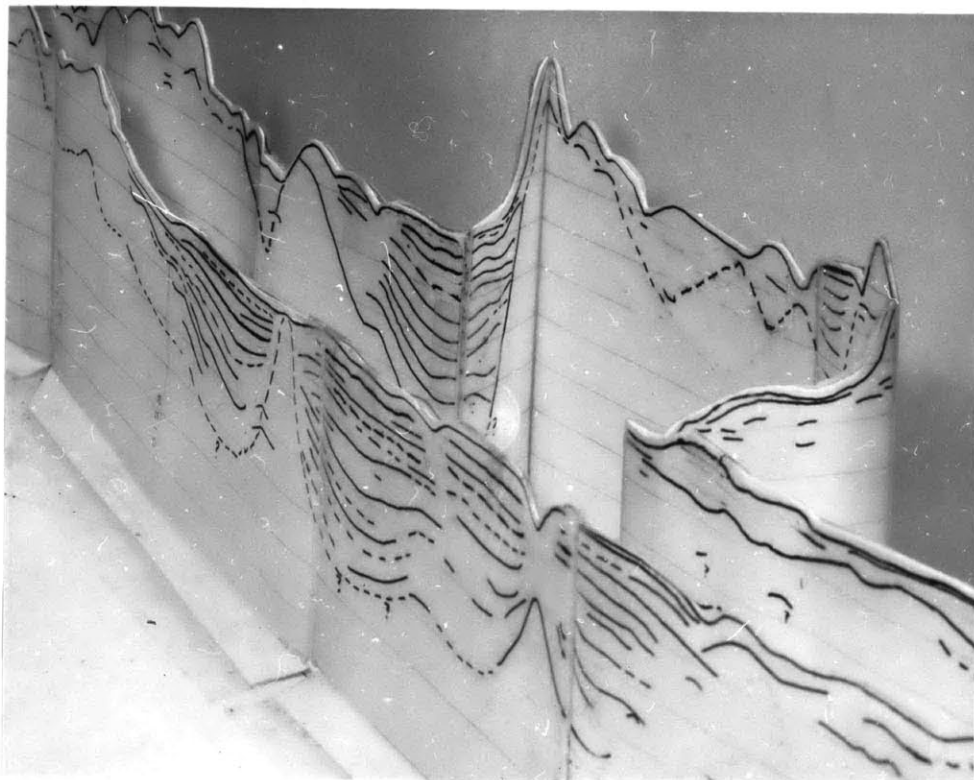


Plate 11. Three-dimensional view of sediment-filled depressions beneath continental rise, between Beirut and Batroun.

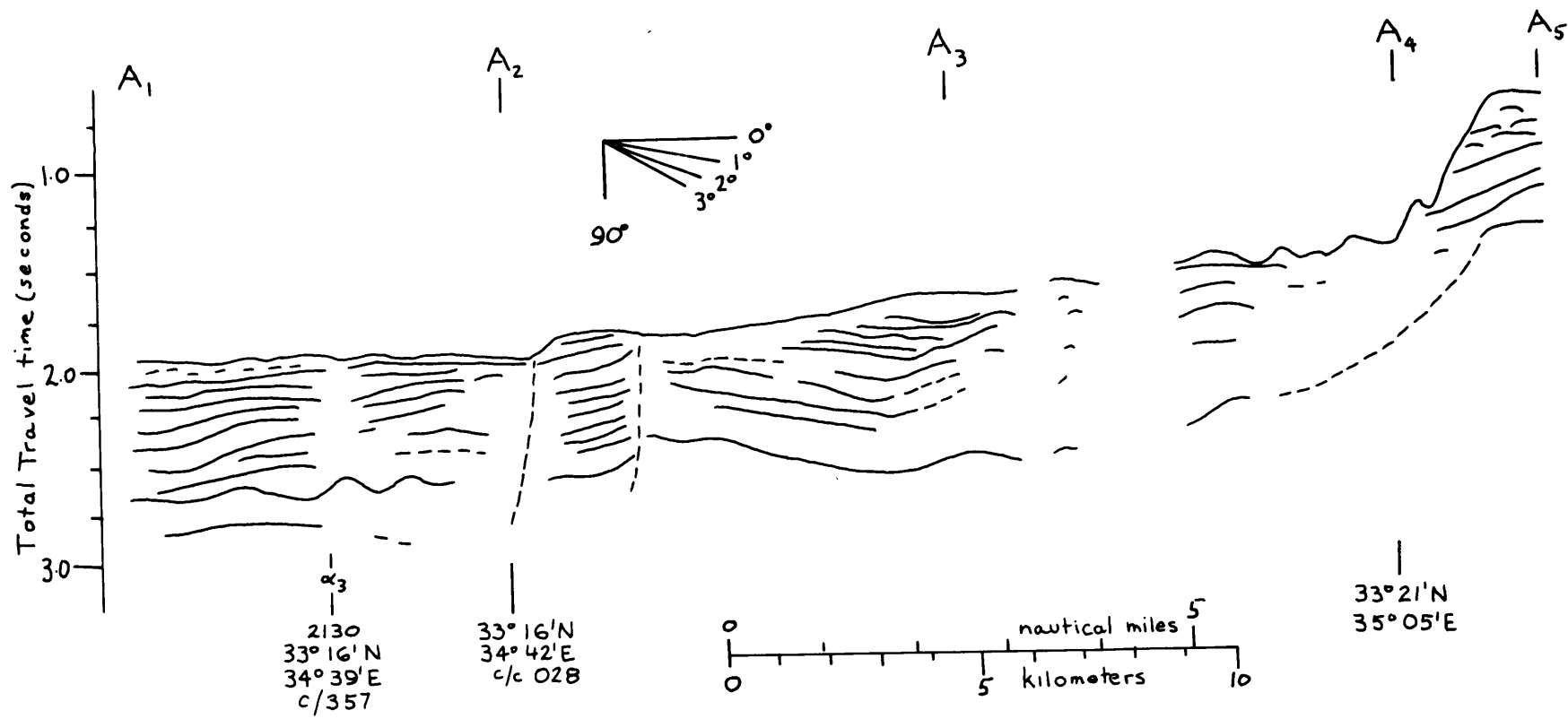


Figure 9: Profile A₁A₅

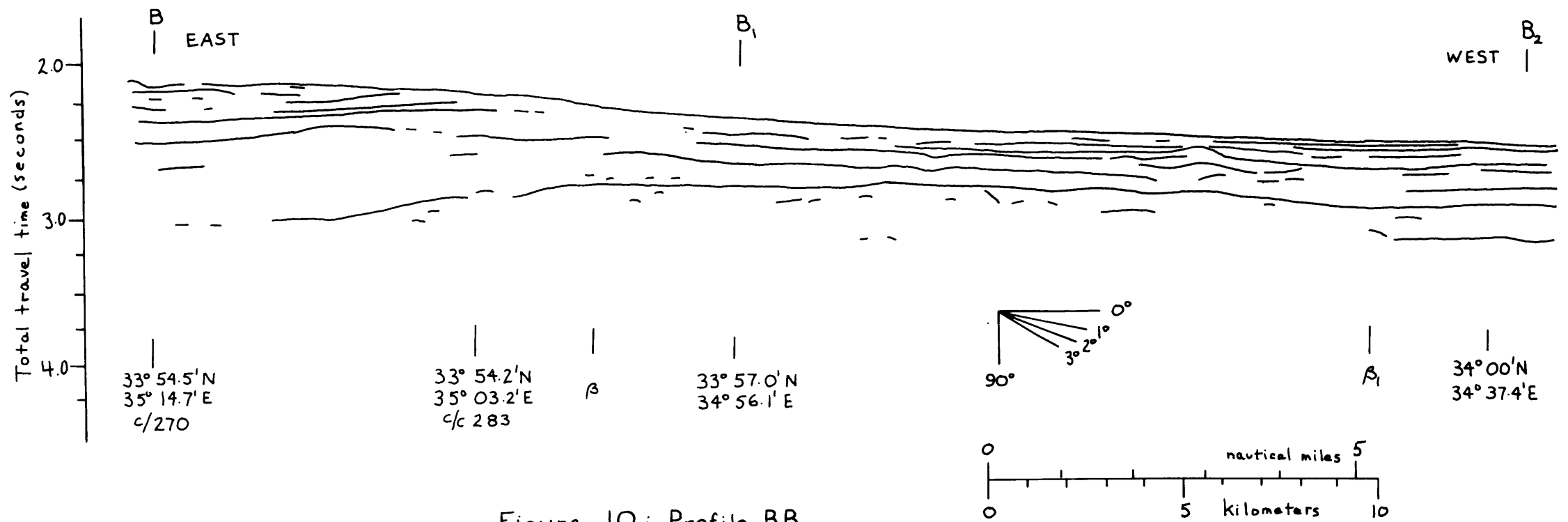


Figure 10: Profile B B₂

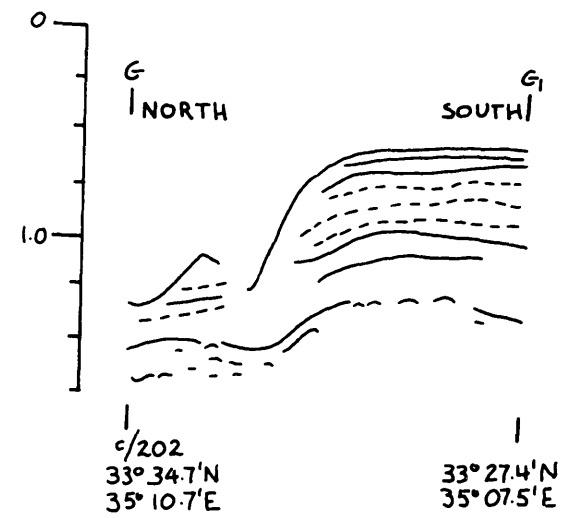
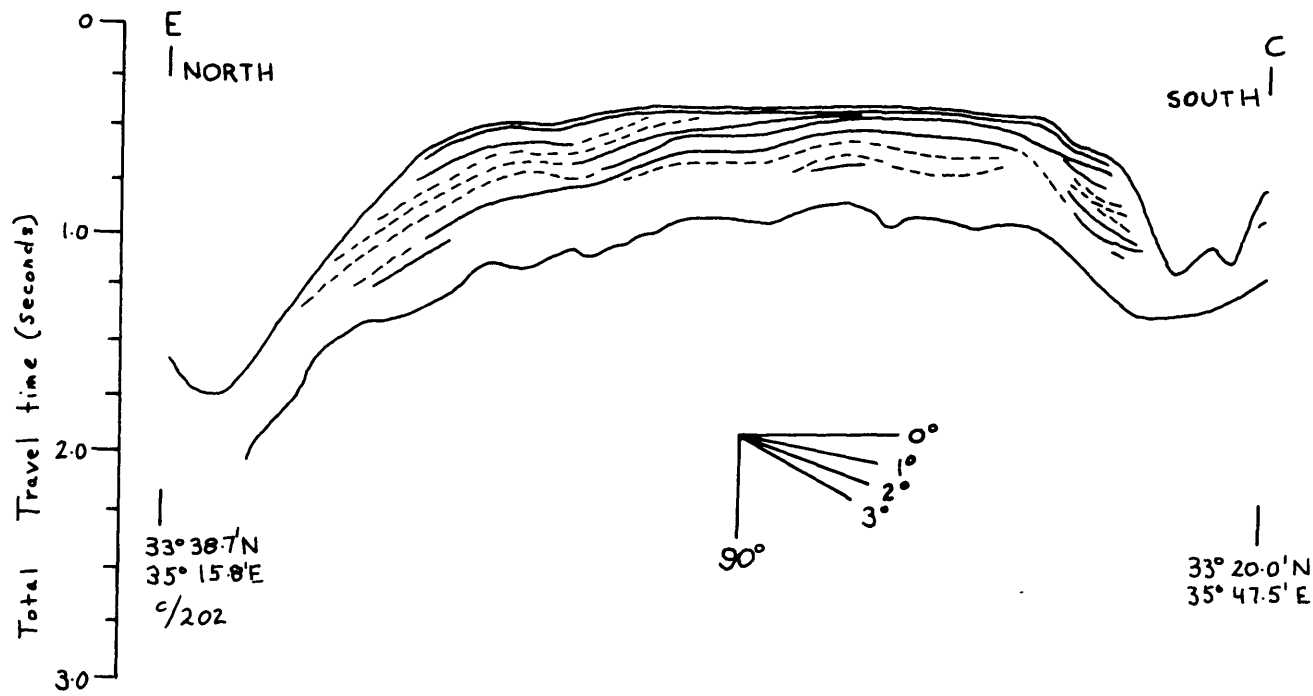


