ANALYSIS OF CONTINUOUS SEISMIC PROFILES

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ABSTRACT

The sequence of operations called continuous seismic profiling is as follows. At a given position, aboard a vessel underway, a short elastic pulse is transmitted through the water, then the echo from the bottom and the elastic discontinuities of the subbottom are received and are amplified and filtered. Next these are inscribed on the paper record, and all these processes are then repeated several times per second or per minute. J.B. HERSEY has pioneered this method which yields a time section of the substrata, and its use is becoming increasingly widespread.

The resolution of a seismic signal depends on the transmitter's frequency band B and its energy — i.e. its penetration — on the signal length T and on the characteristics of the instrument. In general signals in the form of pulses are used. Relation $BT = 1$ means that we only obtain a resolution of less than 2 % of the penetration. Furthermore, the depth of the emitter and the receiver, as well as the sequence of the substrata reflectors, filter the signal which is moreover partially absorbed by the soil. The characteristics of the sound sources will therefore be chosen in function of the result desired, that is, either a deep penetration and weak resolution or else the reverse, or again a compromise between the two solutions. Electronic noise from the bottom, noise from the sea, the hydrodynamic noise arising from the movement of the receiver, and the noise of the instrumented boat, all such interference can be reduced.

For the geophysicist the most important task is to achieve a good record. It is not simple to put to sea again. Therefore every care has to be taken to see that the work at sea is well done. Back on land and well rested, the analysis of the records is undertaken.

The seismic signal reflected by a particular reflector has well marked and individual characteristics that are functions of the geology of the subbottom. An analysis of the character of the reflection makes it possible to distinguish between the various reflectors and to follow them throughout the whole study. Distinguishing between the different types of character and studying the shape of the reflections, we are able to recognize the

geologic characteristics of the formations we have encountered. This, in effect, is tectonic analysis.

In order to be able to interpret the profiles the velocity of propagation of elastic waves in the subbottom must be known. At sea there are hardly any possibilities for drilling to achieve such measurements. Although we may succeed in measuring the velocity in unconsolidated sediment by various methods, we are generally obliged to use data from refraction measurements for the deeper layers, and these do not always yield valid results by reason of the lateral heterogeneity of the subbottom. Making these refraction measurements at sea is difficult.

The interpretation is carried out in various different ways depending on the object of the study.

INTRODUCTION

The sequence of operations called continuous seismic profiling is as follows. At a given position, aboard a vessel underway, a short elastic pulse is transmitted through the water, then the echo from the bottom and the elastic discontinuities of the subbottom are received and are amplified and filtered. Next these are inscribed on the paper record, and all these processes are repeated several times per second or per minute. Today this is the most widely used method for the exploration of the undersea subbottom on account of the easiness of the work, its adaptability, and the simplicity with which the document suggesting a geologic section may be interpreted.

The method is a recent one, pioneered by HERSEY (1963). Since the first experiments were made in 1955 the development of continuous seismic profiling has been uninterrupted and the proliferation of instruments considerable. Although the instruments used by the different operators may have varied characteristics, the principles of the analysis do not change. These principles are part of the store of knowledge of large research teams. I am here giving an account of the experience I have acquired during several years of research and of contact with various groups, some already experienced, others newly formed. I shall describe in broad outline the method of working permitting the best advantage to be taken of the records made at sea.

Obviously the majority of examples refer to the Western Mediterranean, and they are geologically valid only for this small region. Their morphologic value is however general.

I. — THE RECORD

A. — Principle

From the viewpoint of elasticity the subbottom can be considered as a succession of interfaces. The layers separating these interfaces are characterized by their acoustical impedance. Acoustical impedance is the product of the medium's density and the velocity of propagation of compressed elastic waves in this medium. Density and velocity are functions of the water content and of the specific density of the constituent minerals. The velocity also varies with the size and the arrangement of the particles, that is, of the texture of the rock formation of the environment.

Continuous seismic profiling uses a signal in the form of a pulse that is propagated vertically. At each interface one part of its energy is reflected and the other is transmitted. The acoustical impedance of each layer and its thickness determine a characteristic pattern for each reflection, and this we shall call its character. The waves returning to the surface are picked up by a receiver which transforms the acoustic pressure variations into electric voltage and registers them. The resulting record is the basic document.

An emitted seismic signal is characterized by its frequency band B. In the impulse mode band B is tied to the length T of the signal by the relation $BT = 1$. Thus the length T of the signal characterizes the resolution obtained, i.e. the "resolving power" of seismic profiling (*).

The emitted seismic signals undergo two types of filtering in the subbottom. One arises from the arrangement of the interfaces in relation to each other and is comparable to the filtering resulting from the depth of the emitter under the surface. (See below). The other results from the absorption of the seismic signal by the subsoil, this absorption varying in function of the frequency (**). Furthermore, the signal loses its energy during its downward and its upward path. The penetration of the signal — the second characteristic of practical importance — is therefore a function of its energy and of its frequency spectrum.

The ideal seismic equipment will consist of :

a) A transducer producing a signal of very short length and of very powerful energy;

b) A receiver that selectively receives the reflected signal which is propagated vertically, but not the noises that are principally horizontal;

(*) This question can be treated mathematically reckoning from the Dirac signal. A complete account would fall within the scope of the theory of information.

(**) At a first approximation let us consider that the absorption varies with the square of the frequency.

c) A recorder that does not introduce disturbances into the sequence of reflections.

All the operations carried out at sea are basic. The choice of equipment and vessel, the plotting of the track which must take account of the operation's objectives as well as the wind and the sea state, the rate at which the emission is repeated, the depth of both emitter and hydrophone, the ship's speed, all these are necessary factors for obtaining a good record. Work at sea is an irreplaceable exercise, and to put to sea again is far from easy.

In practice we are limited in the development of our equipment by various contingencies. Let us now see how this is chosen.

B. — Emission

1. *Concept*

The emitter is characterized by its energy and its frequency spectrum. To a certain extent an increase in energy entails augmenting the signal length. The spectrum of the frequencies emitted depends largely on the way in which the emitter is constructed. The choice of emitter will therefore be dictated by the aims we have in mind.

If a device could deliver a large energy within a short time and over a wide spectrum it would allow deep penetration and good resolution would be obtained. In actual practice, however, we are obliged to use solutions that are compromises.

For deep penetration, therefore, it is preferable to use an emitter with its energy concentrated in the low frequencies. The signal length, and consequently the resolution, is of secondary importance. On the other hand, for the study of the upper layers much detail is desirable. First of all the signal length is reduced. Since the frequency increases, it becomes materially easy to use directional emitters in place of omnidirectional ones. In this way an increased efficiency is attained.

When penetration to a certain degree is desired, but without in any way neglecting the upper layers, we seek an emitter with a wide spectrum — and this solution is a compromise.

2. *Use*

In the case of omnidirectional emitters the depth H_x of the emitter under the surface plays a role. The signal rising upwards to the surface is reflected with a sign change and is added to the emitted signal after a delay of $t = 2\,H_x/V_e$, V_e being the water velocity. If $2\,H_x = \lambda/2$, the frequency $f = \lambda/V_e$ is intensified. By a judicious choice of emission depth we may favour one frequency, in general the lowest (figure 1). At the time of reception the hydrophone depth plays the same role.

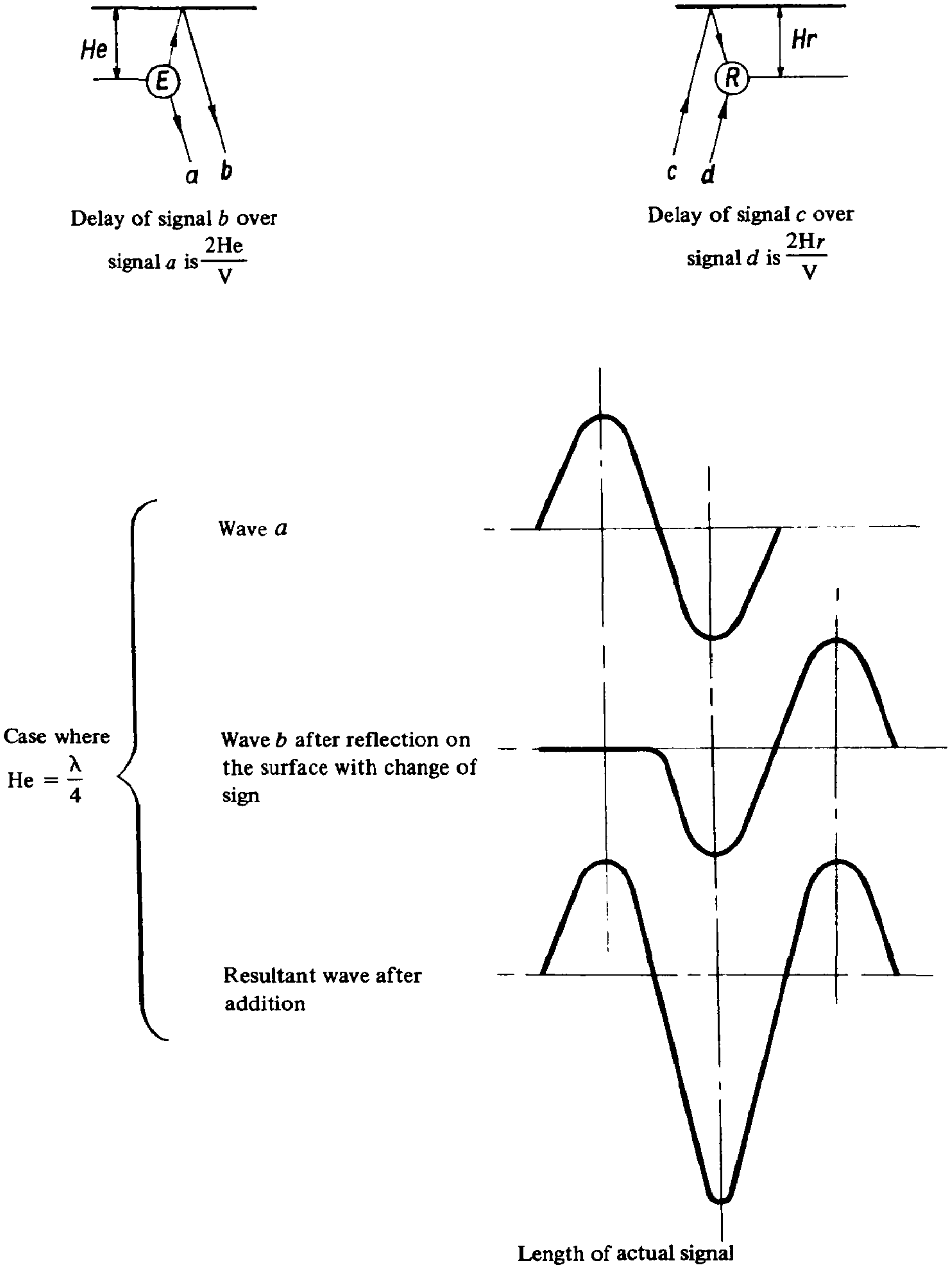


Fig. 1. — Actual signal length.

Top : signal *a* is the signal emitted by the seismic instrument. $a + b$ is the signal transmitted downwards and which after being reflected becomes signal *c*.

The actual signal is the combination of this signal *c* with signal *d* (which is deduced from *c* by means of reflection with a sign change and a delay in the same way as *b* was deduced from *a*).

Bottom : the filtering effect due to the depth of the emitter or the receiver.

3. *Influence on resolution*

Resolution is measured by the length of the seismic signal. The better the resolution, the briefer the signal and the closer are the two distinct reflectors. The seismic signal is made up of :

a) The signal from the emitter, its length characterizing the emitter;

b) Reflected signals whose length is dependant on the depth of the emitter (and the hydrophone) since this same reflected signal, after a sign change and with a delay of $2\ H_e/V_e$ (and of $2\ H_r/V_e$), is added to the emitted signal.

It can be seen that the operating depth of the emitter and of the receiver influences the resolution considerably.

C. — Reception

We endeavour to obtain as highly sensitive and accurate receivers as possible — that is those capable of transmitting even very weak waves without distortion. Obviously these qualities must be selectively applied as far as possible to the seismic signal containing the desired information and not to any surrounding noise, which may in any case be eliminated by mean of devices.

1. *Noises*

We shall now consider the following, given in the order of the importance of their inconvenience :

(a) Background noise in the electronic receiver;

(b) Background noise from the sea;

(c) Hydrodynamic noise created by the receiver moving in the water;

(d) Noise of the instrumented boat.

(a) The electronic background noise is a function of the receiver's principle of construction and of the way in which the first stage of amplification is carried out. In modern equipment this background noise should be negligible.

(b) The noises from the sea decrease by 6dB per octave when the frequency increases (Guieysse and Sabathe). Sometimes the marine fauna create considerable noise. Certain morphologic profiles (the Lake of Geneva is an example) give rise to successive echoes and are therefore noisy. Meteorologic conditions play a predominant role, noises due to wind creating the principal difficulties (*).

(*) Although, for studies of shallow and highly reflecting seabeds it would be preferable to work when there is a choppy sea with short waves. The surface then no longer acts as a mirror for the seismic waves but rather as a diffuser, and the multiple reflections are considerably diminished.

(c) The noise created by the movement of the receiver in the water depends on how the instrument is streamlined as well as on the towing speed.

The sea state is also a factor as it gives rise to related movements. This noise when created at the level of the sensor can be catastrophic. It is only recently that the importance of the profiling of the hydrophone has been fully realized, although its interest became apparent much earlier.