Figure 11: Profile EC

Figure 13: Profile GG₁

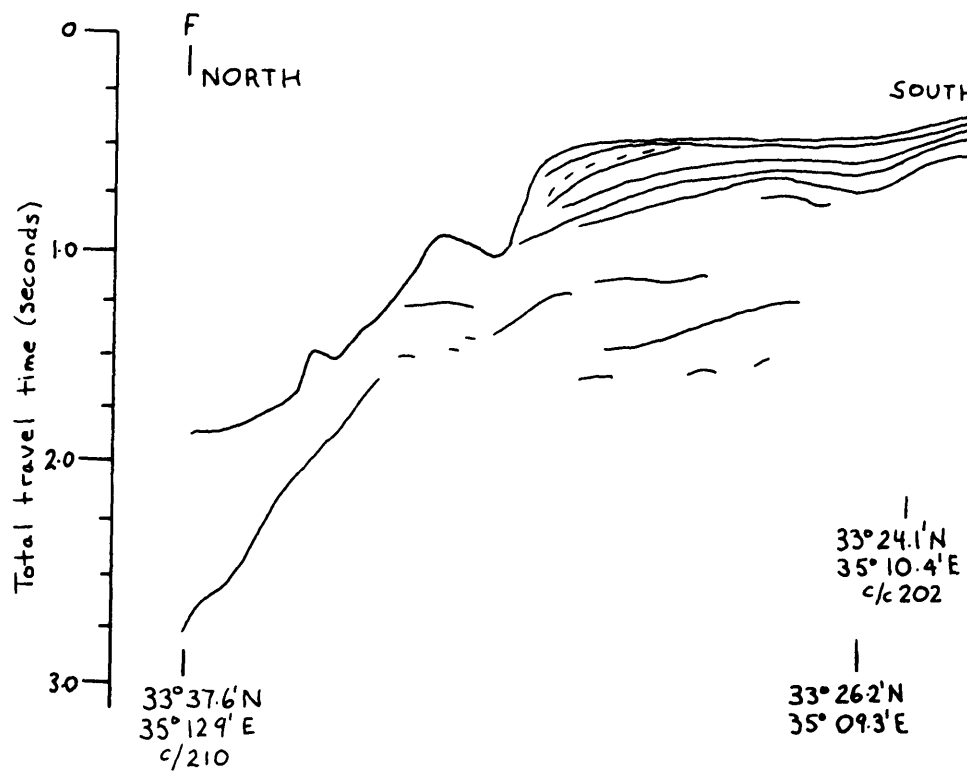


Figure 12: Profile FF

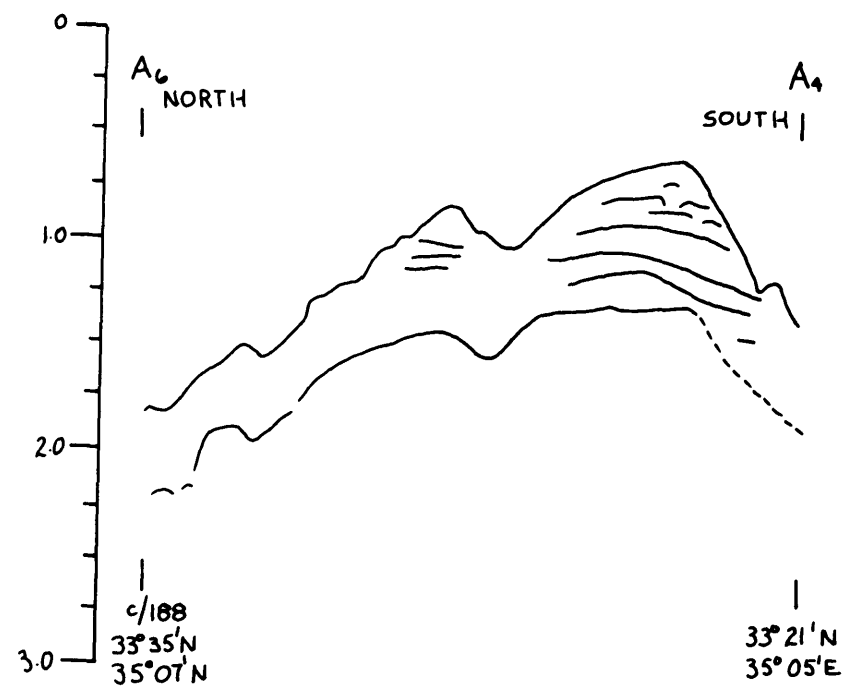


Figure 14: Profile A₆A₄

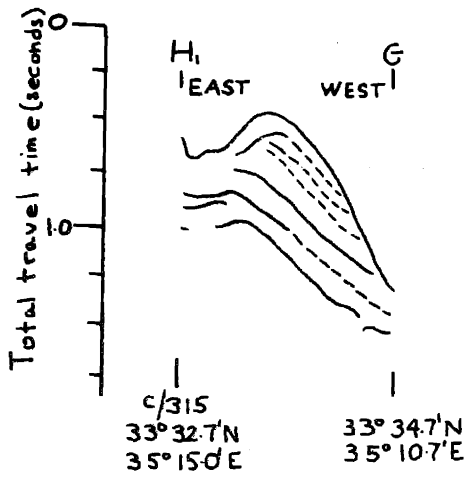


Figure 15: Profile H₁G

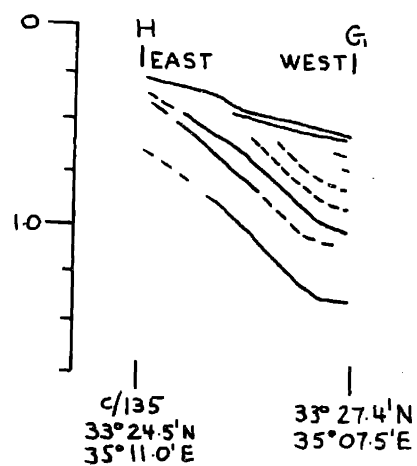


Figure 16: Profile HG

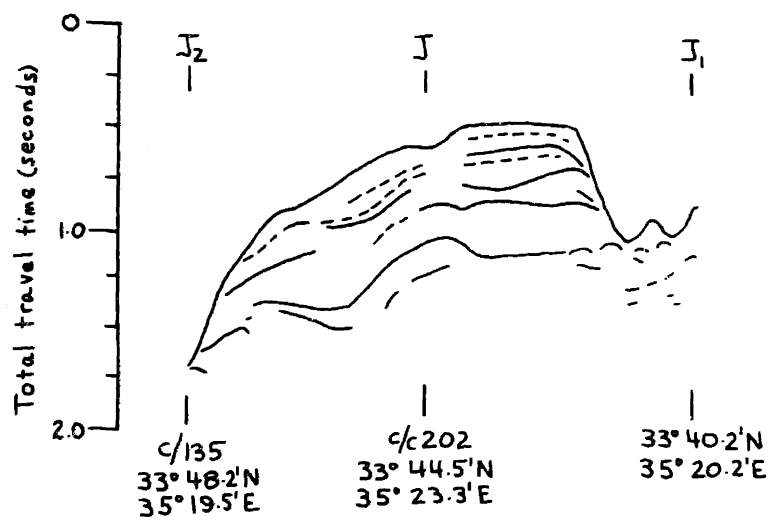


Figure 18: Profile J₂J₁

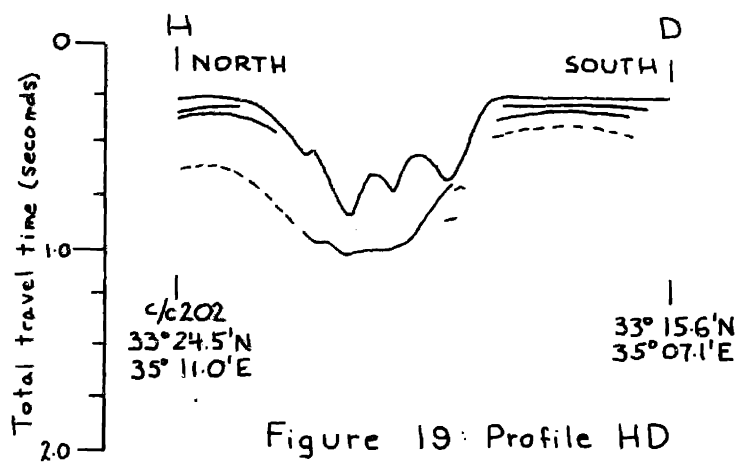
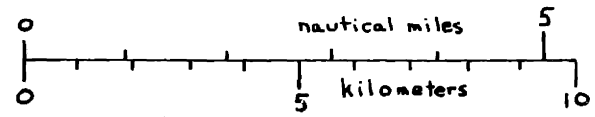
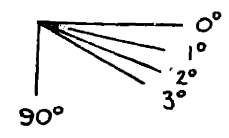
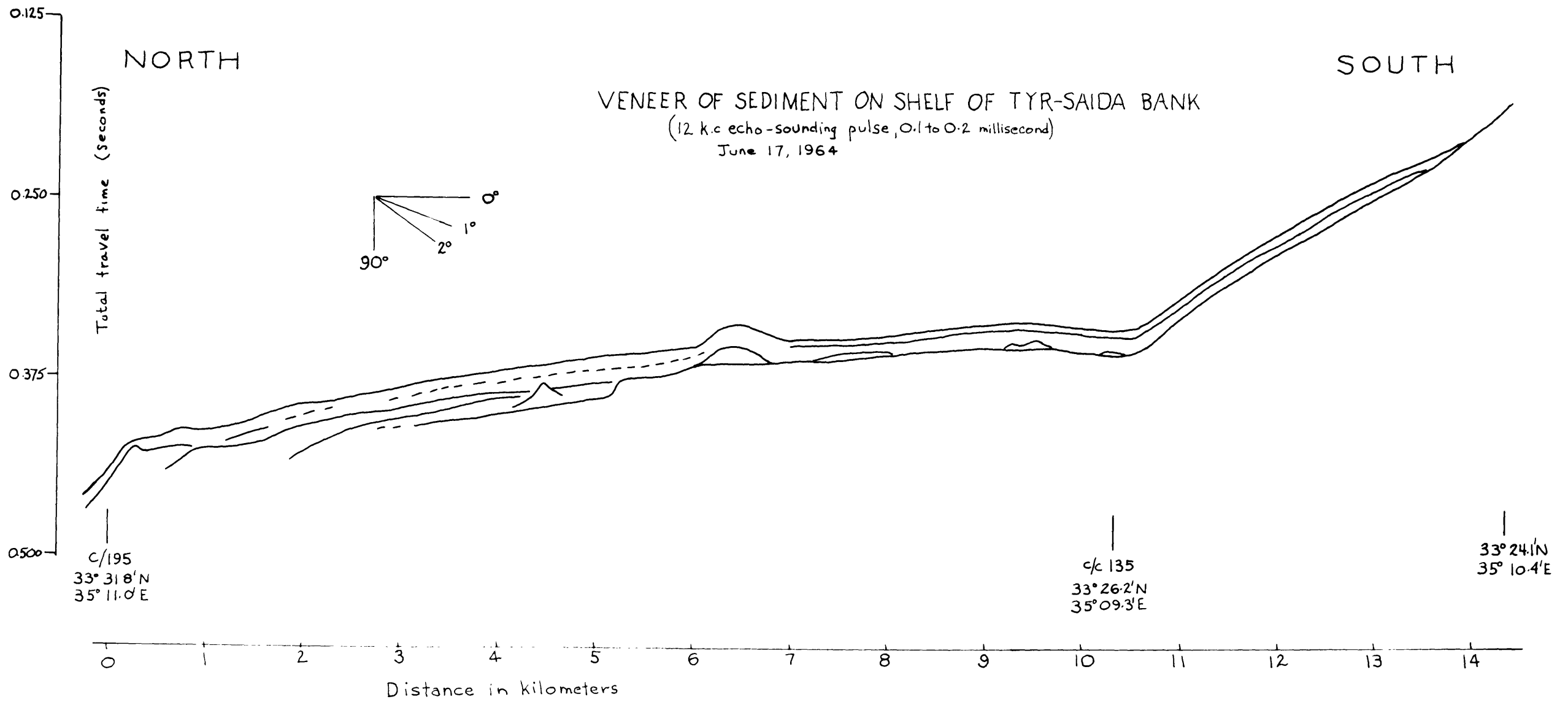


Figure 19: Profile HD





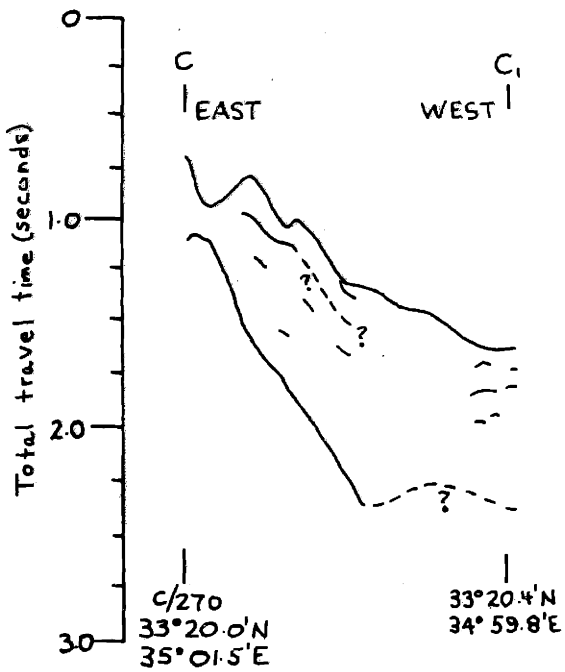


Figure 20: Profile CC₁

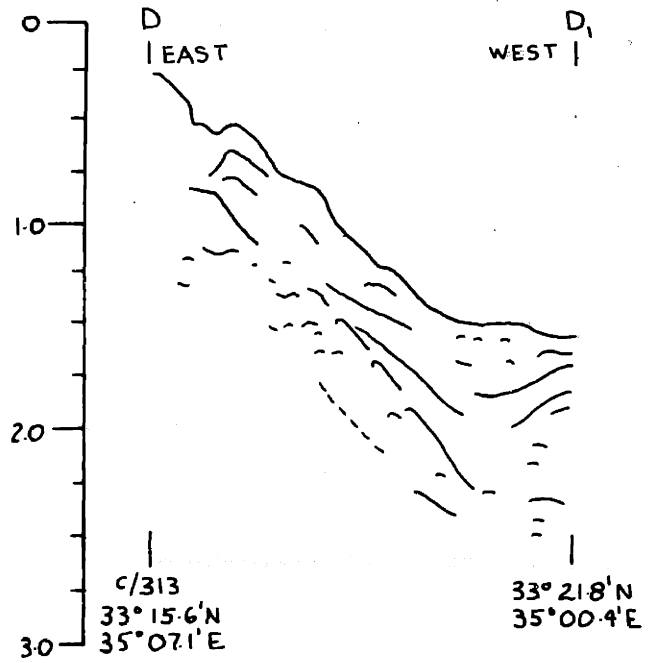


Figure 21: Profile DD₁

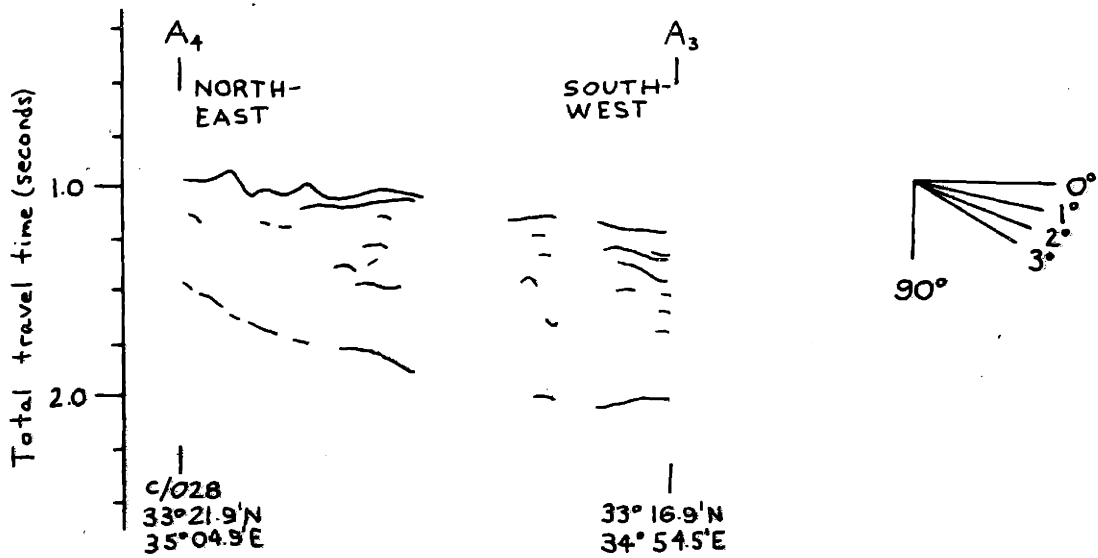
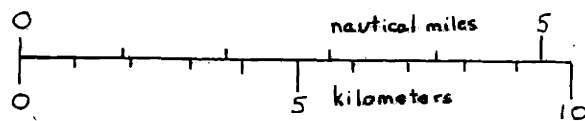


Figure 22: Profile A₄A₃



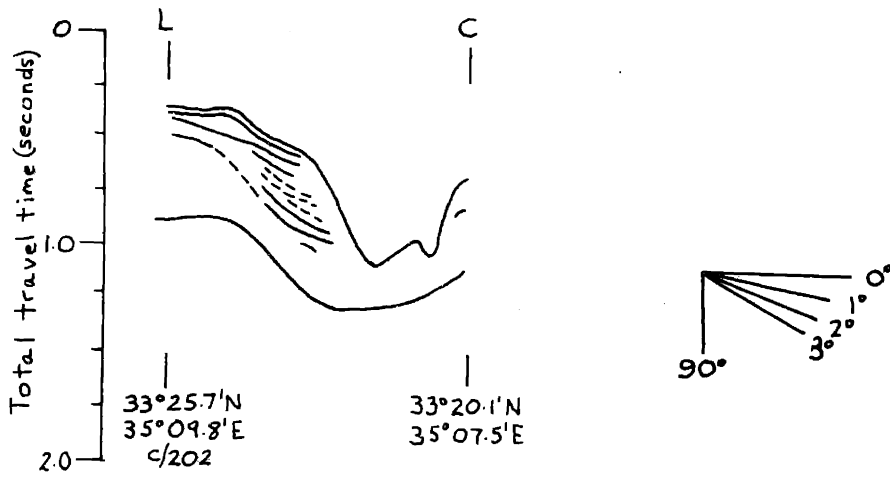


Figure 23: Profile LC

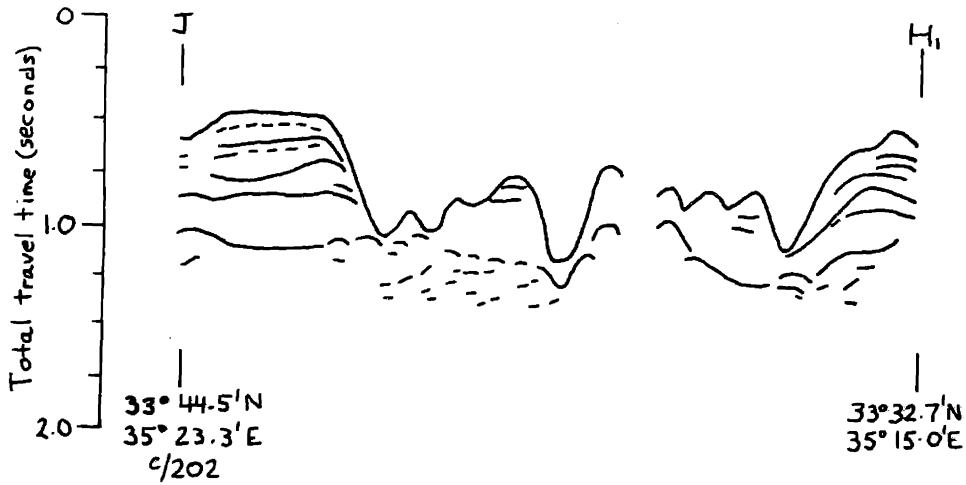
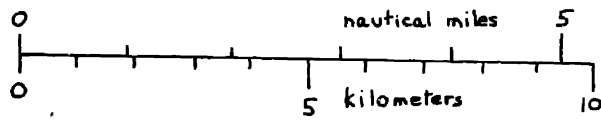


Figure 24: Profile JH₁

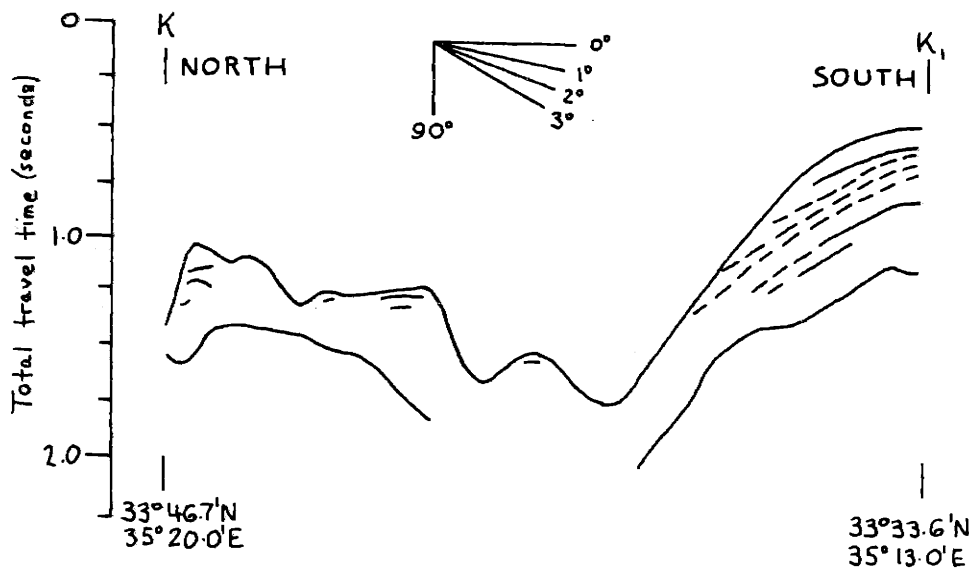


Figure 25: Profile KK_1

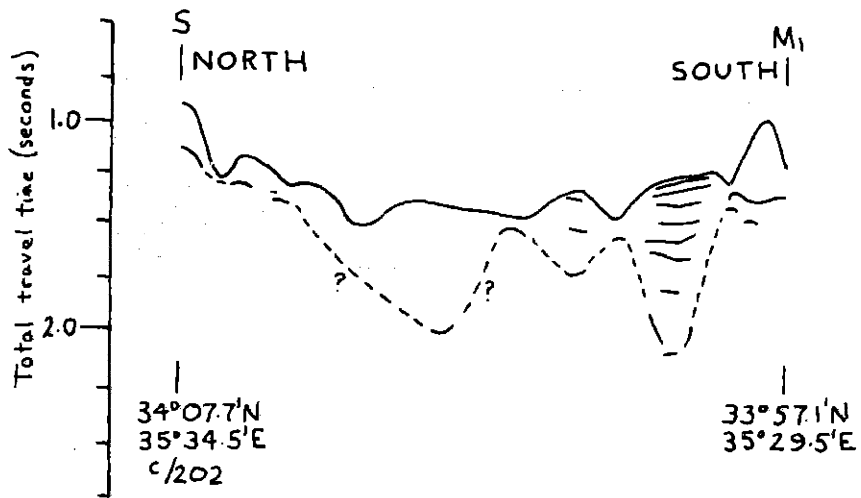
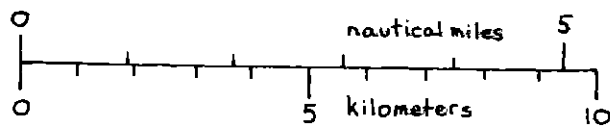