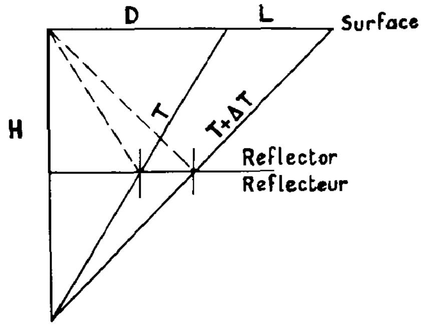
(d) The ship noise has two components :

1. A spectral lines noise transmitted towards the ship's stern. This noise is due to the vibrations of the motor and the hum of the propellers.
2. The noise from the wake which is a function of the hydrodynamics of the hull and of the ship's speed.

In fair weather therefore, and with a streamlined receiver, only the ship noise remains really troublesome.

2. *Filtering*

Ship noises for the most part propagate horizontally, whereas the signal travels vertically. The principles of spatial filtering are conditioned by the theory of antennae, leading us to multiply the sensors, thereby constructing elongated hydrophones. The lengthening of the hydrophone, however introduces a certain loss of resolution.



$$(T + \Delta T)^2 = H^2 + (D + L)^2$$

$$T^2 = H^2 + D^2$$

$$2T\Delta T + \Delta T^2 = 2DL + L^2$$

If $\Delta T = 1$ $\quad \Delta T^2$ negligible

$$D = \frac{T}{L} - \frac{L}{2}$$

FIG. 2. — Relation between the depth T to be sounded, the distance D from emitter to receiver, the length L of the hydrophone and the loss ΔT in resolution.

Let H be twice the depth of the water or target, and D the distance from the emitter to receiver, L being the length of the receiver, T the length of the oblique path of a ray reflected from the emitter to the point on the receiver nearest the emitter, and ΔT the increase in the length of path T to reach the point on the receiver furthest from the emitter (figure 2).

H, D, L, T and ΔT being expressed in the same unit — i.e. either all in time or all in length — the relation

$$D = \Delta T \frac{T}{L} - \frac{T}{2}$$

allows us to fix — for a given T — the magnitude of D and of L in function of T. Taking L as parameter, and with ΔT = 1, we obtain a family of straight lines. Below a straight line corresponding to a given value of L, the loss of resolution (ΔT) is less than 1, but above this line the loss is more than 1 (figure 3).

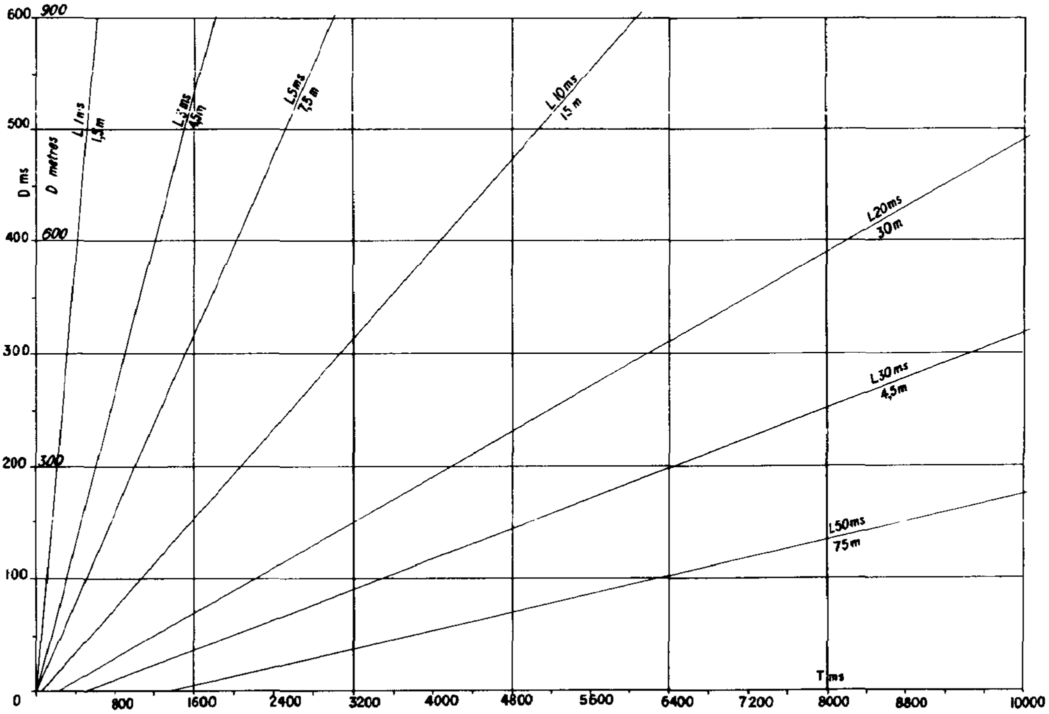


Fig. 3. — Maximum distance D of the tow in relation to T and L in order to retain a resolution of 1 ms.

If a loss of resolution of *k* is entailed it will be necessary to modify the scale T (*) accordingly. (That is, to use T/*k*).

D. — The record

Magnetic records allow the use of data processing techniques and in particular there is a resulting increase in the signal to noise ratio. Much work has been done on this subject, but this is not here my problem. At

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(*) It is not possible to introduce H on the graph because this varies with T and D. *As the depth is not constant, T is chosen at a minimal value in relation to H.*

the present time a magnetic record does not allow a directly visible record to be of more than a few minutes' duration. However, it is thanks to this record that we able to retain in entirety the raw information gathered at sea. Seismic profiling is a repetitive operation. Each operation is inscribed on the paper width in the form of a dash, and the various dashes are lined up vertically alongside each other. Each dash will be either lighter or darker according to the variations in amplitude of the hydrophone voltage after filtering and amplification (figure 4).