Figure 28: Profile SM_1



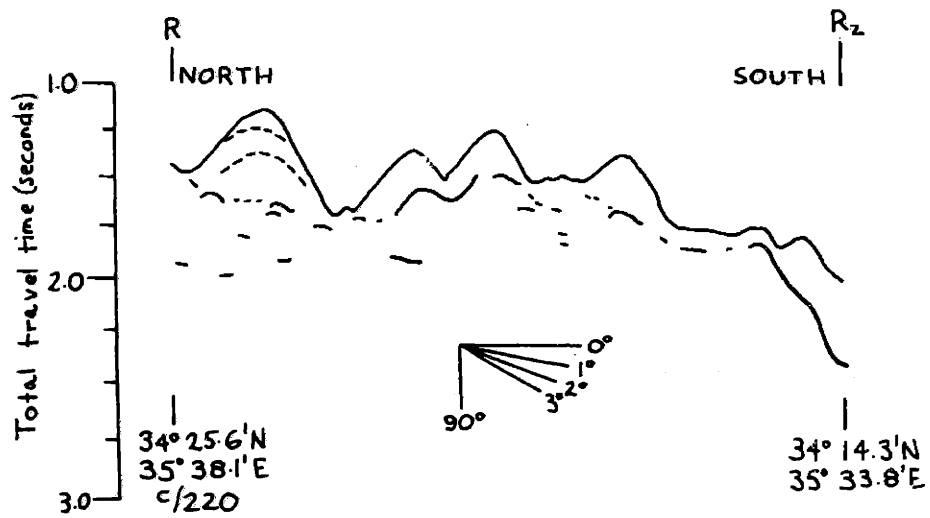


Figure 26: Profile RR_2

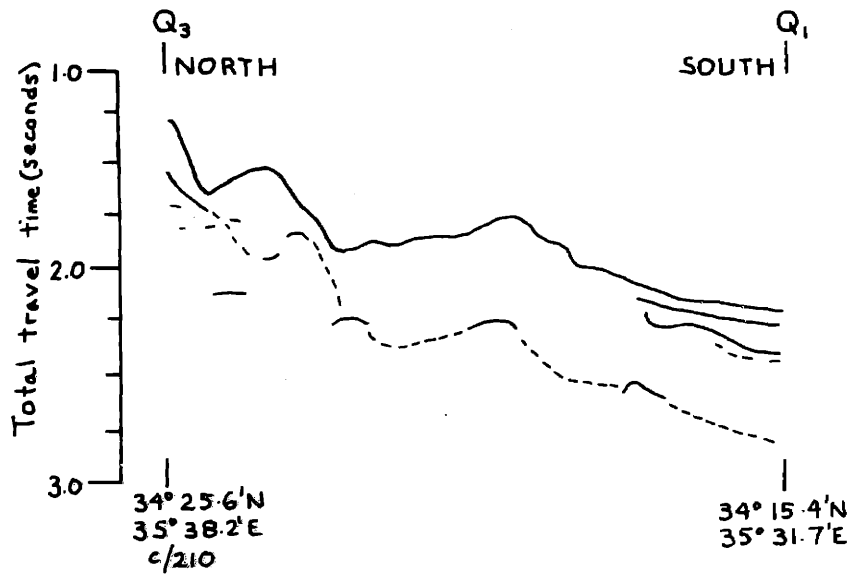
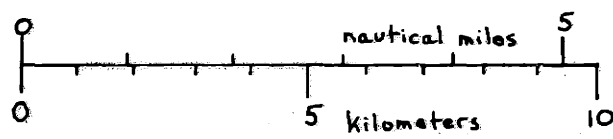


Figure 27: Profile Q_3Q_1



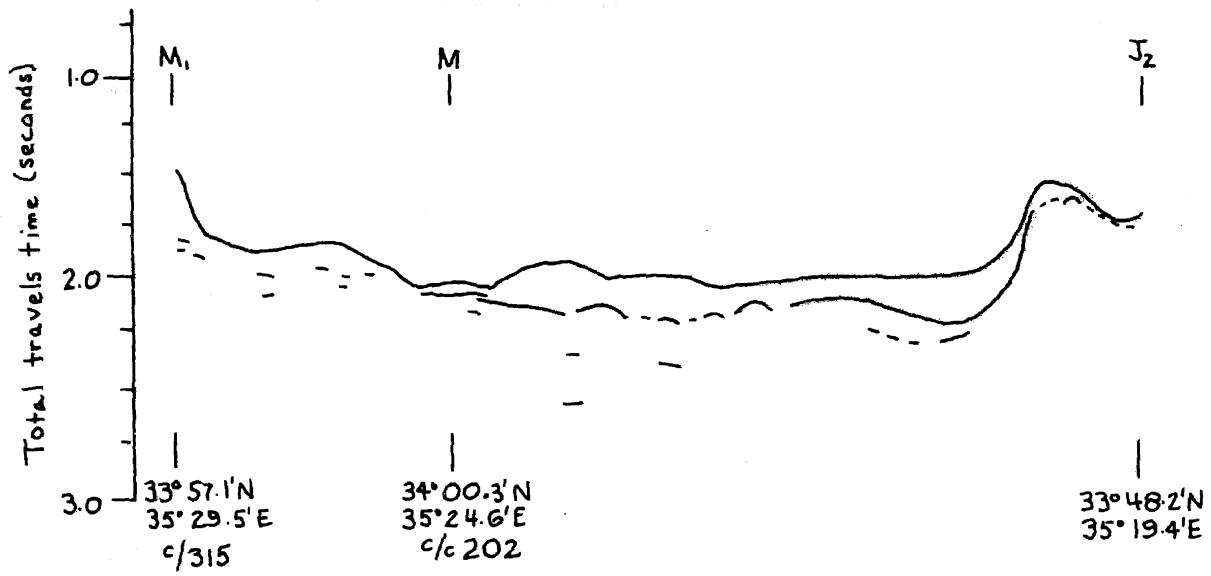


Figure 29: Profile M_1MJ_2

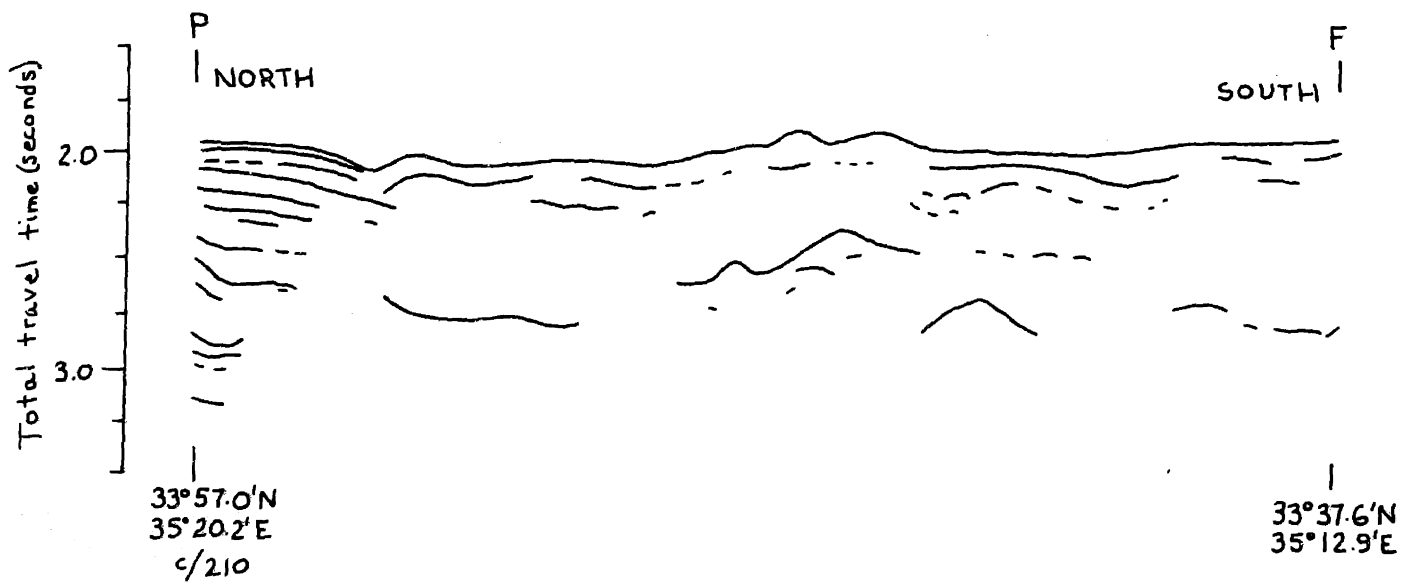
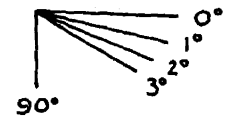
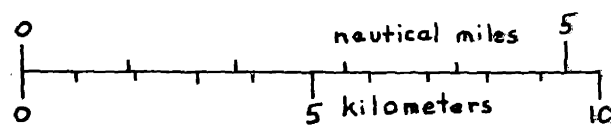


Figure 30: Profile PF



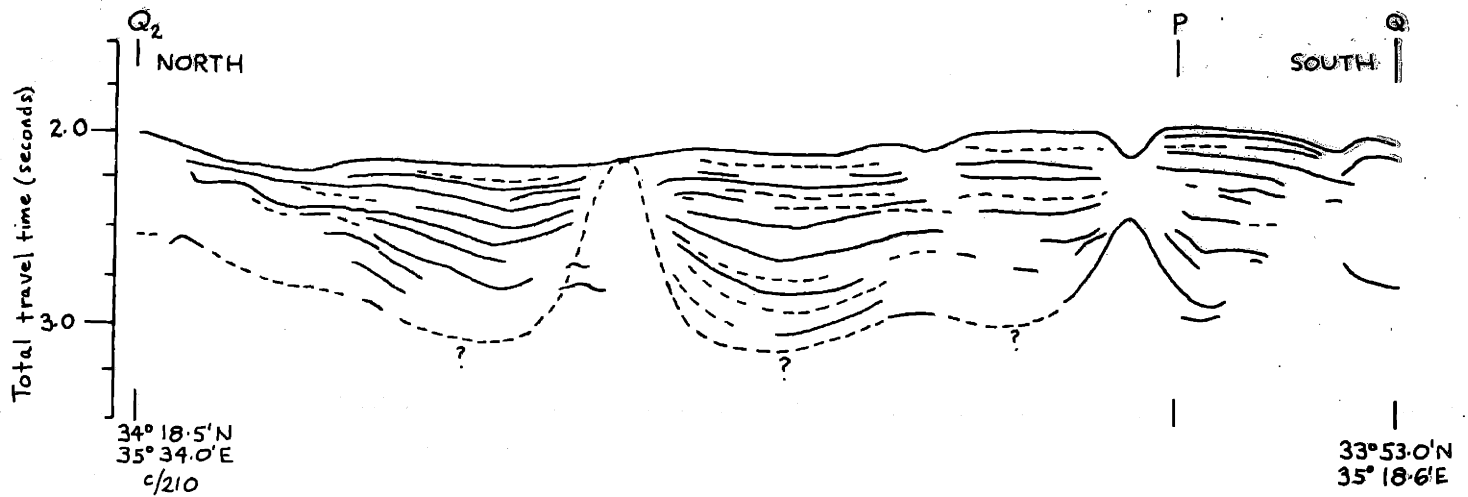


Figure 31: Profile Q_2Q_1

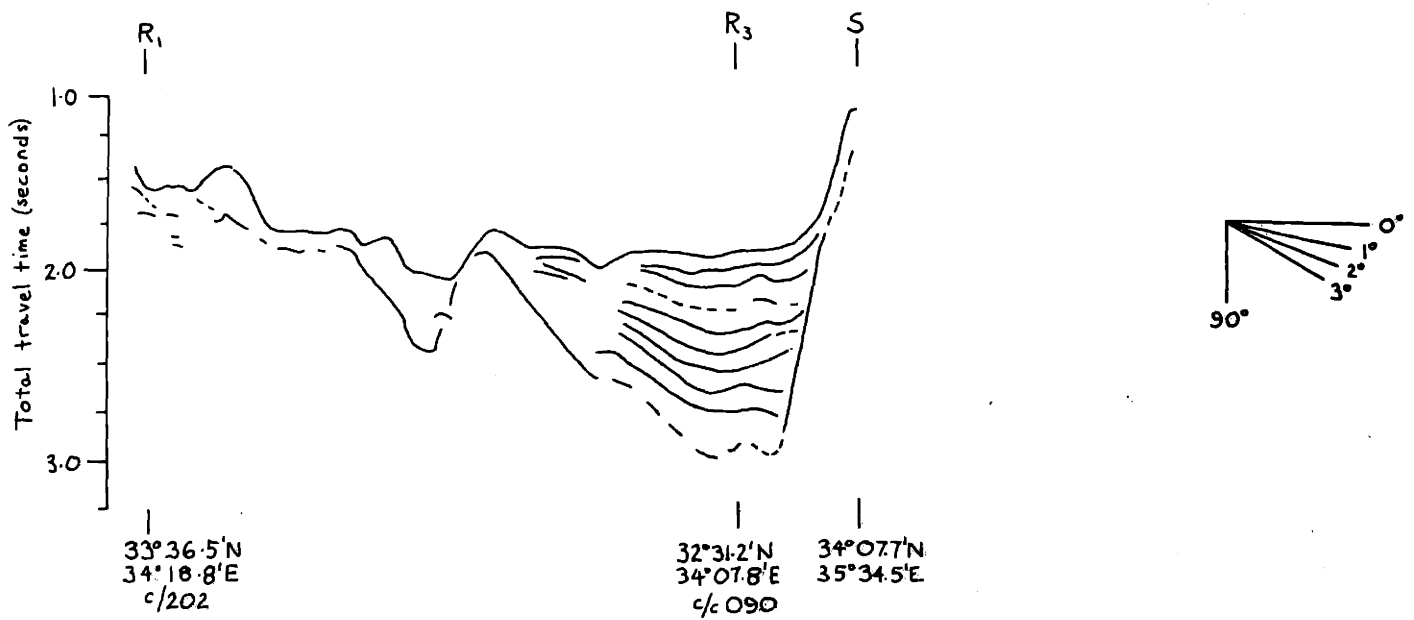
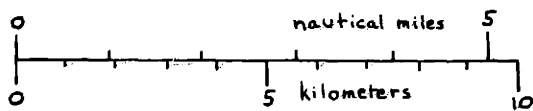


Figure 32: Profile R_1R_3S



The area which will be called the survey area is shown in Figure 7. This area includes the continental shelf, slope, and upper rise of Lebanon. Other profile lines near the survey area are shown in Figure 8 .

Tracings of some of the profiling results obtained south and west of the survey area (Figure 8) will be presented in order to indicate the relationship of the Lebanese continental margin to the adjacent areas of the Mediterranean.

A. RESULTS OBTAINED TO THE SOUTH AND WEST OF SURVEY AREA

1. Profile AA₅ extends from a point 20 kilometers north of Tel Aviv to Tyr along the coast of Israel. A tracing of the seismic reflection records from its northern portion, Profile A₁A₅, is shown in Figure 9. The three principal reflecting units which are seen along profile AA₅ all appear in profile A₁A₅.

a) The deepest reflector, an apparently continuous acoustic interface, is found as far south as point α_1 (Figure 8) where it appears at 1.25 seconds in 650 fathoms of water. It runs horizontally until point α_2 , rises gradually 0.25 seconds and continues horizontally to point α_3 , where it disappears (Figures 8 and 9).

b) Above this reflector, a second reflector, identified by its characteristic strong reflection, is seen not only throughout the area east of Port Said but also throughout the Lebanese coast survey. South of Lebanon, the reflections seem to come from a continuous, single interface.

In shallow water (75 meters) under an embankment 20 kilometers north of Tel Aviv (at point A), the layer lies at 0.75 second below the sea floor and shows marked undulations: a "hill" 750 meters high is crossed in a horizontal distance of 20 kilometers. To the north, in deeper water (550 to 700 fathoms), the layer lies between 0.5 and 0.75 sec. below the bottom, showing slight undulations; the amplitude of the largest is 0.125 second. Under the slope of the Tyr-Saida Bank, the layer rises to 0.66 second under the continental slope in 300 fathoms of water (point A₄). At the same time, the acoustic character of this layer changes from that of a uniform continuous reflecting surface to that of a rough surface, characteristic of the entire Lebanese coast south of Beirut. The nature of this reflector inside the survey area, where it will be called the deep reflector, will be discussed in the next section.

c) The upper stratigraphic unit along profile AA₅ is a section of gently rolling, laterally discontinuous layers. These layers form a complicated pattern: each layer fills in the depressions and laps up against the elevations of the layer beneath it. The lateral extent of individual layers range from 0.8 to 12.0 kilometers. The lowest layers in this series appear to follow the topographic variations of the reflector underlying the unit. Because of the filling-in of depressions, the topographic variations of the layers diminish upwards. These layers are characterized by a "patchy" appearance on the records as the amplitude

of the reflections from an apparently continuous surface varies greatly laterally. Under an embankment 15 miles north of Tel Aviv (at point A) the thickness of the section is 1.25 seconds in 40 fathoms of water; northward, in 700 fathoms of water the thickness decreases, varying between 0.50 and 0.75 second; finally, the section ends abruptly at point α_4 in disturbed sediment at the base of the Tyr-Saida Bank. The thickness of individual layers increases with depth, ranging from 0.08 second to 0.2 second.

2. Profile BB₂ (Figure 10), oriented westward starting at a point 22.5 kilometers west of Beirut, generally shows the same reflecting units as profile AA₅. The echoes from the upper unit, a layered sequence 0.5 seconds thick, are much weaker than those from the corresponding unit south of Tyr. The returns from the reflectors can scarcely be seen in the frequency range 15 to 50 cycles per second. In the 100 to 200 cycle per second range, the acoustic "patchiness" seen in profile AA₅ is observed. The amplitude of the undulations of the layers is less in profile BB₂, oriented east-west, than in profile AA₅, oriented north-south. This unit overlies a continuous reflector which has the strong reflectivity of the reflector underlying the layered unit on profile AA₅. This reflector rises from 0.85 sec. below the sea floor in 900 fathoms of water at point B to 0.5 seconds below the sea floor at point β , westward of which it follows the bottom topography closely. East of point β , discrete reflectors

underlie the upper continuous surface of this reflector. Eastward of point β_1 , a third deeper continuous reflector appears, 0.1 second below the second deepest reflector. The relationship between this third reflector and the individual reflectors below the second reflector east of β_1 , is not clear; they may be the same reflector.

Profiles AA₅ and BB₂ illustrate the nature of the reflecting units outside the Lebanese coastal survey area. The top layered unit stops at the base of the continental slope of Lebanon; a deeper reflector continues into the coastal area; the third, a deepest layer may continue into the coastal region but hints of it are seen only occasionally.

The upper two units of the reflectors seen along profiles AA₅ and BB₂, that is, the layered unit and the reflector underlying it, are also observed along profiles extending from Port Said to Tel Aviv and along a westward extension of profile BB₂ to a point 120 miles due west of Beirut and 60 miles south of Larnaca, Cyprus. A suite of flat-lying reflectors is also seen on the Nile Delta just north of Baltim, 80 miles west of Port Said. Generally, however, west of a line joining Larnaca and Port Said, the layers are disturbed by folding and faulting.

B. RESULTS OBTAINED INSIDE SURVEY AREA

The deepest reflecting surface inside the survey area appears everywhere along the coast of Lebanon. This interface will be called

the "deep reflector". South of Beirut, it has a characteristically strong echo, returned from an acoustically rough surface. The echo in some places appears to come from discrete reflectors on the surface of the deep reflector. Generally, individual reflectors are hard to identify, and the reflecting surface, although rough, appears to be continuous. The return is further confused by secondary reflections apparently coming from below the top surface of the layer: the entire wave train is often 0.25 seconds long. These secondary echoes often appear to represent discrete reflectors, and have been shown as such on the tracings by small crescentic arcs; they cannot be correlated into a continuous sub-surface. Part of the wave train may also be due to reverberation between the surface of the deep reflector and reflectors beneath it.

To the north of Beirut, the acoustic character of the deep reflector changes markedly. Here, the reflector is recognized by characteristic, individual crescentic echoes which represent discrete reflectors, and the strength of the returned pulse is considerably weaker. In some places, returns from the deep reflector are not seen between these echoes. In such cases, the dotted lines which represent the deep reflector on the tracings are intended only to infer that the crescentic echoes which they join belong to the same reflector. On the most seaward profiles north of Beirut, the deep reflector is often not seen at all, presumably because the thick sediments which overlie it absorb most of the energy from the acoustic pulse.