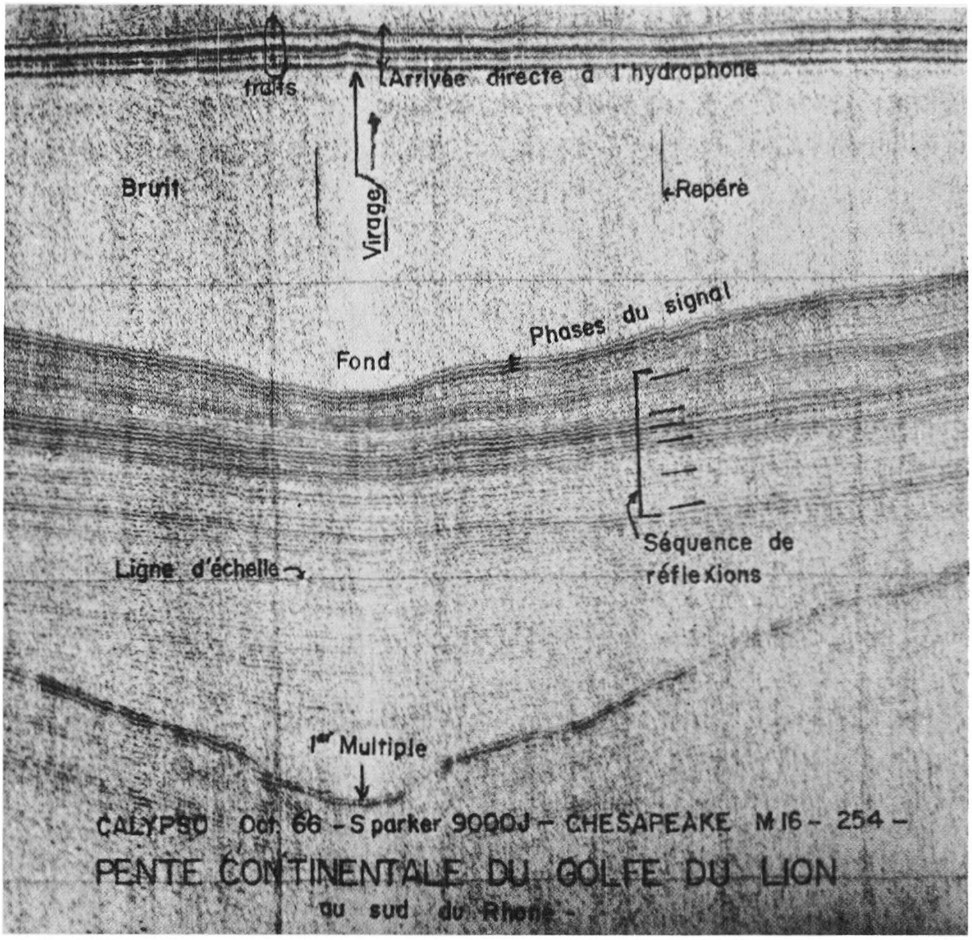


Fig. 4. — Description of a record.

The reflections are therefore denoted by short, dark segment marks which line up beside each other. The visual integration effect allows us to distinguish these segments from noise which is chiefly distributed in a random manner.

A record is made up as follows. The paper unrolls from left to right and, reading from top to bottom, we first observe a straight line that corresponds to the time of transmisison. This is coincident with a scale line or is noted by the induction effect. (This line is not visible on figure 4). Then there is a series of parallel lines representing the signal's direct arrival at the hydrophone. The interval between the time of the emission and the signal's arrival at the hydrophone represents the distance of the emitter to the receiver. Non-constant intervals express variations in the distance of the emitter to the hydrophone (at the time of the turn round). This direct arrival does not exist on mud pinger probes where emitter and receiver are combined in the same instrument. Next comes the bottom, and reflections from the underlying strata, and finally sometimes also multiple echoes from the bottom. A simple diagram will show that the double echo from the bottom is at twice the depth that indicated the bottom. The slope of the false bottom shown by the double echo will be magnified by a factor of two in relation to the value of the true bottom slope.

The greater the scale of the record the easier it is to read. The programming of the record (ALDEN and FARRINGTON) is a procedure allowing enlargement of the interesting portions of the record as well as the elimination of parasite reflections that arise outside the desired time interval (i.e. the Deep Scattering Layer, multiple reflections, etc.).

The record paper must be of good quality as regards dynamics (i.e. its sensitivity). Between the threshold of writing and the point that the paper burns the variation in voltage of the signal amounts to at least 24 dB. Digital recording techniques, however, make it possible to go well beyond this.

E. — Remarks

We shall now deal with several other points.

The problem of positioning is assumed as having been already solved.

When plotting the profiles we must systematically seek the greatest possible number of intersections. This permits the establishment of a grid according to the topographic method, and a check of the soundings against each other. A cross section of the profile appears contrary to usual hydrographic practice, but for the geophysicist this cross section is absolutely essential.

For the illustration given, the instruments used were for the most part of Edgerton, Germeshausen and Grier manufacture.

In conclusion — a quick look at the record enables us to judge the quality of the sounding and is a guide for the continuation of the work. Once this work has been effected and the essential document obtained (i.e. the record made aboard ship) the subsequent operations in general take place ashore. In the first place comes the analysis.

II. — ANALYSIS OF THE CHARACTER

The galvanometers formerly used registered the amplitude of the received waves. On present-day electro-chemical records the amplitude is shown only by the degree of darkness of the mark of the reflection. Furthermore, interference is often not very visible on these records, and thus a considerable part of the recorded information is lost. Against this can be set the ease and rapidity of the method.