Despite the apparent change in the reflectivity from the deep reflector north and south of Beirut, the reflector can be followed from one area to the other.

As explained before, the discussion of the seismic profiling results inside the survey area will be organized into the divisions of continental shelf, slope, and rise.

1. Continental Shelf

Profiles cross portions of the Continental Shelf at three places, all located south of Beirut:

- (1) At the Tyr-Saida Bank,
- (2) At an area south of the bank, near point D (Figure 7),
- (3) At the wide portion of the shelf south of Beirut.

It appears that similar stratigraphic units may be common to all three areas.

a.) Tyr-Saida Bank

The Tyr-Saida bank is the best-mapped area in the coastal survey. Profiles EC, FF₁, and GG₁, (Figures 11 , 12 , and 13) cross the shelf of the Tyr-Saida bank, approximately parallel to its strike; profile A₆A₄ (Figure 14) crosses the seaward slope of the bank; and profiles H₁G and HG₁ (Figures 15 and 16) run east-west (down dip) across the shelf and upper slope. Plates 4 , 5 , and 6 show the three-dimensional relationships of the profiles.

On the shelf of the bank, the following stratigraphic units are recognized:

(1) The deep reflector rises under the bank from the north, south, and west. Starting from a maximum depth of 0.725 second below the bottom in 750 fathoms of water to the north, (Profile GG₁, Figure 13), and 0.7 second below the bottom in 650 fathoms of water to the south (Profile A₆A₄, Figure 14), the deep reflector rises to a maximum elevation along a line projected seaward through point γ , (Figure 7).

(2) The deep reflector is overlain by a wedge of seaward-dipping, conformable layers, thickening seaward along profile G₁H from 0.3 second at point H to 0.83 second at point H. These layers, sloping seaward under the shelf with a dip of 4.7° (uncorrected), are truncated at a surface 12 meters below the present shelf surface and parallel to it. The separation between the four or five layers shown in the upper part of this sequence, typically 0.025 second, is less than the resolution of the seismic profiling system, (50 milliseconds). Because the first multiple bottom reflection masks returns from the lower part of this unit, it is not possible to determine whether the lower part of the unit is layered, or whether the unit is conformable with the deep reflector.

At the north end of the Tyr-Saida Bank, the upper layers of this unit crop out. These sediments appear to have prograded, or built out, northward off the shelf, as the following argument will indicate. A

calculation of the velocity of sound in these layers, assuming that they are horizontal and that their apparent downslope dip is due to the differences between the velocities of sound in seawater and in sediment (Roberson, 1964) yielded velocities between 6.5 and 7.0 kilometers per second. These velocities, much greater than those expected for sediments with this depth of overburden (Nafe and Drake, 1957) result from the assumption that the layers are horizontal. In fact, they do appear to possess a downslope dip which has resulted, presumably, from progradation off the edge of the shelf. (The organization of this thesis suggests that it is better to include arguments concerning the dip of layers in this section, rather than in Chapter.4)

At the south end of profile EE_1 , the upper layers of this sequence appear to have slumped toward the canyon at the south end of the bank.

On Profile A_6A_4 , across the seaward slope of the Tyr-Saida Bank, the upper layers in the sequence which overlies the deep reflector appear to have been disturbed or eroded. The lower layers, which directly overlie the deep reflector, are thicker than the layers seen on the shelf. They may represent the seaward continuation of layers on the shelf which are not seen because they have been obscured by multiple reflections. In the absence of a downslope profile from the shelf to the rise, it is hard to correlate the layering on Profile GG_1 , across the shelf, with the layering on Profile A_6A_4 , across the slope.

(3) A veneer of layers having a maximum thickness of .008 sec. is seen on profile FF₁ with the short-pulse, 12 k. c. echo-sounder (Figure 17). As many as four layers are seen, apparently prograding into the canyon to the north. These layers are seen extending to depths of 300 fathoms on the upper wall of the canyon, disappearing when the slope of the sea floor reaches 7°. On the shelf of the Tyr-Saida Bank, side echoes from the deepest layer indicate that it might be rock. Buried lenses of material lie on this lowest interface. Due to a high gain setting, these layers are not seen with the echo-sounder on the adjacent profiles across the shelf, but their existence is inferred from the rather long pulse returned from the bottom.

Farther out to sea, Profile A₆A₄ (Figure 14), across the slope of the Tyr-Saida Bank, shows that the interval between the bottom and the deep reflector does not possess the finely-layered character of the corresponding interval on the shelf. At the south end of the profile, the upper 0.3 second of this unit consists of discontinuous, possibly disturbed, layers. Below these layers and above the deep reflector, three continuous layers are recognized, spaced between 0.08 and 0.18 second apart. The total thickness of the unit above the deep reflector reaches a maximum of 0.66 second. If layering exists in the northern part of this profile, it is obscured by side echoes.

b.) Wide Part of Shelf Opposite Damour

Profile J₂JJ₁ (Figure 18 and Plate 7) shows a portion of the shelf and upper slope at a wide portion of the shelf south of Beirut. Profile JJ₁ runs north-south along the strike of the shelf; profile J₂J runs down-slope at the north end of profile J₂J.

On the shelf, a stratigraphic unit 0.35 second thick overlying the deep reflector is similar in its finely-layered character to the corresponding sedimentary unit on the Tyr-Saida Bank. This unit may actually represent two or more sequences, as the layers in the upper 0.13 second of the unit are not conformable with the layers below them. Because the echosounder was inoperative in this area, it is not known whether the veneer of layers found on the shelf of the Tyr-Saida Bank also exists here.

An attempt to calculate velocities of sound in the layers which appeared to crop out at the south end of profile JJ₁, assuming that these layers are horizontal, indicated that the average velocity of sound in the unit lies between 2.5 and 3.0 kilometers per second. This figure seems slightly high, but not unreasonable for sediments with this depth of overburden (Nafe and Drake, 1957), indicating that these layers may be nearly horizontal.

Under the slope, the deep reflector descends in two steps. The over-lying unit pinches out downslope. Several layers in the upper part of the unit appear to crop out in the upper part of the slope, between 230

and 300 fathoms below the apparent shelf-slope break. At the bottom of the slope, the deep reflector crops out.

c.) Continental Shelf Opposite Tyr

On a portion of the continental shelf, at the south end of profile HD (Figure 19), a stratigraphic unit having fine layering similar to that on the Tyr-Saida Bank overlies the deep reflector. This unit differs from similar units seen on other parts of the shelf because it is thinner, (0.075 second) and is apparently conformable with the deep reflector.

Echo sounding records reveal that a layer .0025 second thick overlies the stratified unit.

2. Continental Slope

Those portions of the continental slope which have not already been described previously in connection with the shelf sediments will be discussed here. The sediments overlying the deep reflector on the slope appear to fall into recognizable groups.

a.) Slope Opposite Tyr

At the south end of the survey profiles CC_1 and DD_1 (Figures 20 and 21 ; Plate 8) run downslope from near the shelf-slope break to the continental rise. Profile A_4A_3 crosses the sediments at the base of the slope, and intersects profiles CC_1 and DD_1 .

Under the slope, the deep reflector descends seaward with an uncorrected slope of 6° from the shelf-slope break to the base of the slope, beyond which it is almost horizontal. On profile DD₁, one of the few indications of a reflecting interface below the "deep reflector" is observed. This strong reflector is defined by a series of crescentic echoes. It appears at 0.15 second below the deep reflector in 575 fathoms of water at the base of the slope, rises parallel to the deep reflector for 1.0 second, and is lost in multiple bottom reflections.

A wedge of material thickening from 0.3 sec. near the top of the slope to 0.75 second at the base overlies the deep reflector. On profile CC₁, this interval shows little, if any, layering; on profile DD₁, patches of material reflect sound. Except possibly for the lowest layer, no obvious stratification appears in this wedge. It is possible, however, that the reflecting patches represent some sort of discontinuous layering.

Seaward of the base of the continental slope, the sediments on the slope are replaced by material peculiar to the continental rise. This material will be described in the next section.

b.) Slopes in Rugged Canyon-Eroded Areas

Profiles which cross rugged, canyon-eroded parts of the continental shelf and slope, were made in three areas:

- (1) Just south of the Tyr-Saida Bank,

(2) North of this bank to Damour,

(3) At the north end of the survey, between Batroun and Tripoli.

Area 1 is represented by profiles HD and LC (Figures 19 and 23 ; Plate 5); area 2 is represented by profiles JH₁ and KK₁, (Figures 24 and 25 ; Plate 9); and area 3 by profiles RR₂ and Q₃Q₁ (Figures 26 and 27 ; Plate 10). The profiles in the first two areas are approximately parallel to the strike of the slope. The north ends of the profiles in the third area are closer to the shore than the south ends, so that the sea floor rises toward the north.

In all these profiles, the interval between the bottom and the deep reflector is largely without reflections; that is, it is nearly transparent. In the two more southern areas and on the shoreward side of the northern areas, the apparent lack of layering in this interval may not be real, since the record is crowded with side-echoes from hilly topography in the region. On the more seaward profile in the northern area, however, the interval overlying the deep reflector is clearly transparent.

c.) Continental Slope Between Beirut and Batroun

Profile SM₁ extends across the strike of the continental slope between Beirut and Batroun. On the slope, the deep reflector forms depressions whose depths range between 0.4 and 0.88 second. As the returns from the deep reflector are partially masked by side echoes, this

reflector can be recognized only by its characteristic individual echoes, which are joined by dotted lines on the tracing.

The depressions are apparently filled with sediments. The southernmost and deepest depression contains a series of nearly-horizontal, conformable layers, spaced typically 0.06 second apart. There are too many side echoes obscuring the returns from the other depressions to determine if there are similarly layered sediments in them.

3. Continental Rise

In the survey area, nearshore profiles cross the continental rise in the area at the south end of the survey and along a line extending southward to Damour from a point 10 kilometers north of Beirut. A long profile, farther offshore, extends from Tripoli to the Tyr-Saida Bank. The areas of the rise south of the Tyr-Saida Bank and between Beirut and the Tyr-Saida Bank will be described here.

a.) Continental Rise Opposite Tyr

At the base of the slope, along profiles DD₁ and CC₁ (Figures 21 and 20), and along profile A₄A₃ (Figure 22), a wedge of material 0.75 second thick, overlies the deep reflector. This unit, in which random discrete reflectors are seen is interpreted as being composed of disturbed sediments. This wedge separates the disturbed slope material from the layered reflectors to the south and west of the survey area.

Plate 8 shows the relationship between profiles DD₁ and A₄A₃.

b.) Continental Rise Between Beirut and Tyr-Saida Bank

The continental rise in this area is represented by the nearshore profile M_1MJ_2 (Figure 29) the more offshore profile PF (Figure 30). Profile M_1M extends 9.5 kilometers seaward from the base of the continental slope and profile MJ_2 extends across the continental rise. Profile PF is oriented north-south, 6 kilometers seaward from profile MJ_2 . On the rise, two sequences of reflecting interfaces are recognized: the deep reflector, and overlying sediments.

(1) The deep reflector slopes gently seaward along profile M_1M , then steepens seaward from profile MJ_2 to profile PF. Moreover, although the deep reflector is continuous on the inshore profile, it appears on the more seaward profile as discontinuous sections of strongly-reflecting material similar to that seen earlier on the continental slope south of Beirut.

(2) The unit overlying the deep reflector appears to have the same acoustic characteristics along both profiles MJ_2 and PF. It is thought to be composed of apparently disturbed sediments, in which only sparse and broken layering is seen in the top 0.25 sec. This unit thickens seaward. At M_1 , the deep reflector crops out; on the base of the slope along profile M_1M only a few meters of sediment overlie the deep reflector; and along profile MJ_2 the maximum thickness of the sedimentary unit is

0.18 second. However, 6 kilometers seaward, along profile PF , the thickness of the material overlying the deep reflector ranges between 0.37 second and 0.90 second.

c.) Continental Rise Between Beirut and Batroun

Profiles Q₂Q and R₁R₃S (Figures 31 and 32 ; Plate 10) represents the continental rise between Beirut and Batroun. Under the rise, the deep reflector forms large depressions. These depressions are bounded to the north and east by the descent of the deep reflector under the continental slope. Near Batroun, the boundary is quite steep (20°, uncorrected). Farther seaward, the depressions are separated by deformations of the deep reflector which are dome-like in cross-section. At least two domes are seen along profile Q₂Q. The deep reflector can only be seen on the records in the domed areas; under the deepest parts of the basins, its position is inferred from the shape of the overlying sediments. Since this area has not been surveyed in detail, it is not possible to correlate these domes with structures closer to shore, either on the rise or on the slope. These deformations, then, may be quite localized.

The depressions are filled with conformable, nearly-horizontal layered material extending from the sea floor down to the deep reflector. These layers are interpreted as stratified sediments. They are very similar in their layered nature to sediments which fill a more shoreward

depression on the continental slope (profile SM₁). In places, the thickness of these sediments is as great as 1.0 second, and may be greater. The thickness of individual layers ranges from 0.0125 second to 0.2 second, being typically 0.05 second. The layers, which in cross-section are dish-shaped in the depressions, lap up against the sides of the domes.

III. STATION RESULTS

1. Station 77 (Camera Station)

Approximate location: 33°55'N, 35°22'E, just westward of the base of the continental slope off Beirut, located between two submarine canyons.

Depth: 700 fathoms.

Reported as: A few acres of monotonous mud flats, with animal holes. One beer bottle of undetermined age.

2. Station 78 (Rock Dredge with Bag)

Approximate location: 33°22.5'N, 35°10'E, southern part of Tyr-Saida Bank, on shallow, flat part of shelf.

Depth: 30 fathoms.

Reported as: fine, dark-grained mud, many shells of great variety (including murices), and three or four coral bank fragments.

Writer's examination of sample confirms this, except that no mud samples could be found from this station at WHOI.

3. Station 79 (Rock Dredge with Bag)

Approximate location: 33°23.5'N, 35°7.5'E. Southern part of Tyr-Saida Bank, just seaward of shelf break.

Depth: 300 fathoms.

Reported as: Chunks of dark-grey clay.

Dr. W. A. Berggren of the Oasis Oil Company in Libya has examined the benthonic and planktonic foraminifera of this sample. He calls it an homogeneous silty clay-stone, of probable Quaternary age.

CHAPTER IV

DISCUSSION

In this section, the results from the previous discussion will be summarized and interpreted. As a background to this discussion, a detailed description of the geology of Lebanon is presented in the Appendix to this thesis. The reader's attention is particularly directed to the geological map of Lebanon, (Plate 1), a structural map, (Figure 36), stratigraphic columns for various areas of Lebanon near the coast, (Figure 37), and descriptions of erosional and sedimentary processes on land which effect the offshore survey area.

I. Topographic data presented in the previous section, show that the continental shelf off Lebanon is generally narrow, between 3 and 7 kilometers, with the shelf-slope break occurring at a depth of about 50 fathoms . Broadenings of the shelf occur between Tyr and Saida and off Damour. The slope, which steepens from 5° near Tyr to nearly 30° near Beirut, is incised with canyons, most of which are deeply cut to the base of the continental slope. The slope off the north coast of Israel is as steep or steeper than it is at Tyr, reaching a maximum of 8° . Along the south coast of Israel, it decreases to 2.7° , where sediments from the Nile have built out the continental slope (Emery et al. , in press). An echo-sounding survey along the shelf of Israel indicates that the system of canyons found along the Lebanese coast does not appear to the south (Emery and Neev, 1960). Emery et al. have found only two large canyons

off Israel: one at the Lebanon-Israel border, the other off Gaza. The continental slope in this area, however, has not been thoroughly surveyed.

II. From the seismic profiler survey, the following stratigraphic units were recognized:

A. A deep strongly-reflecting surface is found both south and west of the survey area, where it is underlain by a still deeper reflecting surface, and inside the survey area, where it is commonly the deepest reflecting layer seen. Outside the survey area, to the west of Beirut, this reflector slopes gently westward, and lies 0.5 second below the sea bottom; south of the survey area, off the coast of Israel, it shows gentle undulations beneath the continental rise, and marked deformations beneath the continental shelf near Tel Aviv. Inside the survey area, the deep reflector rises from a level of 0.725 seconds below the sea-floor in 900 fathoms of water beneath the continental rise to a minimum noted depth of 0.075 second below the sea-floor in 40 fathoms of water on the continental shelf. Along profiles parallel to the coast across the shelf and upper slope, south of Beirut, the surface of the deep reflector has minor irregularities, but is generally horizontal; farther downslope, along north-south profiles, these minor irregularities are superimposed on much larger-scale hills and depressions. Between Beirut and Batroun, on the upper slope, the deep reflector forms small

depressions. North of Batroun, on the slope, a pattern of minor irregularities appears again.

Beneath the continental rise, along a north-south profile just seaward of the base of the continental slope off Beirut, the deep reflector is continuous and horizontal. Four kilometers seaward of this point, along a north-south profile, the deep reflector is deformed. South of Beirut, it is discontinuous, suggesting that either (a) it has not been deposited in the places where it is not seen, (b) that it has been subjected to erosional or faulting processes or, (c) that acoustical properties may not distinguish it, although it may still be present. North of Beirut, it forms large depressions which, off Batroun, extend shoreward to where the deep reflector rises under the continental slope. These structures may extend even further to the upper slope, where small depressions appear.

This deep reflector may represent an old slope which in places has been eroded or deformed. A contour map of the deep reflector between Tyr and Saida has been calculated with an assumed velocity of sound in the overlying sediments of 1.7 kilometers per second. The map was prepared using this velocity at the suggestion of Dr. K. O. Emery, before later calculations for sediments on the shelf off Damour indicated that velocities of 2.0 to 2.5 kilometers per second might be

more appropriate. Subsequent calculations of the position of the deep reflector was made along one profile using several velocities up to 3.0 kilometers per second. These calculations indicate that the effect of the various velocities in the overlying sediment is to change the overall computed depth of the reflector but not its computed shape. Since the shape of the deep reflector is the quantity of interest here, it is felt that the present contour map is satisfactory for purposes of discussion.

The map shows that south of the Tyr-Saida Bank, the deep reflector falls seaward with an average slope between 6° and 12° . On the Tyr-Saida Bank, the seaward slope of the deep reflector between 400 and 600 fathoms is 4° . At greater depths the slope steepens slightly at the north and south ends of the bank, but becomes flatter in the center. A canyon is seen to the north of the bank, and north of this feature, the slope steepens to 15° . These slopes vary in the same way as present topographic slopes in the same regions, and suggest that the Tyr-Saida Bank existed as a topographic feature at a time when the deep reflecting surface formed the sea bottom. This suggestion is supported by the conclusion reached in the last section that the sediments overlying the deep reflector have prograded off the shelf. It appears that they were deposited on the old Tyr-Saida Bank.

On the basis of the following information, an age of Upper Cretaceous is suggested for the rocks whose upper surface forms the deep reflector.

(1) Cenomanian rocks crop out all along the coast. The extensiveness of the rocks along the coast would explain the similar continuity of the deep reflector.