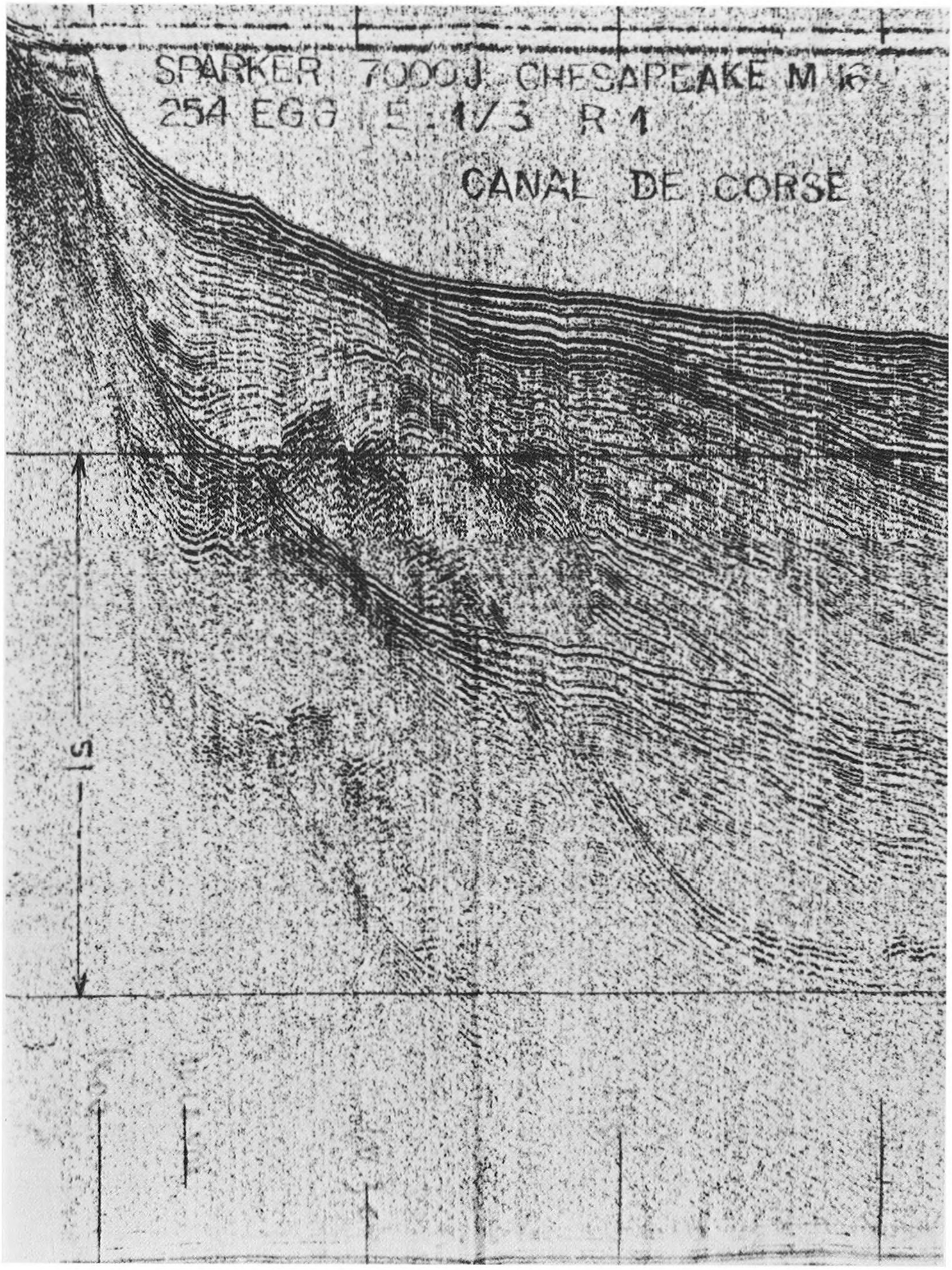


FIG. 5. — High and low frequencies on a record.
Sparker section East of Bastia (*Winnaretta Singer,* February 1967).
The double echo has a lower frequency than the reflections from the upper layers of sediment. A particularly clear-cut bevel in the unconsolidated sediment can also be seen as well as the broken aspect of the Corsican basement which is faulted, with a lowering of the eastern portion.

A. — The character of the reflection

The seismic signal pattern peculiar to a given reflector characterizes the reflection, and enables the different reflections to be identified. The pattern, however, is not always clear, and we must be able to recognize it.

For his study of the character of a reflection QUARLES based himself on the following suppositions :

1. Most stratified terranes are relatively homogeneous both in thickness and, laterally, in composition. A lithographic variation conveys a change of character.
2. Each layer or sequence of layers reflects a wave of a particular and characteristic shape, resulting from the layer's thickness, its composition and its other physical properties.

The significant reflections are therefore to be recognized by their particular appearance and their lateral continuity. Their characterizing factors are their amplitude, frequency and sequence which represent the physical properties of a particular arrangement of strata.

A large variation in elastic impedance to either side of the reflector is shown by an elastic wave of important amplitude and by a larger dark trace on the record.

The wave frequency is registered by the time interval separating the successive dark lines on the record. This frequency arises from the particular characteristics of the layers and from the contrast in impedance between two adjacent layers.

When several successive reflections are not in phase with the dominant one this shows up as additional waves, giving the impression of high frequencies on the graphic record.

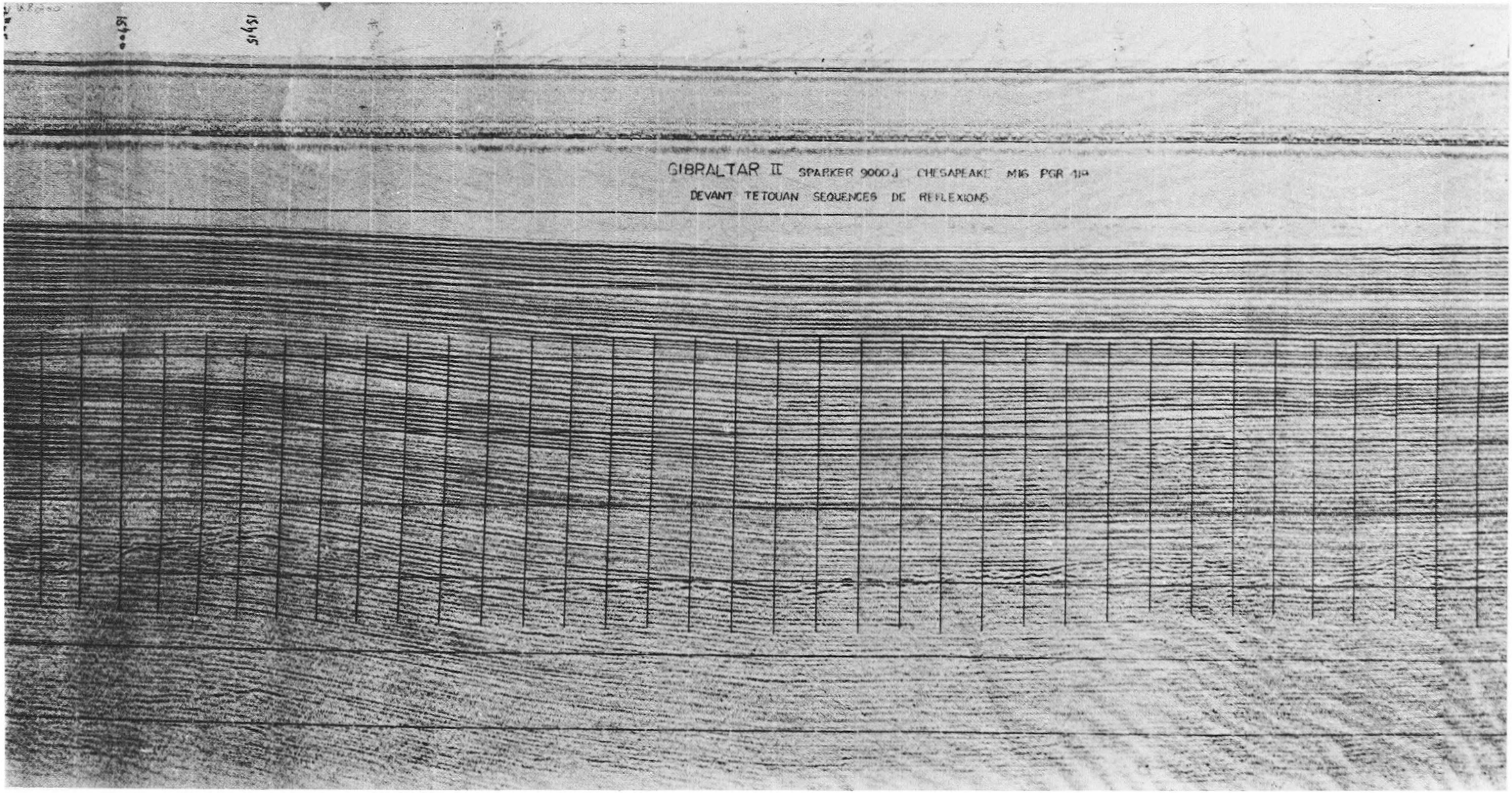
I mean by sequence of reflections a series of reflections that are particularly constant in space. Determining a sequence (*) amounts to correlating throughout a profile two or more series that are stable in character, that is of constant amplitude and frequency and with a constant interval of time. This last criterion is not always infallible for it presupposes that the thickness of the geologic terrane which the sequence represents is constant over a wide area (figure 6).

(*) The sequence must not be confused with the signal proper which is composed of a succession of from 2 to 4 (or more) lines on the record, the number varying according to the quality of the instrument.

FIG. 6. — Sequence of reflections.

The effective signal is made up on the bottom of a light line and two dark lines, but in the substrata only the dark lines come out clearly. Near the bottom of the figure the reflections follow one another regularly. A very slight pinch on the left has sometimes given rise to additions to the signals which seem to be of high frequency.

Lower down, an antipliocene reflector is observed. This photograph (*Charcot*, October 1967) is a typical example of the regular sedimentation all along the Rif coast. (Vertical scale 250 ms between the scale lines).



15h00
15h15
15h30
15h45
GIBRALTAR II SPARKER 9000 J CHESAPEAKE M16 PGR 1/2
DEVANT TETOUAN SEQUENCES DE REFLEXIONS

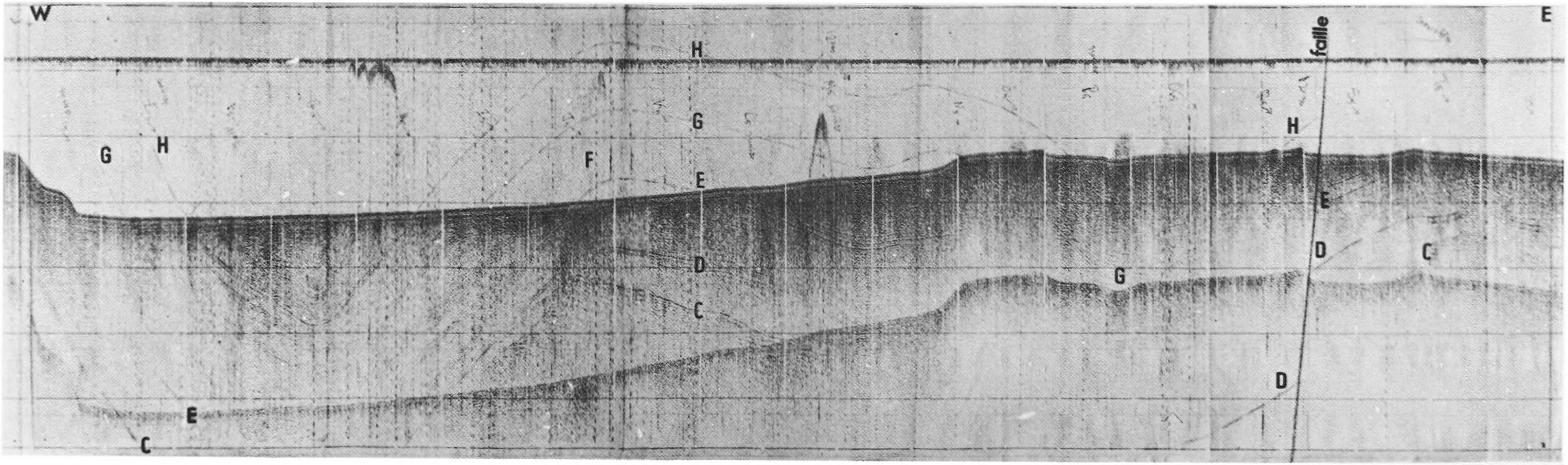


FIG. 7. — The character of the horizons on the Monaco Shelf. (Boomer section, 1965).

In general it will only be necessary to take a quick look at the record to check the clear-cut reflections and the notable sequences.

Where the reflection appears typical the description of the character of each separate reflection is noted in a simple but detailed manner. These reflections are plotted on the record or on a good duplicate of it. It is always the first phase of a reflection that is plotted since this is the one measuring the transit time to the reflector. In this way we can follow the principal reflectors laterally along the profiles, and from one profile to another at their intersection. The various reflectors can be distinguished vertically.

The absence of continuity in the character of a reflection, in other respects well defined, is essentially caused by geologic variations. There may be either a slow and gradual loss of standard characteristics, implying a bevel, or a lateral alteration of the facies, or else an abrupt break in a reflection, indicating respectively a geologic fault, unconformity or truncation. In the first case the reflection is likely to be seen again at a different level, allowing identification of the irregularity.

Example : Figure 7 was taken near Monaco. The analysis of the character of the reflections makes it possible to distinguish the horizons (*). (EDGERTON *et al.*).

C) — Used as baseline
— Irregular
— Thick
— Clear;

D) — Above the preceding
— Sometimes slightly divergent
— Fairly similar to C;

E) — At 70-80 ms above C
— Always regular
— Double mark on east side of the anticline
— Two double marks on west side of the anticline;

F) and G) — These are less characteristic;

H) — Clear and regular at 75 ms above E;

K) and L) — Less characteristic, but can be deduced from the preceding horizons by continuity, as was done for F and G;

N) — Forms a "Knee Line" at 100 ms above H.

However, the quality of the character of these reflections is not in all cases good.

B. — The different types of character

1. *Good*

Certain reflections have a typical well-marked and clear character. On the bottom, and when these are the only reflections, they represent

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(*) The surface separating two layers is called a horizon, which is synonymous with mirror.

the actual seismic signal, i.e. the simple echo from the emitter against a good reflector, and they indicate a hard bottom.

Under the bottom they show up as continuous over very large areas. They then form a clearly marked horizon. This, for example, is the case for MAUFFRET's horizon S to which I would give the following description : (See figure 10).

S) — Strong
— At about 1.5 s under the bottom, and forming broad undulations
— With three always visible phases
The first is dashed in appearance,
The other two are furthermore undulated,
Small diffractions can be observed on the third at the base of the reflection.

This reflection is encountered over considerable stretches of the Western Mediterranean.

2. *Poor*

Other reflections are more weakly inscribed, and their character is difficult to define for they have no outstanding features. The elastic discontinuity giving rise to these reflections is less marked. Some are almost entirely continuous reflections, an example being horizon G (figure 8) :