(2) In particular, at Beirut, where the deep reflector lies close to the sea floor on the continental rise, the Cenomanian rocks which form the seaward side of the Beirut headland are faulted against younger Miocene rocks.

(3) A seaward projection of the formations shown on Section CC₁ in Plate 1 to the profile line nearest to shore places the top of the Senonian at 750 meters and the top of the Cenomanian at 1100 meters below sea level on Profile JH₁. The deep reflector, at the point of intersection on Profile JH₁, lies at 910 and 1100 meters, assuming that the velocity of sound in the overlying sediments is 1.7 and 2.5 kilometers per second respectively. Projections of this kind are speculative because no nearshore reflection profiles have been made. Moreover, the dips of the formations on land are assumed to continue seaward, and no allowance is made for possible faulting of the coastline. Nevertheless, these rough projections may be good enough to indicate that a

likely age for the deep reflector is Upper Cretaceous. It may correspond with the top surface of the thick Cenomanian limestone mass.

The geological map of Lebanon (Plate 1) shows that a great number of east-west faults which cut into Eocene and Cretaceous sediments extend to the coast. It is possible that the deep reflector on the upper slopes has been cut by a seaward extension of this fault system. In particular, the depressions on the slope between Beirut and Batroun may be fault-formed. This interpretation seems to be the most probable one for the origin of these features. It is unlikely that they are formed by folding, as the axes of the folds would extend east-west from the coast. No corresponding folding is noted on shore; the folds which do exist near the coast have north-south-oriented axes. If these depressions on the slope are formed by faulting, then they are probably not related to the dome-bounded larger depressions under the rise, although they appear to be filled with the same kind of layered sediments.

The writer has not been able to extrapolate faults seen on shore to these depressions. This observation, however, does not discount the possibility that the slope is faulted. Nearshore profiling may reveal extensions of continental faults which are not seen farther seaward.

The domed structures beneath the continental rise do not appear to be related to the volcanic intrusives which are seen to the north at

Tripoli (Dubertret, 1949), as they are not associated with a magnetic anomaly. It is possible that these structures are diapiric, related to some deep incompetent layer. The Triassic, which in Israel is composed of anhydrite (Ball and Ball, 1953) could provide a source of salt for such domes. A good check for such an hypothesis would be a low gravity reading over the domes. Unfortunately, the ship's gravity meter was inoperative at the time. Further speculation on the origin of these domes seems futile in the absence of information about the rock beneath the deep reflector.

B. The sediments which overlie this deep reflector appear to fall into the following groups.

1. Area South and West of Survey Zone

To the south and west of the survey zone, a series of layered, horizontally-discontinuous sediments overlies the deep reflector. The thickness of these sediments in most places is greater than 0.5 second. If the deep reflector is of Upper Cretaceous age, as has been suggested earlier, then these sediments are of Eocene to Recent age.

These sediments could have had several sources:

(1) The seas which covered the land areas could have provided biogenous material from the settling organic material and from bottom-growing organisms. This sort of deposition was predominant in Lebanon through the Jurassic and Cretaceous,

(2) Since the end of the late Cretaceous, when the first Alpine orogenies started, material could have been provided to the Mediterranean by the erosion of uplifted land areas (i. e. the mountains in Lebanon).

(3) The most probable source for much of the material contributed to the Eastern Mediterranean since the Miocene is the Nile River. Enough material has been dumped into the Eastern Mediterranean to form the Nile Cone, which extends from the Nile Delta northward past Lebanon to the Herodotus Abyssal Plain. (These features are defined by Emery et al. , in press.) Cutting of the Nile valley began in the Miocene, ceased in the Pontian (Mio-Pliocene), and resumed at the end of the Pliocene (Harrison, 1955). The Nile deposits are thus of two different ages. Emery et al. have estimated that perhaps 100 meters of material have been deposited in the Pleistocene.

It is suggested that much of the material forming the layered sediments is Nile-derived. In fact, the layered sediments can be traced to Port Said, near the mouth of the Nile. The same layered series may occur north of Baltim, opposite the central mouth of the Nile. The layers may have been laid down in successive fluxes of the Nile. The lateral variations in the reflectivity of an apparently continuous layer suggest that the composition of the layers changes laterally. These variations may result from the mixing of Nile-derived lutite, deposited by general diffusion, and Nile-derived sands and silts, deposited

by turbidity currents (Emery et al. , in press).

These sediments, seen near the Israeli coast south of Tyr and westward of a point that is 18 kilometers west of Beirut, surround the survey zone, but are not seen inside it. This information indicates that the Nile does not contribute much sediment to the shelf, slope, and upper rise of Lebanon in comparison with other sources. The same conclusion has also been reached by Emery and George (1963) for the beaches of Lebanon.

2. Inside the Survey Area

a) Continental Shelf and Slope

1. The youngest sediments which are seen on the continental shelf appear on the outer part of the Tyr-Saida Bank as a veneer of thinly-layered sediments up to 0.008 second thick, and on the wide part of the shelf off Damour as a single layer 0.003 second thick. If the surface of the shelf on which these sediments are deposited was cut in the Pleistocene at a time of lowered sea level (Dietz and Menard, 1951), then these sediments are probably of late Pleistocene to Recent age. On the Tyr-Saida Bank, the lenses of material overlying the lowest layer may represent buried sand dunes; sand deposits are exposed on the shallow portions of the inner shelf directly adjacent to the coast (Boulos, 1962). On the outer parts of the shelf, the topmost layer of

these sediments is mud (Boulos, 1962). This latter observation is confirmed by the dredging of mud from the top of the shelf (Station 78). An homogeneous silty clay-stone of Quaternary age (Station 79), dredged just seaward of the shelf break may have sampled these sediments where they have prograded off the edge of the shelf.

The fact that these sediments appear to prograde towards the edge of the shelf indicates that on the outer shelf of the Tyr-Saida Bank, sediments have been accumulated rather than eroded since the Pleistocene.

2. The next deepest stratigraphic sequence, a wedge of finely layered sediments overlying the deep reflector, appears in places on the continental shelf and upper slopes. The thickness of this unit varies: on the shelf off Tyr, the unit is 0.075 second thick; on a wider part of the shelf off Damour, the unit has a maximum thickness of 0.35 second and crops out downslope; on the Tyr-Saida Bank, the unit thickens seaward from 0.3 second to 0.8 second.

This unit is interpreted as being a stratified wedge of sediment or rock. If the cutting of the surface which truncates the sediments on the shelf of the Tyr-Saida Bank occurred in the Pleistocene, and if the age of the deep reflector is really Upper Cretaceous, then the age of these sediments ranges from Eocene to Pleistocene.

Although the layered, conformable, and uniform nature of the continental shelf deposits suggest that they may be related to the

similarly layered, conformable rocks on the adjacent coastal plateaus, no attempt is made to correlate the shelf deposits with the rocks seen on land. The many fluctuations of sea-level which have occurred since the end of the Cretaceous (see Appendix, pp. 111 to 112) imply that erosional and depositional processes were different on the shelf than on the land areas. For instance, while lagunar material was being deposited on the shore (i. e. during part of the Vindobonian), neritic deposits were probably being formed on the shelf. One notable feature of the shelf deposits is that, except for their upper truncated surface, they show no recognizable unconformities which might represent a surface of erosion, whereas the land areas do show these surfaces. Dubertret (1954) points out that a Miocene surface of erosion cuts across the stratigraphic surfaces on the coastal plateau adjacent to the Tyr-Saida Bank. No sign of this severe erosion is seen in the shelf deposits.

Possible sources of the material which forms the shelf deposits have been the following:

(1) Detrital material derived from erosion of the land areas (see Appendix, pp. 113 to 115). This erosion began in the Senonian, when the horsts in Lebanon were uplifted, and was greatly increased in the Miocene, when this uplifting was accentuated (Dubertret, 1954). Erosion has been effected mostly by rivers which have cut deeply into the mountain

blocs and coastal plateaus, bringing the eroded material to the coast. During the various transgressions of the sea, wave-cut material could also have been put into suspension and supplied to the shelf.

(2) Biogenic deposits from bottom-growing organisms and animals which were deposited by settling-out.

(3) Nile-derived material, which could have been brought northward along the coast by offshore currents. Emery and Neev (1960) suggest that this sort of transport occurs along the coast of Israel. Emery and George (1963) find that the present contribution of Nile-derived material to the beaches of Lebanon is small.

It is not known from the available seismic profiling information whether the layered sediments which are found along the broader portions of the shelf also exist where the shelf is narrower. A few speculations are offered here. The seismic profiling data from the portions of the shelf which have been examined suggest that the present shelf resulted from deposition of sediments which were laid down where the deep reflector was horizontal or gently dipping. Conceivably, the shelf may have formed in this way all along the coast. Although layering cannot be seen in the sediments which overlie the deep reflector in the canyon-eroded portions of the upper slope, these sediments could be eroded, outcropping shelf sediments. Such outcropping occurs on the continental

slopes fronting the shelf off Damour, and possibly on the Tyr-Saida Bank. The layered unit, therefore, may constitute the shelf and upper slope along much of the coast.

One place on the slope where shelf sediments do not appear to crop out, however, is the area at the south end of the survey. The "patchy" reflections from the slope material in this region suggest that slipping or slumping of once-layered slope sediments has occurred. The factor which determines the stability of slope sediments in this area may be the dip of the deep reflector on which they are deposited. The contour map of the deep reflector shows that the dip of the deep reflector in the area at the southern end of the survey, where slope sediments may have been disturbed, ranges between 6 and 12 degrees. On the seaward slope of the Tyr-Saida Bank, where the slope sediments are stable, it is about 4 degrees. Estimates of the maximum angle of stability of slope sediments vary. Athearn (1963) has found that carbonate sediments are stable on slopes up to 12°, and Moore (1961) has found that wherever deposition is slow and clay content is high, sediments will develop stability on slopes up to 14°. However, such stability would not occur during a time of lowered sea level, when the edge of the shelf was agitated by surf or even exposed. In any case, it is not inconceivable that sediments on a 6 to 12 degree slope will slump or slip.

b) Continental Rise

On the continental rise, three different areas of sedimentation were noted:

1. At the south end of the survey, a wedge of sediments 0.75 second thick, showing no recognizable layering, separates the slope sediments from layered sediments which are found in the Mediterranean to the south and west of the survey area.

2. West of Beirut, the sediments overlying the deep reflector thicken from a few meters near the slope-rise break to as much as 0.90 second, 4 kilometers seaward. These sediments, which are apparently disturbed since they show broken layering, can be traced on the most seaward north-south profiles from Beirut to the Tyr-Saida Bank.

3. Between Beirut and Batroun, conformable, finely-layered, nearly horizontal sediments, reaching thicknesses up to 1 second, fill deep depressions formed by the deep reflector. These sediments are similar to those found in shallower depressions on the continental slope.

None of these sediments show the lateral variations in reflectivity which were noted in the sediments outside the survey area. Instead, the

above observations indicate that material is being transported down the continental slope and is being deposited on the rise.

In the area at the south end of the survey, the thick pile of inhomogeneous sediments at the base of the slope appears to be material that has slid to the bottom of the slope. West of Beirut, material transported down the slope appears to have been carried beyond the base of the slope, where scarcely any sediment overlies the deep reflector. It has been deposited farther seaward, where the deep reflector reaches its maximum depth and becomes horizontal. North of Beirut, the material transported downslope has accumulated into layered deposits in depressions formed by the deep reflector. The similarity of these sediments on both the slope and the rise indicates that the material forming these sediments is land-derived.

The apparent sources of this material are the canyons which are known to incise the slope south of Beirut, and which may exist to the north. The fact that neither seismic profiling nor short-pulse echo-sounding has revealed any filling of these canyons may indicate that they are being regularly flushed. The topographic map (Figure 6) suggests that the canyons are related to the deeply cut rivers

which reach the coast, implying that not only material eroded from the shelf and slope, but also that land-derived material eroded from the mountains and coastal plateaus of Lebanon, is deposited at the base of the slope. The boundaries of the sediments on the rise are not well enough delineated to make a calculation comparing the minimum volume of sediments deposited on the rise with the maximum amount of material which could have been eroded from the shelf and slope, as Hoskins has done (Hoskins, 1965). However, the severe erosion of the mountains and coastal plateaus of Lebanon (Renouard, 1956; and Dubertret, 1949, 1954, Appendix, p. 113) has produced huge quantities of material which must have been deposited somewhere. On the east side of the Lebanese mountain chain, this material has been dumped on to the Bekaa plain; on the west side, the material which has not been deposited on the coastal plateaus appears to have been eventually transported to the continental rise.

There are several mechanisms which could transport this material. Some of these have been observed by Dill (1964), who made intensive underwater studies of erosion in Scripp's Canyon. This canyon, like the canyons off Lebanon, is steep-walled, cutting into a steep slope, and is located near to shore. Dill finds that the head of Scripp's Canyon is filled with a thick sedimentary deposit made up of interbedded layers of

sand, detritus, and a mat of interwoven plant material. This material is continually removed from the canyon head by three processes:

(1) Slow gravity creep, at the rate of about a foot per month, results from a decrease in the shear strength of the sediment due to the decay of the organic material in it and the generation of gas during this decay.

(2) When the external and internal stresses acting on the sediment exceed its shear strength, slumping and sliding occurs over short distances. Minor slumping affects the top three or four feet of sediment fill. Major slumping, in many cases triggered by minor slumping, can remove much of the fill in a canyon head. Dill reports an instance where 35 feet of fill was removed in two days.

(3) Material can also be transported seaward by downslope flow of sand. Heezen (1956, 1963) has claimed that turbidity current flow is the mechanism whereby land-derived material is deposited over large areas of the Atlantic Ocean. He has also suggested (Heezen, 1956) that turbidity currents were active in the submarine canyons adjacent to the Congo River and to the Magdalena River in Columbia. The layering in the sediments on the rise north of Beirut may represent sharp lithological changes similar to those found in Atlantic Ocean sediments which have an apparent turbidity current origin (Ericson et al. , 1952,

1961). Dill has found, however, that the occurrence of turbidity currents in Scripp's Canyon is unlikely. The cohesive nature of the sedimentary fill and its lack of a metastable structure prevent spontaneous liquefaction (as defined by Terzaghi, 1956), and hence the formation of turbidity currents, when lateral stresses are suddenly applied.

Trigger mechanisms which could initiate both turbidity currents and slumps could be earthquakes, high bedload discharge of rivers, hurricanes impinging on the shore, or failure resulting from the gradual over-steepening of a depositional slope (Heezen, 1963). Earthquakes are apparently common in Lebanon. An earthquake is known to have destroyed Baalbek, and Ball and Ball (1953) mention that earthquakes have been recorded in Israel for the last 2000 years. Gutenberg and Richter (1941) note that several severe, intermediate-depth earthquakes have occurred along the Levantine coast for the last 80 years. In Scripp's Canyon, however, Dill has noted that earthquakes cause little slumping in the canyon sediments. Slumping is initiated instead by the failure of the organic sediment fill when a load of shore-derived sand is suddenly deposited on it. This movement is especially noticeable after storms. Discharge from the rivers off Lebanon may thus provide an important source and triggering movement for the seaward transportation of sediments.

There is no obvious explanation for the difference in the character of the rise sediments to the north and south of Beirut. Although both

sets of sediments are thought to have originated from movement of material down the slope, the differences in the layering of these sediments may reflect differences in transport mechanisms. The broken appearance of the sediment overlying the deep reflector between Beirut and the Tyr-Saida Bank may also be the result of faulting in the layers below the deep reflector.

The sediments in the depressions to the north of Beirut are dish-shaped in cross-section, lapping up against the sides of the domes which are formed by the deep reflector. This observation alone is not sufficient enough to determine whether the sediments are older or younger than the domes. If the sediments are younger, then the dish-shaped appearance could have resulted from differential compaction of the sediments as they were deposited; if they are older, then the increase of slope of the sediments toward the edge of the basins could have resulted from the upward displacement of these sediments as the domes were formed (Hersey, 1962).

III. POSSIBLE AGE OF SUBMARINE CANYONS

Although little data are available for determining the age of the canyons off the Lebanese coast, the following argument may indicate that some of the canyons were cut in the Pleistocene. In the previous

section, it was found that sediments which crop out in a canyon at the southern part of the broadening of the shelf off Damour may be nearly horizontal. This implies that the canyons were cut into the sediments rather than that the sediments were deposited on the shelf after the canyons had formed (in which case, they would have a real dip, as the layers on the Tyr-Saida shelf seem to have). Thus the canyons would be younger than the sediments which they have eroded. If the age of the upper sediments in the layered sequence is upper Pliocene or lower Pleistocene, then the canyons are of post-Pliocene age.

Variations of sea level in the Pleistocene seem to have been considerable, and part of the canyons may have been cut at a time of lowered sea level. Dubertret (1954) has noted six Quaternary erosional terraces near Beirut and three near Saida, the highest of which was 100 meters above sea level.

Some canyons may have been cut as early as the Upper Cretaceous. The contour map of the deep reflector, which may represent an Upper Cretaceous layer, shows a canyon-like feature on the north side of the Tyr-Saida plateau.

This sparse set of observations suggests that the cutting of the canyons along the coast of Lebanon may have started as early as the end of the Cretaceous, and that intense cutting of the canyons may have

occurred in the Pleistocene. As an alternative point of view, Emery et al. (in press) point out that stratigraphic evidence from wells drilled on land in Israel suggest that a canyon off Gaza has been cut into Cretaceous and Eocene strata and filled with Miocene and Pliocene sediments.

IV. ORIGIN OF CONTINENTAL MARGIN

Guilcher (1963), Shepherd (1963), Dietz (1952, 1964), and others have reviewed possible theories for the formations of continental margins. In view of the tectonic influences which have acted on Lebanon (see Appendix, pp. 118 to 122), a structural origin for the Lebanese continental margin seems most probable. In particular, if vertical movements of the basement are responsible for the north-south linear faults and resulting horst and graben structures which characterize Lebanon (Henson, 1951; Dubertret, 1954; Renouard, 1956) then the continental margin may represent a deep fault along which blocks of the basement have moved. The deformations of the deep reflector on the upper rise may be the surface manifestation of such a fault. If this is the case, then the deep reflector, which extends from the Mediterranean basin to the top of the continental shelf, may be the surface of a flexure which was formed when vertical uplifting occurred under an originally flat-lying layer of sediment. Angenieux (1951) suggests that the flexures

which border the west side of the Lebanon mountains originated from such a process. The faulted continental margin would then be a westward extension of the structural features seen on land. Movement along the Levantine north-south faults started in the Jurassic; uplift of the horsts which form the mountains in Lebanon occurred at the end of the Senonian and was accentuated in the Miocene (Dubertret, 1954). The formation of the Lebanese continental margin, if it is structurally related to these features, may have occurred at the same time.

CHAPTER V

SUMMARY AND CONCLUSIONS

I. The continental shelf of Lebanon is generally 3 to 7 kilometers wide, with broadenings at Damour and between Tyr and Saida to as much as 14 kilometers. The shelf break is about 50 fathoms deep in the narrow regions of the shelf, and about 200 fathoms deep in the broader regions. The slope steepens northward from 6 degrees near Tyr to 30 degrees at Beirut. South of Beirut, canyons as deep as 270 fathoms incise the slope.

II. The deepest reflector seen in the survey area is ubiquitous, and is considered to be an old slope. Possibly, it represents a flexure which was formed when the continental margin was block-faulted. Outside the survey area, the deep reflector extends as far westward as Cyprus, and as far southward as Port Said. South and west of the survey area, it is underlain by a still deeper reflector.

Overlying this deep reflector, the following sequences of sediments are seen:

(1) South and west of the survey area, a sequence of horizontally-discontinuous sediments, presumed to be mostly Nile-derived, extend from Beirut to Cyprus, and from Beirut to Port Said. This sequence is at least 0.5 second thick. It is not seen inside the survey area.

(2) Inside the survey area,

(a) The broad portions of the shelf, where observed, consist of

(i) A veneer of sediments as thick as 0.008 second,

probably of Pleistocene to Recent age.

(ii) A sequence of layered, conformable sediments, as thick as 0.83 second, possibly of Eocene to Upper Pliocene or Pleistocene age.

(b) The slope, where observed, consists of

(i) Outcroppings of the layered shelf sediments, on the slopes fronting the Tyr-Saida Bank and the shelf near Damour, and possibly in other, canyon-eroded areas.

(ii) Possibly slipped or slumped layered sediments, at the south end of the survey.

(iii) Conformable, layered sediments filling depressions formed by the deep reflector, between Beirut and Batroun.

(c) The rise, where observed, consists of

(i) A pile of inhomogeneous sediment at the base of the slope, in the southern part of the survey.

(ii) Sediments showing either no layering or broken layering and thickening seaward, between Beirut and Saida.

(iii) A sequence of conformable, layered sediments filling deep depressions formed by the deep reflector, between Beirut and Batroun.

III. These observations indicate that the shelf was formed as the result of the deposition of land-derived material, and, along with the slope, has since been eroded by canyons. The eroding mechanisms may be slumping and turbidity currents.

IV. The rise has probably been formed by the deposition of eroded material from the adjacent land areas, and from the shelf and slope. Since the conformable layering in the shelf sediments show little if any subaerial erosion, and because the adjacent land areas have undergone intense erosion, most of the sediments on the rise consist of land-derived material. This material probably began to be deposited on the rise at the end of the Cretaceous, and has been more heavily deposited during and since the Miocene. Sediments from the Nile may constitute part of the rise deposits.

Since the layered sediments which appear in the Mediterranean outside the survey area are seen as close to Lebanon as 18 kilometers,

most of the material which is dumped into the Mediterranean from Lebanon may remain fairly close (18 kilometers) to shore.

V. According to Dietz (1952) the continental margin of Lebanon is in a stage of early maturity. As erosion of the mountain areas of Lebanon continues, it is expected that the rise sediments will build seaward and also will begin to encroach upon the base of the continental slope.

APPENDIX A

GEOLOGY OF LEBANON AND ITS RELATIONSHIP TO SURROUNDING AREAS

As a background to the present study, a summary of the geology of Lebanon and its relation to the regional geology of the Middle East and the Mediterranean Sea will be presented in this chapter. Since a comparison of the results of the CSP survey to the accompanying land geology was attempted, particular attention will be paid to the coastal regions of Lebanon.

I. GEOLOGY OF LEBANON

The numerous geological studies which have been made about Lebanon have culminated in a set of geological maps (scale of 1:50,000), published by Louis Dubertret, covering about three-quarters of the Lebanese territory; these maps in turn have been assembled into two maps (scale 1:200,000), dealing with the areas south and north of Beirut respectively. These maps, kindly provided to the writer by Professor Raven of the American University of Beirut, are accompanied by explanatory notes. Of the 1:50,000 - scale maps covering the coast of Lebanon, only the Saida sheet was available to the writer. However, the 1:200,000 - scale maps and their accompanying texts present the existing geological information and indicate stratigraphic and structural possibilities in considerable detail. Among the more general papers on Lebanon, Renouard, (1956), provides information from two wells drilled

in Lebanon and clarifies some of Dubertret's earlier work. Dubertret (1947) and Gibert (1949) discuss the outstanding stratigraphic and structural problems of the Levant.

A. Main Structural Units. (Figure 34)

The topography of Lebanon is dominated by two chains of mountains: the Lebanon and Anti-Lebanon mountains. They are parallel to the coast, and are separated by the high plain of Bekaa.

The Lebanese chain extends from Homs Gap in the north to Marjayoun at the border of Israel, where it gradually ends. In the north, a narrow coastal plain lies between the Lebanese chain and the sea: the plains of Koura and Akkar. In the south, the plateau of Tyr-Nabatiye (as named by Reynouard, 1956), stretches out between the coast and a line from the mouth of the Nahr Damour through Roum and Marjayoun, to the frontier of Israel on the west edge of the Dead Sea rift. Lebanon is cut transversely by the Baidar Gap through which run the roads connecting Damascus and the Bekaa plain with Beirut. North of this gap, the high mountain is really a plateau, culminating at 3084 meters, whereas in the south a narrow chain rises with relatively sharp summits.

The Anti-Lebanon Mountains are composed of two structurally different units: the Anti-Lebanon in the north (*sensu stricto*), and the

mountain group of Hermon in the south. The Damascus-Beirut road forms an approximate separation between these two units. Renouard (1956), has pointed out that these three chains are actually the radii of a wide fan-shaped system, whose prolongation is the Damascene-South Palmyrene range in Syria, and whose convergence is the shelf which separates the Houle depression from the Bekaa. These different radii, diverging toward the north, are gradually separated by a high plain, the Bekaa. This plain, closed at the south by the convergence of the mountain system, widens northward to a width of 20 km. at Baalbek. Beyond the Syrian border to the north, it gradually mingles with the wide sub-desert plain of Homs.

B. General Tectonics and Resulting Structural Units

Descriptions of both tectonics and of the resulting main structural units will be presented in this one section, since the two are closely inter-related.

Both faulting and folding occur in Lebanon, and as a result, there are many opinions on which mechanism is the most dominant. The discussion which follows will be derived mostly from the point of view of Dubertret, who favours faulting. Other viewpoints will be presented afterwards.

Although Plate 1 seems to imply extreme dislocation in the geology of Lebanon, the tectonics are actually dominated by the faults and flexures which trend NNE - SSW. These features appear to be related to the Dead Sea rift valley system, which in turn can be traced southward to Aqaba. The major extension of the west flank of the rift valley is the fault of Yammoueth, which runs as far northward as the Taurus Mountains in Turkey. Its throw reaches 3000 meters in the South Bekaa, whereas it is only 500 meters near the Qornet es Saouda. The fault of Roum is a branch of the Yammoueth fault; its throw reaches 2000 meters. It is limited in extent, and toward the north it becomes a flexure. The fault of Hasbaya, also related to this system, has weak throws. The eastern border of the Dead Sea rift is continued northward by the fault of Chebaa-Rachaya, which has a 600 meter throw toward the east. The fault of Serrhaya, related to the latter fault, has a throw to the west. The flexures shown in Figure 36 are similarly related to this fault system. The flexures on the seaward side of Lebanon are an extension of the Roum fault, and the western flexure of the Anti-Liban is part of the Chebaa-Rachaya fault system. Dubertret (1954), considers that these flexures are actually the surface representations of sediment-covered, deep-seated vertical faults. Angenieux (1951) has proposed a mechanism whereby a deep-seated fault appears as a flexure at ground level.

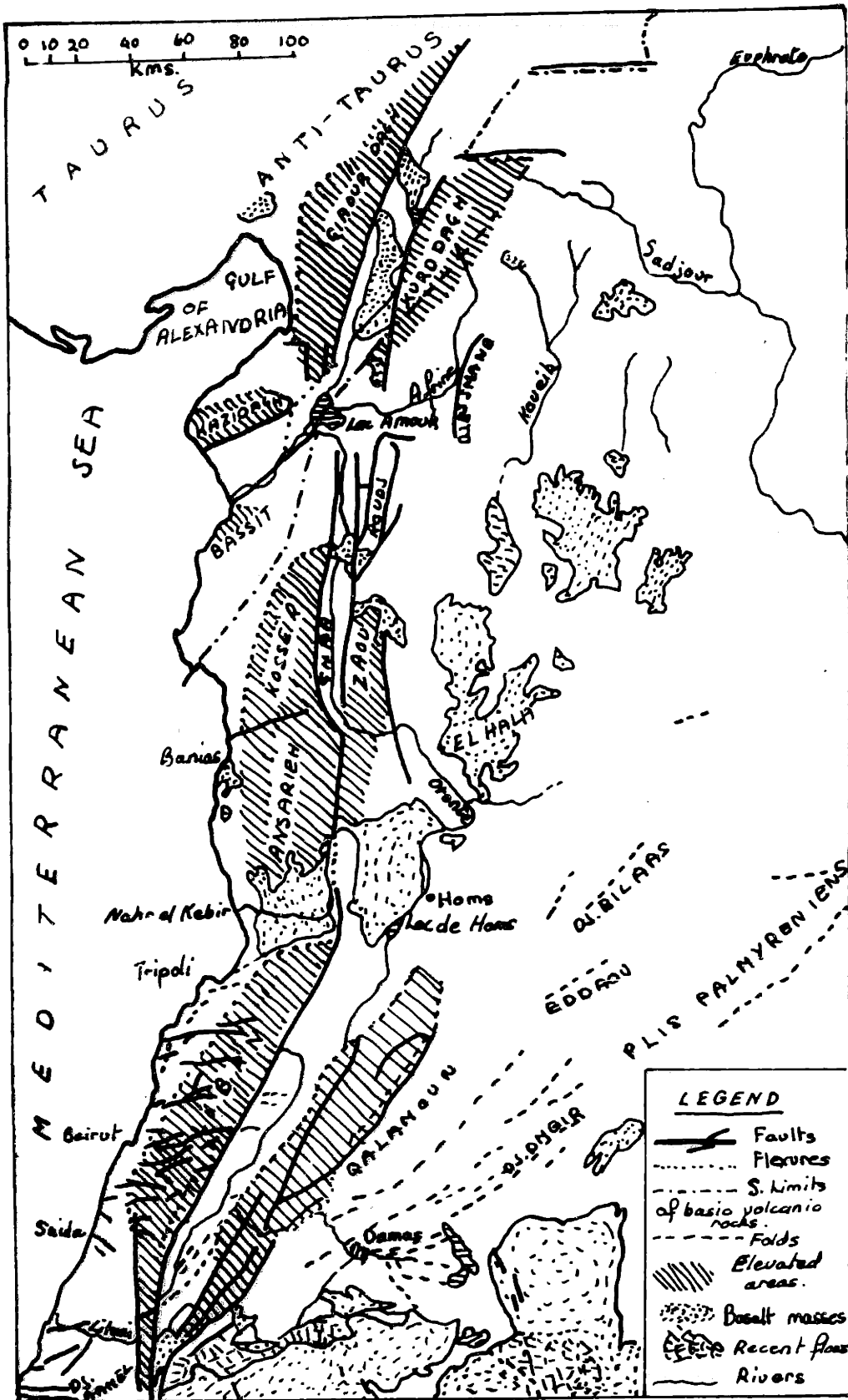


Figure 35. Main structural units of Levantine coast between Israel and Turkey.

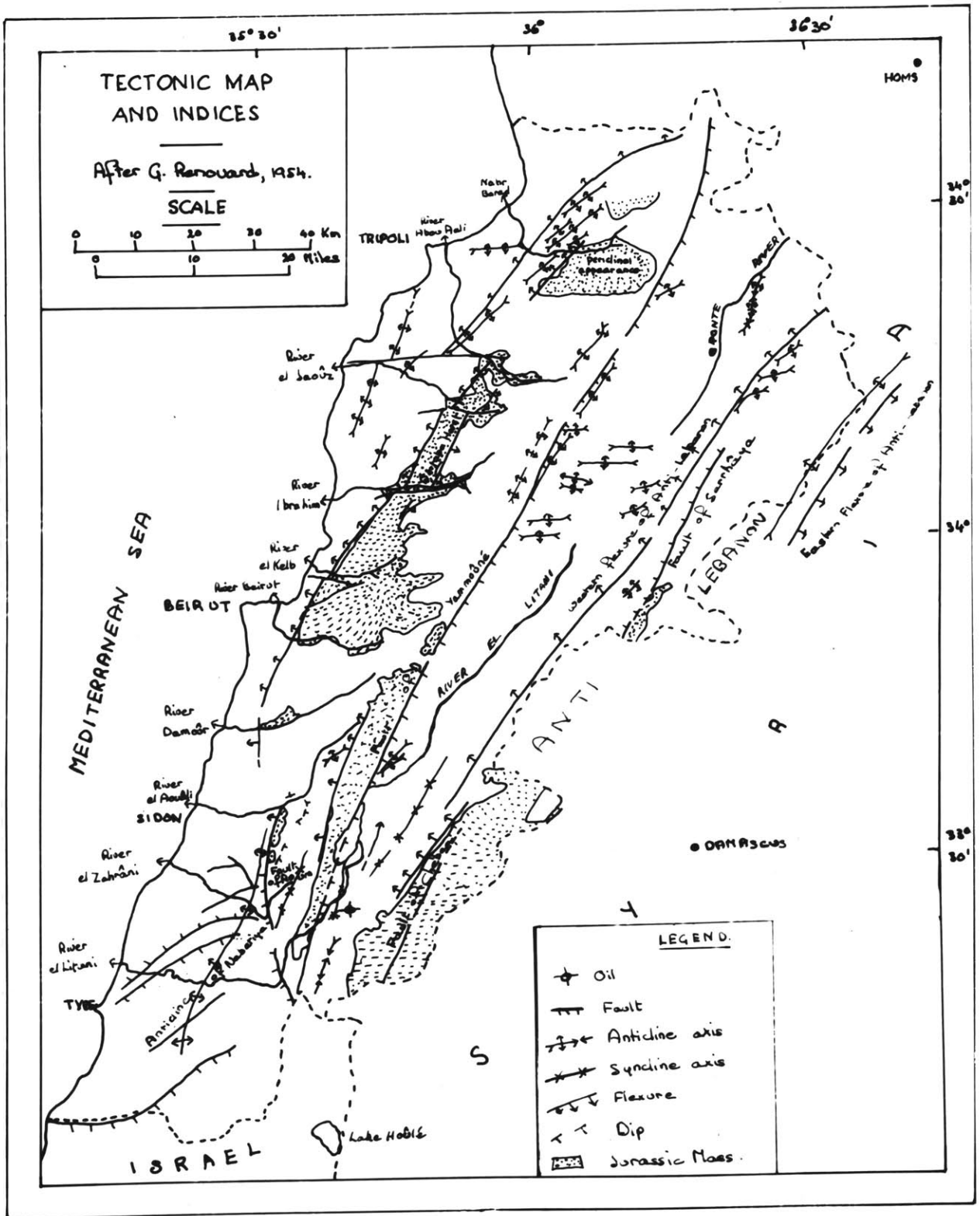


Figure 36. Tectonic map of Lebanon.

By dividing the countryside longitudinally NNE - SSW, this tectonic system determines the main structural units not only of Lebanon, but also of the entire coast as far north as Turkey. (See the over-simplified diagram in Figure 35).

Over this main NNE - SSW tectonic system, a secondary structural network of faults was impressed. These faults appear in the Lebanon mountain system striking E - W north of Beirut and NE - SW south of Saida. Cutting diagonally across the mountain chains, the faults divide the different longitudinal masses into slices. This division was commonly accompanied by a lateral shift of the blocks as if each of them had moved eastward along the side of the adjacent block on the south. This pattern appears clearly on the horst of Qartaba, where the throws are rarely more than 100 meters, except at the crossing of the flexures where, due to lateral shift, the faults appear locally as major movements.

The structural map (Figure 36), the geological map of Lebanon, and sections A to D (Plate 1) show how the NNE - SSW faults and flexures divide the country into structural units. These units will be discussed briefly.

The mountains of Anti-Lebanon and Hermon, composed of Cretaceous and Jurassic rocks, are bounded to the west by a flexure; their slopes rise from the Bekaa without any sharp break. The

Anti-Lebanon mountains are bounded on the east by a flexure. These mountains, resembling a flattened arch with steep flanks and tabular center, are similar in form to the northern Lebanon mountains. The Hermon group, to the west, is faulted against younger sediments in the north and against the Houaran basalts to the south. Between its eastern and western limits, the Hermon is folded in an arch cut by vertical faults. The intensity of folding of the arch increases toward the south, (see sections A to D, Plate 1).

In the zone dividing the Lebanon and Anti-Lebanon mountains, the plain of Lake Houlé is considered to be a trench, bounded by the extensions of the Dead Sea faults. It is not clear whether the Bekaa, to the north, is a syncline or a fault-bounded trench. At any rate, it is delineated on the east by the bordering flexure of the Anti-Lebanon-Hermon regions, and on the west by the fault of Yammoueth.

The mountain chain of Lebanon, consisting of an elevated bloc and a more seaward plateau, is bounded on the east by the Yammoueth fault, whose throw ranges from 1000 to 2000 meters. This system is divided into northern and southern sections at Beirut by faults. In the northern section, the elevated bloc, delineated by a flexure extending from north of Tripoli to the southern part of the Nahr Damour, has been raised as much as 2000 meters. This bloc, considered to be a horst by Dubertret (1954), is a high Cenomanian plateau with a Jurassic

core running longitudinally north-south down its center. The Jurassic mass in the center of the bloc is also a horst (Renouard, 1956). The elevated plateau is tabular except near Beirut, where it develops high peaks on its eastern flank. The lower plateau, lying between the elevated bloc and the sea, slopes seaward with slight undulations. Its average slope is the same as that of the elevated bloc (100 m. /km.). Near the coast, the Cenomanian sediments disappear under terminal Cenomanian (between Beirut and Jbail), Turonian (between Jbail and El Heloue) or Neogene sediments (Koura plain), or extend to the coast (between El Heloue and Bartroun). Emery and George (1963) point out that at many points along the coast, the slopes of the plateau are steep, rising up 100 meters or more from sea level.

In the southern half of the Lebanon mountain chain, the elevated bloc is bounded by the fault of Yammoueth to the east, and the fault of Roum to the west. The Jurassic core is delineated to the east by a flexure which, toward the south, unites with the Roum fault. The elevated bloc, 24 kilometers wide at Beirut, narrows southward, terminating at the bend of the Litani River. This elevated bloc is structurally lower than the corresponding bloc to the north, and lacks the latter's structural simplicity. Section C (Plate 1), shows that it is both faulted and folded. The Tyr-Nabatiye plateau, lying between the

sea and the fault of Roum, widens southward from its narrow northern limit, the Beirut peninsula, to nearly 17 kilometers at the Lebanon-Israel border. Its topographic character changes from north to south. Between Beirut and Damour, where the plain is only 4 kilometers wide, the plateau slopes toward the sea with a declivity of 100 m. /km. , the same as that of the coastal plateau north of Beirut; farther south, this seaward slope decreases gradually to 25 m. /km. at Saida. At the same time, the plateau becomes tabular. Its near-horizontal surface is interrupted by faults and deep, river-cut valleys. Between Beirut and Saida, the slopes of the Cenomanian plateau fall to the sea. In this region, a series of east-west faults, whose north sides have dropped, have produced a series of indentations in the coastline. Between Saida and a point 8 km. south of Tyr, the plateau is partially covered by Eocene and Miocene sediments. The plateau slopes gently seaward from 500 meters at the base of the elevated bloc to 180 meters near the coast, then descends steeply to a narrow alluvial plain fronting the coast. South of this point, in Lebanese territory, Cenomanian rocks dip gently to sea level.