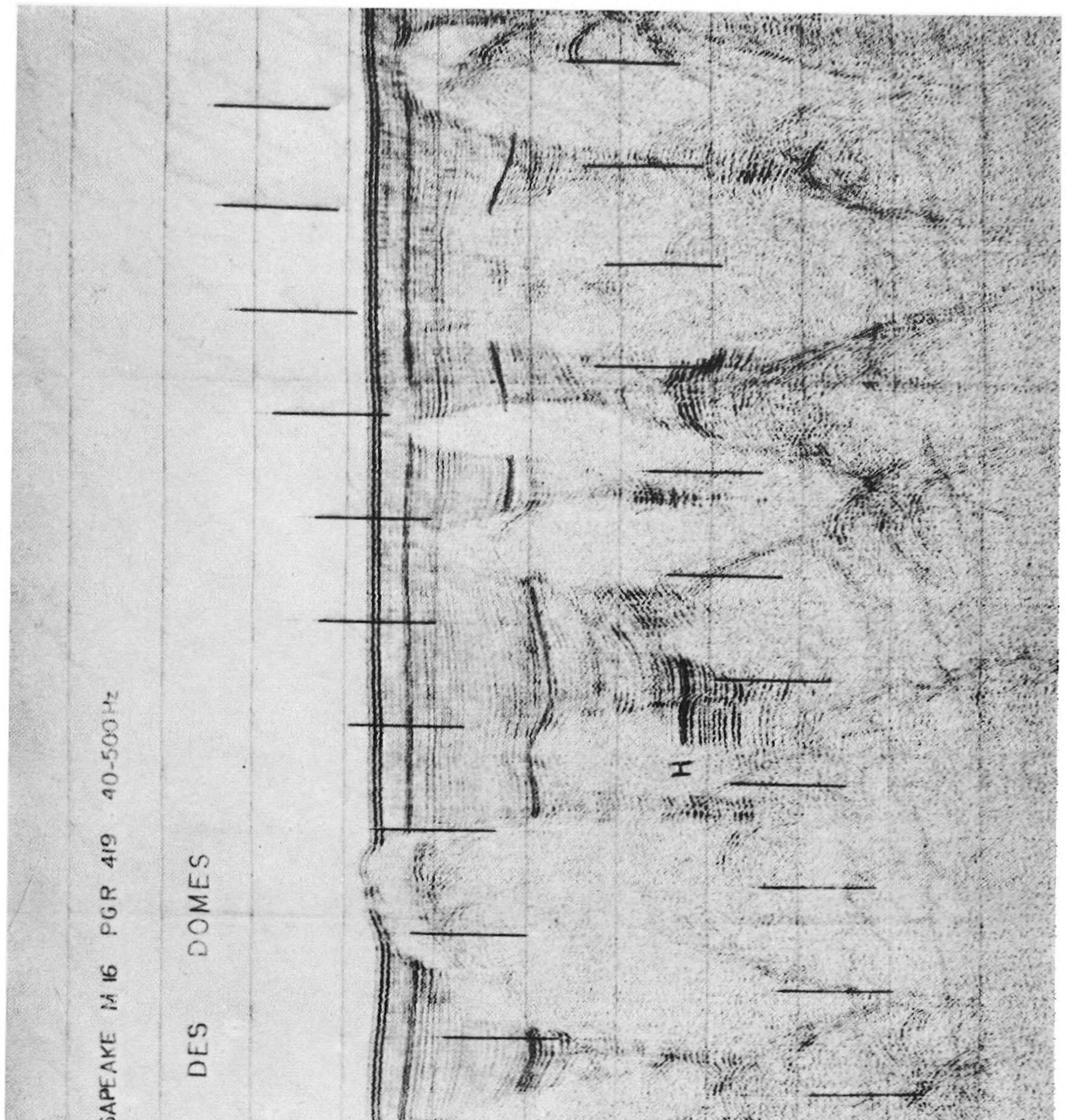
G) — Fairly strong reflection
— At about 400 ms below the bottom in the dome area
— Last reflection of the upper sequence
— Consists of two or three phases
— The frequency is not characteristic
— Softly shaped

This horizon is encountered repeatedly over almost all the abyssal plains where we have worked and it can be assigned to a renewal of sedimentation at the time of the early Quaternary.

3. *Changing*

Some reflections are abnormal and do not have a stable character : the intensity of the traces on the record, the frequency, the number of phases, these all vary. They cannot be defined in extent nor can they be of use in the interpretation except where there is a very close network of profiles. These reflections provide evidence of variable facies or thicknesses.

FIG. 8. — Horizon G in the dome area.
A typical section in the dome area, with clear cut hyperbolas.
(Sparker section, *Calypso*, March 1966).


SPARKER 9000 J CHESAPEAKE M 16 PGR 419 40-500Hz
ZONE DES DOMES
250 ms
G1
G
H

C. — Phantom horizons and multiple reflections

When the reflections are not clear cut all along the profiles we can plot a phantom horizon. This will appear on a given profile where the character is ill-defined only if the particular reflection is well determined on another profile and if the grid is closed with good agreement as regards the time of reflections at the intersections.

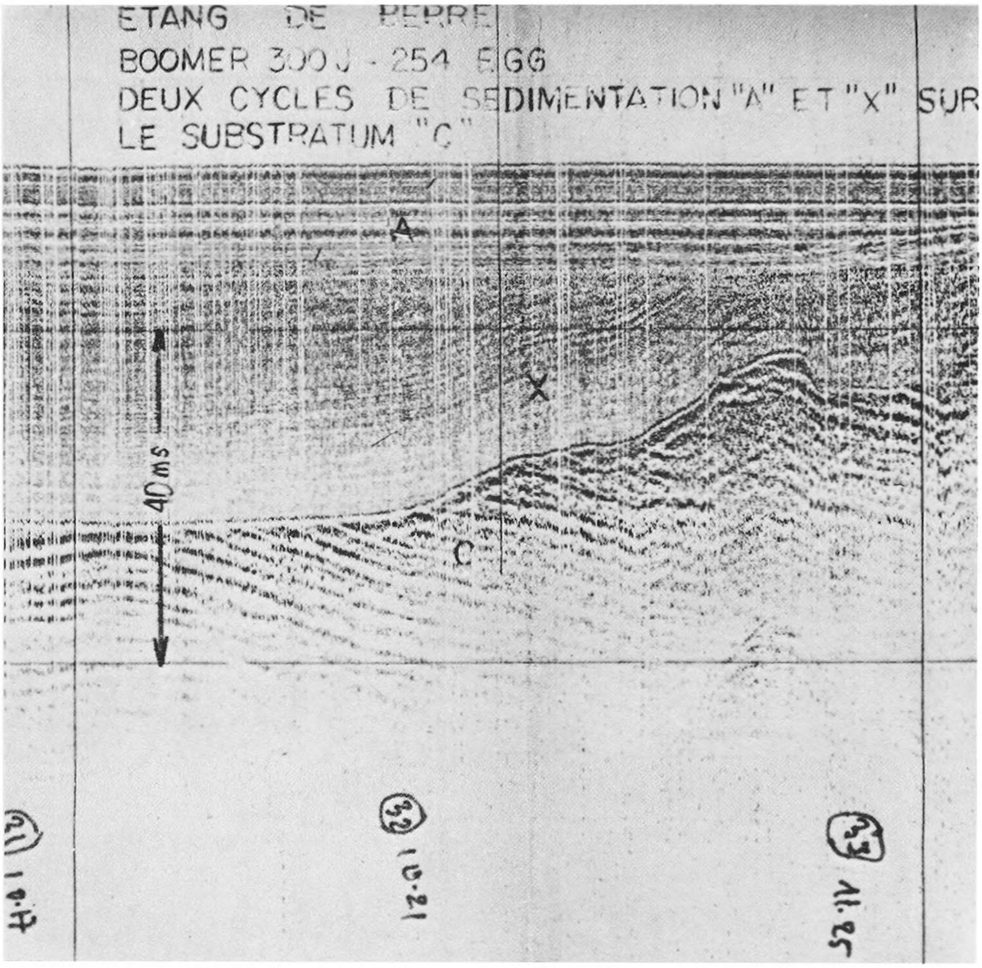


Fig. 9. — Rectilinear reflectors.