The above discussion summarizes the view of Dubertret, whose emphasis on faulting as the dominant tectonic mechanism follows the views of C. Diener (1886) and M. Blanckenhorn (1914). E. Krenkel

(1924) claims that the main structural units are due to folding; according to him, the Lebanon and Anti-Lebanon mountains would be truncated anticlines belonging to the Syrian arc, which is in turn related to the Taurus Mountains (Alpine) in Turkey. Vaumas (1947) generally supports this latter opinion, suggesting, in addition, that the fault of Yammoueth is a result of sinking of the edge of the continent, a process tending to lower Lebanon with respect to Anti-Lebanon. Dubertret (1947) dismisses the views of Krenkel and Vaumas as being incompatible with known geological information.

C. Stratigraphy

With the exception of a few volcanic rocks, most of which are interstratified, Lebanon is almost entirely formed of sedimentary rocks. The known thickness of these rocks is more than 5000 meters, but the total thickness is probably much greater, for the basement has not yet been found and there is no sign of its proximity at the lowest level of the stratigraphic scale.

Stratigraphic columns for North Lebanon, Hermon, and the Tyr-Nabatiye plateau are presented in Figure 37. The first two are by Renouard (1956); the third, less detailed, has been compiled by the writer from information in various papers by Dubertret. The following discussion will point out the salient features of these columns in the

North Lebanon and Tyr-Nabatiyé regions, the areas of Lebanon of most interest to this present study.

(1) Lower Jurassic-Liassic(?) - Triassic(?): The oldest formation dated with certainty in Lebanon belong to the Bajocian (lower Jurassic). It is possible that even older Liassic formations underlie the Nahr Ibrahim in North Lebanon (Renouard, 1951). Moreover, Renouard (1956) believes that an electrically conducting bed, 650 meters below the bed of Nahr Ibrahim, represents the Triassic.

(2) Jurassic: The Jurassic, which has a measured thickness of 1600 meters in Lebanon, appears in the center of the elevated mountain blocks. The middle and lower Jurassic unit (Lias(?), Bajocian, Bathonian) exposed in North Lebanon and Hermon but not in the Tyr-Nabatiyé plateau, is a limestone and dolomite mass, 1200 meters thick. This sequence is followed by Oxfordian-Lusitanian (Upper Jurassic) limestones and marls, 130 meters thick in North Lebanon and 50 meters thick in South Lebanon. The Kimmeridgian-Portlandian formations consist of littoral limestones and marls. In North Lebanon, volcanic rocks, occurring at the beginning of the Kimmeridgian, are interstratified with marls. No corresponding volcanism is noted in South Lebanon.

(3) Cretaceous: A transition zone appears at the beginning of the Cretaceous. At the end of the Jurassic, the sea regressed nearly everywhere, and the Jurassic was covered with continental sandstone,

(grès de base). This unit is 250 meters thick in South Lebanon and thins northward.

The lower Cretaceous formations (Albian and Aptian) surround the Jurassic masses in the mountain blocs. They are littoral deposits, having a thickness of 430 meters in North Lebanon and 300 meters in South Lebanon. The transgression of the sea, which first appears in the lower Aptian, is not well defined. Continental and littoral deposits lie between the beds of clay, marl, oolitic limestone, and subreefal limestone. Volcanic flows, interstratified with sediments, appear in both North and South Lebanon.

The uniformity and thickness of the middle Cretaceous (Cenomanian-Turonian) throughout Lebanon is proof of a general invasion of the sea during this time. These formations, covering half of the Lebanese territory, appear on the coastal plateaus.

Eroded fragments of the Upper Cretaceous (Senonian) are exposed in Northern Lebanon between Beirut and Jbail, and in South Lebanon on the western half of the Tyr-Nabatiyé plateau. The stage is essentially chalky, with intercalated marls. Variations in the total thickness occur, from 200 meters in Northern Lebanon and the western half of the Tyr-Nabatiyé plateau to 20 meters on the eastern edge of that plateau.

(4) Eocene: Eroded but extensive Eocene formations on the Tyr-Nabatiyé plateau, consist of two stages: an Ypresian complex of limestone and marls, and above this, a wide distribution of soft Lutetian limestone, reaching a maximum thickness of 200 meters. Dubertret (1954) has found a fragment of upper Lutetian consisting of breccia enclosed in limestone. In North Lebanon, in the littoral region, some Ypresian is recognizable, but no Lutetian.

(5) Miocene: The Miocene in Lebanon consists of two types: marine (Burdigalian and Vindobonian) and continental (Pontian). Eroded fragments of marine Miocene are found at the seaward edge of the Tyr-Nabatiyé plateau south of Saida, and form headlands north of Beirut. In this region, the Burdigalian (marly limestone) is 80 meters thick and the Vindobonian (conglomerate overlain by limestone) is 100 meters thick. North of Beirut a gap appears in this sequence: only the Vindobonian is found. It is 265 meters thick, and is discordant on Eocene formations. Pontian Miocene (torrential deposits and lacustrine mud) is 225 meters thick on the Koura syncline.

(6) Pliocene: The Pliocene is not found in South Lebanon. In North Lebanon, it begins with volcanics which form the vast flows in the Homs-Tripoli trough. This is followed by marine deposits (reefal limestone and marls, 40 - 60 meters thick) seen on the Koura.

(7) Quaternary: The Quaternary is represented in North Lebanon by ancient dunes and by torrential deposits on the Koura, and in South Lebanon, together with recent sedimentation, by arable plains extending from Saida to a point five miles south of Tyr. Near Beirut, six Quaternary terraces are observed, the highest being 100 meters above sea level; three such terraces occur south of Saida. The position of the beaches results from a combination of fluctuations of sea-level and movements of the continental bloc during the Quaternary. Dubertret (1954) indicates that the age of these terraces increases with height above sea level, and using archaeological dating, correlates the terrace at 15 meters with the Riss-Wurm interglacial period.

D. Orogeny and Volcanism

If the sandstone and the lignite-bearing clays of the Syrian side of Hermon are really pre-Bajocian, then in this period the Jurassic began with a period of emergence. The 1200 meters of limestone which follow, however, are marine deposits. In Anti-Lebanon, Hermon, and South Lebanon, the sea remained without interruption to the end of the Jurassic, whereas in North Lebanon, from the Sequantian-Kimmeridgian period onward, a subaerial and even continental period occurs (Renouard, 1956). This emergence was accompanied by volcanic activity, as the sediments are interstratified with basalt flows.

It is possible that an orogenic crisis affected the Jurassic platform. Dubertret (1954) shows that the NNE - SSW faults delineating the large structural units were active at the end of the Jurassic; later, they were rejuvenated, cutting through the sediments which had covered them. There are indications that the upper Jurassic surface was intensely eroded. In Hermon, erosion penetrated to the middle Bathonian. In Anti-Lebanon and South Lebanon, the ring of terminal Jurassic is nearly intact.

With the "Grès de base" a continental system began with a few slight marine incursions. These became more pronounced during the Aptian and were predominant during and after the Aptian. Volcanism persisted during the Lower Cretaceous with two particularly active periods: "Grès de base" and upper Aptian.

Conditions in the Cenomanian-Turonian were similar to those which produced the Jurassic limestone mass. At times, slight uplifting caused the land to emerge. It is possible that similar uplift occurred at the beginning of the Senonian, (Renouard, 1956). The end of the Senonian, when this uplift is best known, marks the beginning of an orogeny. At this time, the Lebanon and Hermon horsts were raised, and the bottom was deformed into gentle shoals and depressions (Dubertret, 1954). Renouard (1956) suggests that at this time the east edges of what

are now the Tyr-Nabatiyé plateau and the Bekaa were eroded, while a depression on the west side of the Bekaa was filled with the eroded material. The irregular uplifting of the bottom did not happen everywhere at the same time.

At the beginning of the Nummulitic, the sea withdrew from South Bekaa, but still remained on the northern coastal area until the end of the Ypresian, and in South Bekaa and on the Tyr-Nabatiyé plateau until the end of the Lutetian. Finally, in the Neogene, the present topography was formed. The Burdigalian Sea, which covered the lower Lebanese plateaus and Syria, was forced back by the orogenic movements which caused general uplifting and accentuation of the horsts. The coastal regions north of Beirut were raised somewhat during this orogeny, but the corresponding regions south of Beirut were not. A subsequent Vindobonian transgression and regression then occurred. The end of the Neogene was marked by volcanism and a third final transgression of the sea limited to the littoral regions of the Mediterranean. After its regression in the Pliocene, the shoreline was fixed near its present position (Dubertret, 1937).

Volcanism occurred again in the Pliocene, indicating that further orogeny may have occurred, and in the late Quarternary.

E. Sources of Supply to Offshore Areas of Lebanon

The previous discussion indicates that before the end of the Cretaceous, much of the material supplied to the offshore areas was biogenous, resulting from deposition of bottom-growing organisms and from the settling out of animals which lived in the seas covering the land areas. Some of the offshore material, especially at the end of the Jurassic and during the early Cretaceous, was derived from the erosion of land areas.

The orogenies which have occurred since the end of the Cretaceous, however, produced two new major sources of supply to the offshore areas: material derived from the erosion of the uplifted horsts in Lebanon, and material derived from the cutting of the Nile. A discussion of these processes follows.

(1) Intense erosion has attacked all parts of Lebanon since the end of the Eocene, for the last 30 million years. If Renouard's statement that the Hermon would be 5000 meters high if erosion had not affected it is correct, then the Hermon has lost up to 2200 meters of rock. On the Tyr-Nabatiyé plateau, Dubertret (1944) points out that the erosion surface (probably Miocene) does not correspond with stratigraphic surfaces, but cuts across them.

The degree of erosion in various areas depends on the nature of the rock. The limestone of the massifs is very permeable. Water tends to be absorbed by them rather than running across their upper surfaces, with the result that they are not as intensely eroded as the less permeable marls and sandstones.

Erosion today is effected by several large rivers running from the mountains to the coast. These rivers have cut deeply into the mountains and coastal plateaus. As well as being the chief erosional agents, they bring much of the eroded material to the coast. They are well supplied by rainfall, which, falling mostly between the months of October and April, averages 1500 millimeters per year on the mountains and 800 millimeters per year on the coast (Dubertret, 1949). The rivers of Lebanon have various sources:

1. Water is supplied directly by rainfall,
2. Water which circulates underground acts as a source for rivers near the edge of the permeable limestone coastal plateaus,
3. The limestone massifs, being very permeable, act as resevoirs for water. As a result of over-saturation, water is ejected at the base of these mountains and forms rivers.

4. Under the Tyr-Nabatiye plateau, water absorbed in the limestone cannot rise to the surface of the plateau because of the overlying, impermeable rock cover. Instead, it flows seaward in an underground network, finally forming offshore underwater springs.

Material put into suspension by wave-cutting of the land areas during the various transgressions of the sea since the end of the Miocene has also been supplied to the offshore areas.

Thus, it is apparent that since the Miocene, there have been abundant sources on land for detrital material, and powerful agents of transport to bring it to the coast. Erosion is still active today. Emery and George (1963) describe heavy erosion of sea cliffs and sand beaches along the shores of Lebanon, and point out that large rivers, carrying land-derived material, form alluvial fans at their mouths.

(2) The other major source of supply to the Eastern Mediterranean is the Nile river. Enough material has been dumped into the Mediterranean to form the Nile Cone, which extends from the Nile Delta to the Herodotus Abyssal Plain, north of Lebanon (Emery et al. , in press). Cutting of the Nile Valley began in the Miocene, ceased in the Pontian (Mio-Pliocene), and resumed at the end of the Pliocene. The Nile deposits

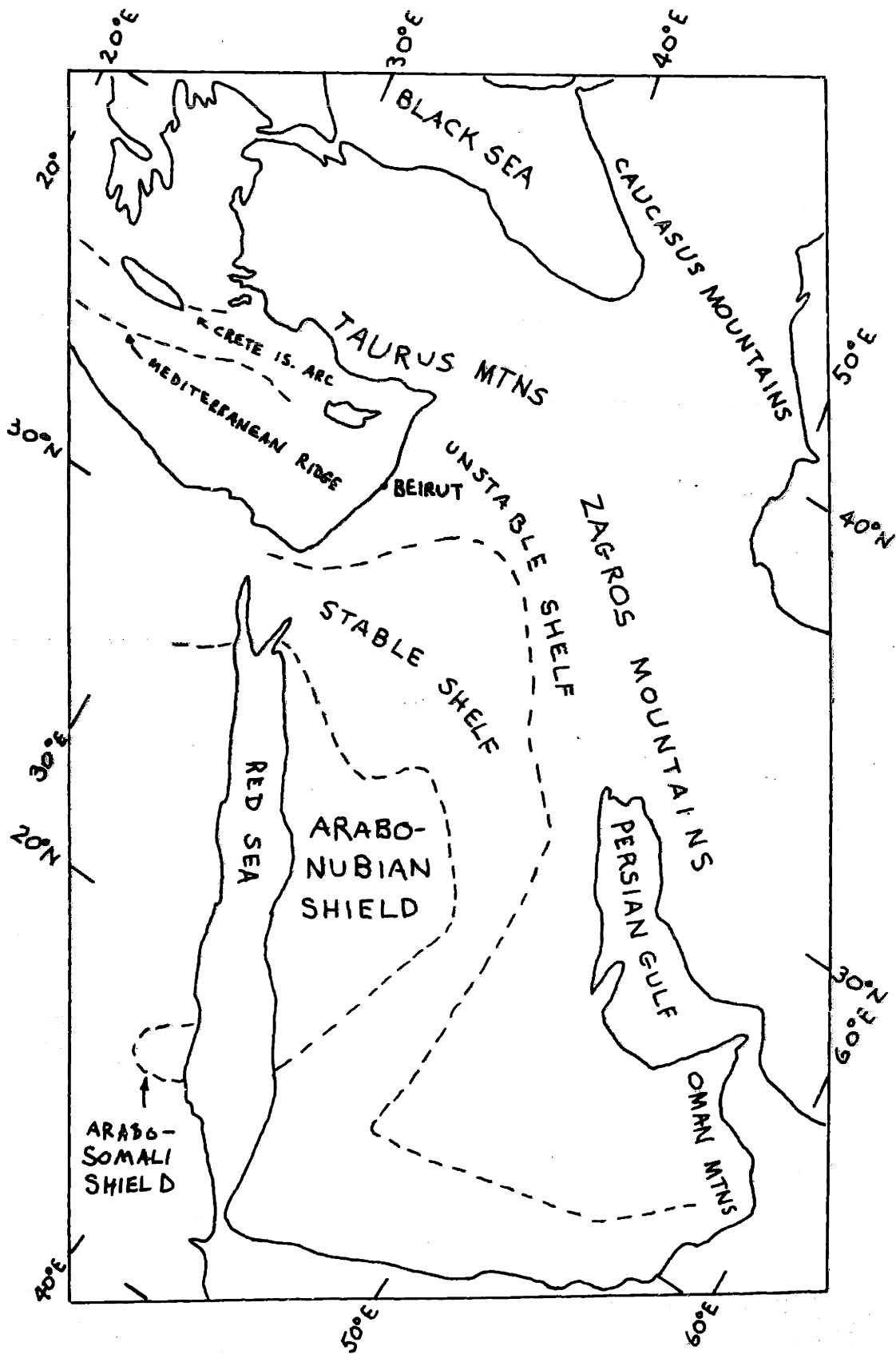


Figure 38. Regional structures surrounding Lebanon.

are thus of two different ages. On the basis of a rather uncertain figure for the annual contribution of suspended sediments by the Nile River (57 million tons per year), Emery et al. (in press) have estimated that perhaps 100 meters of material have been deposited in the Pleistocene.

Material ejected by the Nile is brought northward along the Eastern Mediterranean coast by offshore currents. The contribution of Nile sediments to the continental slopes of Israel is heaviest in the south, where the slope is 2° , and decreases toward the north, where the slope is 8.5° (Emery and Bentor, 1960). The contribution of these materials to the beaches of Lebanon is small (Emery and George, 1963).

F. Offshore Geology

A map by Boulos (1962) showing the offshore sedimentation of Lebanon indicates that a step in the continental shelf appears approximately at the 100 meter contour. On the shoreward side of this contour, rock, sands, clays, gravel, and mud are found rather randomly distributed. On the seaward side of the contour, mud, with some clays and sands, appears to cover the shelf. Neither the lithology nor the age of the rock on the inner shelf is indicated.

II. STRUCTURAL AND SEDIMENTARY RELATIONSHIP OF LEBANON TO SURROUNDING AREAS

The geological relationship of Lebanon to the areas which surround it will be discussed from two points of view: structural relationships, and sedimentary relationships. In the discussion of structures, emphasis will be placed on the determining the tectonic forces which have acted on Lebanon.

A. Structural Relationships

Figure 38 shows the place of Lebanon in the general structural pattern of the Middle East. In this large area, Baker and Henson (1952) have identified three geologically distinct provinces:

(1) The massif zone, comprised of the Arabo-Nubian and Arabo-Somali Pre-Cambrian shield.

(2) The Orogenic-Geosynclinal zone, caused by tangential compression (Alpine orogenies) from the north, northeast, and east, and now marked respectively by the Taurus, Zagros, and Oman ranges.

(3) The foreland shelf, bounded approximately by the shield massifs, the Mediterranean, the orogenic belt, and the Gulf of Aden.

Lebanon lies on the north-eastern edge of the shelf province. Generally, this shelf subsided slowly from Cambrian time until the beginning of Cretaceous time, when the orogeosynclinal belt began to

develop and to define the northern and eastern limits of the foreland proper. Before intense late Tertiary thrusting and faulting occurred in the Taurus-Zagros-Oman mountain belt, the shelf was characterized by a changing pattern of gentle basins and swells which have been ascribed either to incipient "Alpine compression" or to vertical movements of the basement or both. In addition, many anticlinal structures rose intermittently in the foreland. There is much discussion as to whether these structures were produced by uplift of basement blocks or by normal folding. For instance, Ball and Ball (1953) have attributed the generally NNE - SSW pattern of anticlines in Israel to a long period of folding starting in the Carboniferous and reaching its intensity in the late Cretaceous, followed by a relatively short-term period of faulting. However, Henson (1951) has assigned Israel, Lebanon, and Syria to an unstable portion of the foreland shelf where movements were produced by taphrogenesis (vertical movement with high-angle faulting) rather than by folding.

The Alpine orogeny produced large-scale structures near Lebanon. The Taurus mountains in Turkey, lying to the north of Lebanon, extend westward in an accurate form through Greece and eventually join the Alps. This range is fronted in Greece by an island arc. Just south of this arc lies the Mediterranean Ridge (as defined by Emery et al. , in press), bounded on each side by trenches or abyssal plains. This ridge, starting

from Italy, passes between Crete and Lybia and curves sinuously north to Cyprus. The ridge may be related to the Alpine-Taurus belt. Emery et al. (in press) have suggested that it was formed in the Miocene as a result of tensional opening of the earth's crust. Cyprus has igneous intrusions which could be associated with an extension of the Mediterranean Ridge. Harrison (1955) has suggested that these intrusions are related to those of the Tripoli-Homs trough, at the north end of Lebanon, by a line of weakness.

To the east of Lebanon lies the folded Damascus-Palmyra mountain chain. Krenkel (1924) has suggested that this feature is a truncated part of the Taurus mountains. Henson (1951) rejects this suggestion on the grounds that the Taurus mountains, characterized by thrusting and folding, were formed earlier than the Palmyrene mountains, which as a whole, reveal horst and graben tectonics. Renouard (1956) suggests that the Damascus-Palmyra range is an extension of the linear fractures which dominate Lebanon.

These are the structures near Lebanon which might have conceivably been formed in the Alpine orogeny. Baker and Henson (1952), Henson (1951), Renouard (1956), and Ball and Ball (1953) all point out or infer that the Pre-Alpine crustal warpings and the subsequent Alpine orogeny should not be regarded as separate phenomena, but as the various

stages in a continuing disturbance of the earth's crust.

An apparently different form of deformation, however, is represented by the great north-south faults which cut through Lebanon. These faults extend from Turkey southward through the Jordan Valley to the Red Sea, where they apparently continue as an axial rift, and are ultimately related to the median rift valley system of the Carlsberg Ridge (Ewing and Heezen, 1960). Drake and Girdler (1964) have suggested that the Red Sea rift is due to tearing of the earth's crust by the separation of Africa and Arabia. The Levantine faults appear to be an extension of this tear.

De Boers (1965) accounted for all these tectonic features by suggesting that Europe has moved eastward with respect to Africa and Arabia through dextral wrench faulting. His hypothesis is based on paleomagnetic and geological data.

The forces that could possibly act on Lebanon, then, are:

(1) East-west tensional forces, represented by north-south-trending rift valleys and faults, possibly resulting from the separation of Africa and India.

(2) Short-term intense compressive forces resulting from the Alpine orogeny. The Taurus range represents forces from the north, the Zagros ranges, forces from the north-east. It is not known whether

the Mediterranean Ridge represents compressional, tensional, or shearing forces.

(3) Long-term gentle forces from Pre-Alpine movements. These could either be vertical forces or, in the vicinity of Lebanon, generally east-west forces, depending on whether the surface features are due to vertical movements of the basement or to folding.

Presumably, the forces in categories 2 and 3 have resulted in the secondary E to W and NNE to SSW faults seen in the Lebanon ranges, and in the broad folds seen in the Anti-Lebanon and Hermon ranges.

B. Sedimentary Relationships

The Middle East foreland shelf defined by Baker and Henson (1952) subsided slowly from Cambrian time onward beneath shallow, epi-continental seas. Generally, successive marine transgressions occurred farther west and south until the late Eocene, when the reverse process of regression began. As a result, thick layers of chemical sediments were deposited in Syria, Lebanon, and Israel. Renouard (1956), comparing stratigraphic columns of Lebanon, Israel, Jordan, Turkey, and Cyprus, has concluded that Lebanon is centered at the center of a vast sedimentary basin whose main axis extends westward toward southern Cyprus, and that consequently subsidence has been more active

in Lebanon than in the surrounding areas. In the present survey, therefore, we would expect to find the deep sedimentary section in Lebanon continued westward.

The only known estimate of sediment thickness in the Eastern Mediterranean has been obtained by Harrison (1955), who, on the basis of several assumptions, found from gravity information that a depression just seaward of the Nile contains about 3000 meters of sediment.

APPENDIX B

TABLE 1

DATA ON CANYONS OFFSHORE OF LEBANON

- Col. 1. Name of area (see Figure 5).
- Col. 2. Name of canyon (see Figure 5)
- Col. 3. Average seaward declivity of canyon axis, along axis, Depths refer to interval in which declivity measured.
- Col. 4. Local average maximum declivity of continental slope. Depths refer to interval in which declivity measured.
- Col. 5. Depth of canyon (elevation of canyon wall above canyon floor).
N and S refer to north and south walls of canyon. Depths measured at actual crossing of canyon.
- Col. 6. Depth of canyon axis corresponding to measurements in Col. 5.
angles to nearest half degree
depths in uncorrected fathoms

(1)	(2)	(3)	(4)	(5)	(6)
A-B	AB 1	9° (55-190)	12°	22S 22N	55
"	"			15N	190
"	AB 2			25N	200
"	AB 3	5° (200-600)	7 1/2° (100-500)	23N 25S	602

(1)	(2)	(3)	(4)	(5)	(6)
A-B	AB 4	4° (200-600)	7 1/2° (100-500)	200S 90N	245
"	"	"	"	55N 23S	605
"	AB 5	4° (300-600)	"	85N 137S	292
"	"	"	"	45N 157S	419
"	"	"	"	90N 30S	580
"	AB 6	5° (320-440)	"	110S 160N	320
B-C	BC 1	2 1/2° (166-180)	7° (100-200)	30N 33S	180
"	"	15° (180-400)	17° (200-400)	40N 260S	400
"	"	3.5° (400-482)	17° (400-500)	75N 282S	482
"	"	3.5° (482-635)	12° (400-600)	40N 300S	635
C-D	CD 1	5° (417-670)	10° (200-600)	133N 270S	417
"	CD 2	8 1/2° (344-670)	13° (300-600)	60N 56S	344
"	CD 3	9° (341-670)	"	67N 56S	341

(1)	(2)	(3)	(4)	(5)	(6)
C-D	CD 4	9° (341-670)	13° (300-600)	108N 67S	341
"	"	"	"	150N 530S	670
"	CD 5	9 1/2° (475-657)	13° (300-600)	242N 205S	475
"	"	1° (637-648)	7° (500-700)	287N 118S	637
"	"	"	"	173N 59S	648
"	CD 6	8 1/2° (323-637)	14 1/2° (300-600)	23N 53S	323
"	"	1° (637-648)	7° (500-700)	287N 118S	637
"	CD 7	5 1/2° (408-637)	14 1/2° (300-600)	73N 108S	408
"	"	1° (637-648)	7° (500-700)	287N 118S	637
"	CD 8	3 1/2° (362-407)	10° (200-400)	208N	362
"	"	2° (407-487)	6 1/2° (400-500)	253N 72S	407
"	"	1° (487-505)	"	170N 95S	497
"	"	7° (505-745)	14 1/2° (500-700)	17N 34S	505

(1)	(2)	(3)	(4)	(5)	(6)
C-D	CD 8	7°(505-745)	14 1/2°(500-700)	32N 100S	745
"	CD 9	8° (200-500)	8° (200-500)	50N 100S	190
"	"	"	"	83N 134S	223
"	"	"	"	100N 175S	325
"	"	"	"	242N 162S	462
"	"	"	"	275N 173S	500
"	"	1/2° (545-565)	6 1/2°(500-700)	145N 240S	545
"	"	5° (565-683)	"	265N 160S	565
"	"	3° (683-762)	"	40N	683
D-E	DE 1	5° (592-670)	13° (300-600)	167N 390S	592
"	"	"	7° (600-700)	30N 450S	670
"	"	1/2°(670-680)	"	22N 479S	680
"	DE 2	7° (543-650)	21 1/2°(300-600)	300N 120S	543

(1)	(2)	(3)	(4)	(5)	(6)
D-E	DE 2	1° (650-680)	3° (600-700)	30S 50N	650
"	"	"	"	50N 30S	680
"	DE 3	"	9° (482-651)	236S	482
"	DE 4	12° (250-440)	30° (200-400)	45E 25W	170
"	"	"	"	102SW 105SE	702
"	DE 5	19° (100-400)	34° (100-300)	20N 50S	90
"	DE 6	8 1/2°(200-600)	14° (100-500)	117SW 165NE	175
"	"	"	"	255NE 234SW	270
"	"	"	"	225N	310
"	"	"	"	80N 400S	443
"	"	"	"	100N 218S	600
"	"	"	"	105NE 102SW	702

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REFERENCES

- Angenieux, J. , 1951. "Une combinaison de mouvements verticaux et de mouvements tangentiels dans l'evolution structural du Liban". Soc. Geol. France, B. S. 6, t. 1, 4-6, pp. 285-301.
- Athearn, W. D. , 1951. "Bathymetry of the Straits of Florida and the Bahama Islands. Part II: Bathymetry of the Tongue of the Ocean, Bahamas". Bull. Marine Science of the Gulf and Caribbean, vol. 13, no. 3, pp. 365-377.
- Baker, N. E. , and Henson, F. R. S. , 1952. "Geological conditions of oil occurrences in Middle East fields". Bull. Amer. Assoc. Petrol. Geol. , vol. 36, no. 10, pp. 1885-1901.
- Ball, M. W. , and Ball, D. , 1953. "Oil prospects of Israel". Bull. Amer. Assoc. Petrol. Geol. , vol. 37, no. 1, pp. 1-63.
- Blanckenhorn, M. , 1914. "Syrien, Arabien, und Mesopotamien". Handb. d. regionalen Geologie, vol. 4, H. 17.
- Blondel, F. , 1951. "Les travaux géologiques de L. Dubertret en Syrie et Lebanon". Int. Geol. Cong. , 18th (Gt. Britain), Rept. pt 14, p. 28.
- Boulos, I. , 1962. "Carte de reconnaissance des cotes du Liban, 2nd ed." Bassile Freres, Beyrouth. 1:150,000, 2 sheets.
- Bunce, E. , and Hersey, J. B. "Continuous Seismic Profiles of the Outer Ridge and Nares Basin North of Puerto Rico". In preparation.

- Caulfield, D. D. , 1962. "Predicting sonic pulse shapes in underwater spark discharges". *Deep-Sea Res.* , vol. 9, pp. 339-348.
- Caulfield, D. D. , Hartley Hoskins, and R. T. Nowak, 1965. "Improvements in the continuous seismic profiler". *Geophysics*, vol. XXX, no. 1, pp. 133-138.
- Curry, D. , J. B. Hersey, E. Martini, and W. F. Whittard, 1965. "The geology of the Western approaches of the English Channel. Part II: Geological Interpretation aided by boomer and sparker records". *Phil. Trans. Roy. Soc. Lond.* , Series B, vol. 248, no. 749, pp. 315-351.
- de Boer, J. , 1965. "Paleomagnetic indications of megatectonic movement in the Tethys". *Jour. Geophys. Res.* , vol. 70, no. 4, pp. 931-944.
- Diener, C. , 1886. "Libanon". Wien, A. Holder, 412 pp.
- Dietz, R. S. , 1952. "Geomorphic evolution of the continental terrace (continental shelf and slope)". *Bull. Amer. Assoc. Petrol. Geol.* , vol. 36, pp. 1802-1819.
- Dietz, R. S. , 1963. "Wave-base marine profile of equilibrium, and wave-built terraces: a critical appraisal". *Bull. Geol. Soc. Amer.* , vol. 74, no. 8, pp. 971-990.
- Dietz, R. S. , 1964. "Origin of continental slopes". *American Scientist*, vol. 52, pp. 50-69.

- Dietz, R. S. , and H. W. Menard, 1951. "Origin of abrupt change in slope at continental margin". Bull. Amer. Assoc. Petrol. Geol. , vol. 35, pp. 1994-2016.
- Dill, R. F. , 1964. "Contemporary submarine erosion in Scripp's submarine canyon". Doctoral dissertation, Univ. of California, San Diego.
- Drake, C. L. , and R. W. Girdler, 1964. "A geophysical study of the Red Sea". Geophys. Jour. Roy Astron. Soc. , vol. 8, no. 5, pp. 473-495.
- Dubertret, L. , 1933. "Le Miocene en Syrie et Liban". Haut-Commissariat de la Rep. France en Syrie et Liban, Serv. Trav. Pub. , Sec. d'Etudes Geol. , Notes et Mém. , t. 1, pp. 61-182.
- Dubertret, L. , 1947. "Problemes de la geologie du Levant". Bull. Soc. Geol. France, s. 5, t. 17, pp. 3-31.
- Dubertret, L. , 1949a. "Carte géologique au 50,000; feuille de Saida". 1 sheet with accompanying text, 43 pp, Lebanon, Min. Trav. Publics, Beyrouth.
- Dubertret, L. , 1949b. "Carte géologique au 200,000; feuille de Tripoli". 1 sheet with accompanying text, 64 pp.
- Dubertret, L. , 1954. "Carte geologique au 200,000; feuille de Beyrouth". 1 sheet with accompanying text, 104 pp.

- Emery, K. O., and Y. K. Bentor, 1960. "The continental shelf of Israel". Israel Geol. Survey. Bull., No. 26, pt. 2, pp. 25-41.
- Emery, K. O., and Carl George, 1963. "The beaches of Lebanon". Woods Hole Contr. No. 1385, 17 pp.
- Emery, K. O., B. C. Heezen, and T. D. Allan. "Bathymetry of the Eastern Mediterranean". In press, Roy. Astron. Soc. (pre-publication version).
- Emery, K. O., and D. Neev, 1960. "Mediterranean beaches of Israel". Israel Geol. Survey Bull., no. 26, pt. 1, pp. 1-25.
- Ericson, D. B., M. Ewing, and B. C. Heezen, 1952. "Turbidity currents and sediments in the North Atlantic". Bull. Amer. Assoc. Petrol. Geol., vol. 36, pp. 489-512.
- Ericson, D. B., M. Ewing, G. Wollin, and B. C. Heezen, 1961. "Atlantic deep-sea sediment cores". Bull. Geol. Soc. Amer., vol. 72, pp. 193-286.
- Ewing, J. I., 1963. "Elementary theory of seismic refraction and reflection measurements". In The Sea, M. N. Hill (Ed.), vol. 3, Interscience-Wiley, New York, pp. 3-19.
- Ewing, M., and B. C. Heezen, 1960. "Continuity of the Mid-Oceanic ridge and rift valley in the southwestern Indian Ocean confirmed". Science, vol. 131, pp. 1677-1679.

- Gibert, André, 1949. "Notes sur la géographie du Proche-Orient; 3: sur la structure du pays Levant". Rev. Géog. Lyon (Études Rhodan.), vol. 24, no. 3, pp. 279-286.
- Guilcher, A., 1963. "Continental shelf and slope (continental margin)". In The Sea, M. N. Hill (Ed.) vol. 3, Interscience-Wiley, New York, pp. 281-311.
- Gutenberg, B., and C. F. Richter, 1941. "Seismicity of the Earth". Geol. Soc. Amer. Spec. Paper no. 34, p. 68.
- Harrison, J. C., 1955. "Gravity anomalies in the Eastern Mediterranean". Phil. Trans. Roy. Soc. Lond., Series A, no. 947, pp. 283-385.
- Heezen, B. C., 1956. "Origin of submarine canyons". Sci. Amer., vol. 195, pp. 36-41.
- Heezen, B. C., 1963. "Turbidity currents". In The Sea, M. N. Hill (Ed.), vol. 3, Interscience-Wiley, New York, pp. 742-775.
- Henson, F. R. S., 1951. "Observations on the geology and petroleum occurrences of the Middle East". Proc. 3rd. World Petroleum Congress, Sect. I.
- Hersey, J. B., 1962. "Findings made during the June, 1961 cruise of CHAIN to the Puerto Rico Trench and Caryn Sea Mount". Jour. Geophys. Res., vol. 67, pp. 1109-1116.
- Hersey, J. B., 1963. "Continuous seismic reflection profiling". In The Sea, M. N. Hill (Ed.), vol. 3, Interscience-Wiley, New York, pp. 47-72.

- Hoskins, Hartley, 1964a. "A primer on reflection and refraction records taken with the Continuous Seismic Profiler". Woods Hole Oceanographic Institution Tech. Memo. #12-64 (unpublished manuscript), viii + 51 p.
- Hoskins, Hartley, 1964b. "Selection and control of scale in the presentation of continuous seismic reflection profiler data". Woods Hole Oceanographic Institution Tech. Memo. #9-64 (unpublished manuscript), i + 15 p.
- Hoskins, Hartley, 1965. "Seismic reflection observations on the Atlantic continental shelf, slope and rise southeast of New England". Doctoral dissertation, Univ. of Chicago.
- Knott, S. T. , and J. B. Hersey, 1956. "High-resolution echo-sounding techniques and their use in bathymetry, marine geophysics, and biology". Deep-Sea Res. , vol. 4, pp. 36-44.
- Knott, S. T. , and Witzell, W. E. , 1960. "Instruction manual for the Precision Graphic Recorder (PGR)". Woods Hole Oceanographic Institution Reference No. 60-38.
- Krenkel, E. , 1924. "Der syrische Bogen". Centralbl. , (9 and 10), pp. 274-281 and 301-313.
- Moore, D. G. , 1961. "Submarine slumps". Jour. Sed. Petrology, vol. 31, no. 3, pp. 343-357.

- Nafe, J. E. , and C. L. Drake, 1957. "Variation with depth in shallow and deep water marine sediments of porosity, density, and the velocities of compressional and shear waves". *Geophysics*, vol. 22, pp. 523-552.
- Nafe, J. E. , and C. L. Drake, 1963. "Physical properties of marine sediments". In *The Sea*, M. N. Hill (Ed.), vol. 3, Interscience-Wiley, New York, pp. 794-815.
- Officer, C. , 1958. "Introduction to the theory of sound transmission". McGraw-Hill, New York, p. 78.
- Renouard, G. , 1956. "Oil Prospects of Lebanon". *Bull. Amer. Assoc. Petrol. Geol.* , vol. 39, no. 11, pp. 2125-2169.
- Roberson, M. I. , 1964. "Continuous seismic profiler survey of Oceanographer, Gilbert, and Lydonia Canyons, George's Bank". *Jour. Geophys. Res.* , vol. 69, no. 22, pp. 4779-4789.
- Shepard, F. P. , 1952. "Composite origin of submarine canyons". *Jour. Geol.* , vol. 60, no. 1, pp. 84-96.
- Shepard, F. P. , 1963. "Submarine Geology". 2nd ed. , Harper and Row, New York.
- Shor, G. G. , 1963. "Refraction and reflection techniques and procedures". In *The Sea*, M. N. Hill (Ed.), vol. 3, Interscience-Wiley, New York, pp. 20-38.

Shumway, G. , 1960. "Sound speed and absorption studies of marine sediments by a resonance method, Part II. ". Geophysics, vol. 25, no. 3, pp. 659-682.

Terzaghi, K. , 1956. "Varieties of submarine slope failures". Proc. 8th Conf. on Soil Mech. , Spec. Publ. No. 29, Univ. of Texas, 41 pp.

Vaumas, E. de, 1947. "Sur la structure du Liban". C. R. Acad. Sci. , t. 226, no. 25, pp. 2166-2168.