Reflector A is here strictly rectilinear, whereas the reflectors X are only warped near the upward trend of layer C taking its exact shape.

Mud probes (6 kHz) had indicated X layers, so this stretch of water was gone over again with the precision boomer, resulting in a fine example of a good record. A = Upper mud layers; X = layer of indeterminate age; C = the upper Cretaceous substrata. The flat bottom to this substrata, on the left side of the figure, was unexpected and has not yet been successfully interpreted.

(Boomer section, *Espadon*, March 1966).

By plotting we may eliminate multiple reflections, both the internal multiple reflections — i.e. those originating between two reflectors in the substrata — and multiple reflections from the bottom that arise from additional double paths of the signal between the surface and the bottom. These last are by far the most frequent, and they are particularly strong reflections since the surface of the water has a good reflecting quality, above all when the sea state is good.

In any case a multiple reflection is geometrically speaking a mirage. A study of the symmetry of reflectors makes it possible to detect the multiple reflections. The term "singing" is applied to the aspect taken on by the record when the water depth and the seismic frequency are such that at the first approximation the phenomena of multiple reflections becomes stationary. Here it is as if we were dealing with an open pipe.

III. — THE GEOMETRY OF THE REFLECTORS

The reflectors represent geologic horizons. It will therefore be useful to examine their shape as this will teach us about the tectonic structure.

A. — The different shapes of reflector

1. *Rectilinear*

Rectilinear reflectors usually reproduce roughly the shape of the bottom up to the approaches of either a basin's edge or irregularities. This is the case for nearly all the surface layers (horizon G of ALINAT *et al.*, layer X in the Etang de Berre of LEENHARDT and ROUX, etc.) (Figure 9). From the often indistinct character of the reflections, and the fact that they are straight and shallow, we conclude that we are dealing with unconsolidated and recent sediments that have not been subjected to tectonic processes and which often date from the plioquaternary era.

2. *Curved*

Curved reflectors may or may not be simple in shape.

A hard bottom provides such a reflector which is often jagged in appearance. Deeper horizons are in general more regular, some having a relatively simple curvature, others — such as MAUFFRET's reflector S — show undulations with "a wide radius of curvature" (GLANGEAUD, 1966). These horizons are in general clear cut and constant in character, and thus can be followed without difficulty. They are also at greater depths and they always indicate geologic layers that have undergone tectonic alteration. GLANGEAUD interprets horizon S as being folded Neogene. (Figure 10).

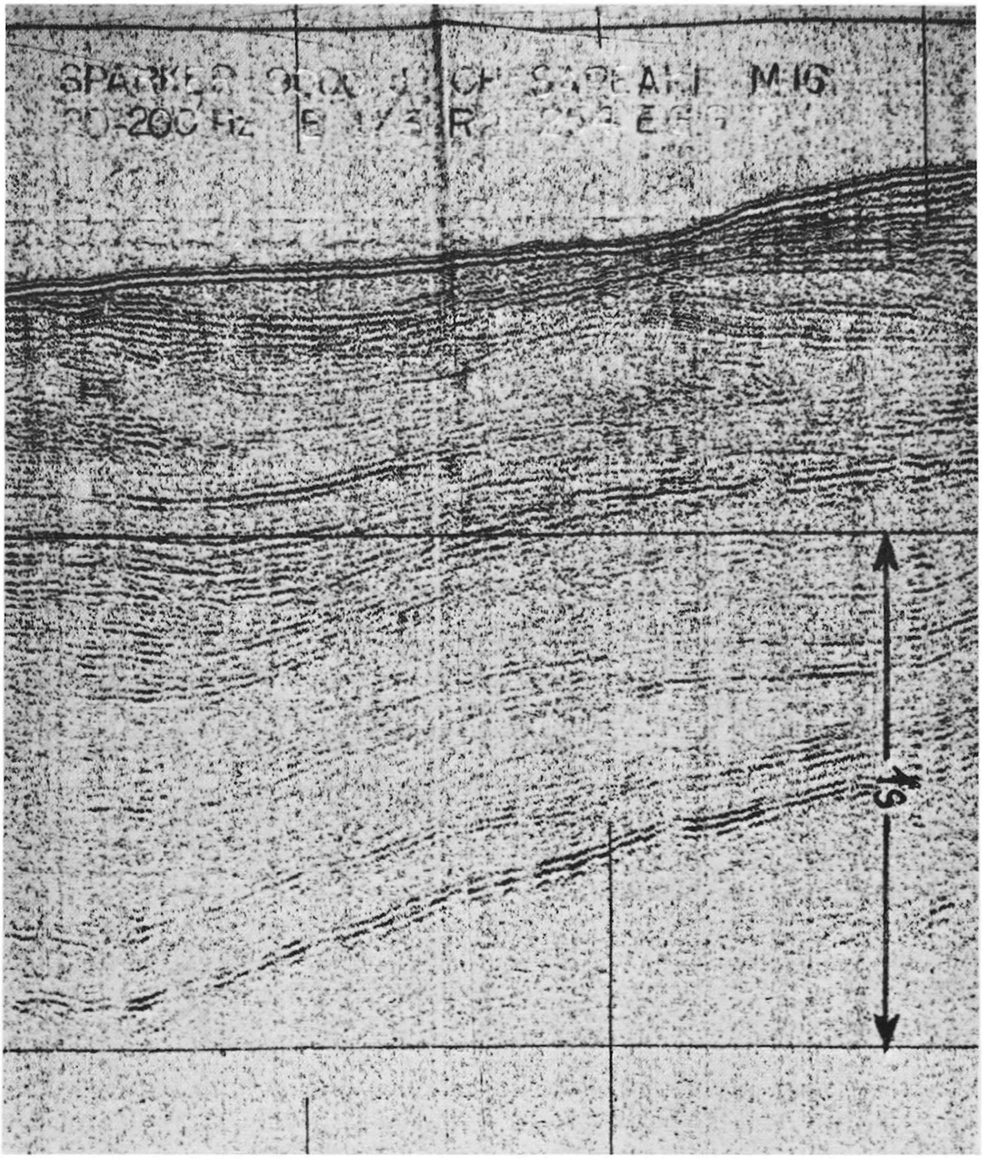


FIG. 10. — Horizon S starts to climb upwards towards Provence.

This is the deepest horizon. Very large waves can be seen in the sediment layers lying under the bevels of unconsolidated sediment at the foot of the slope.

(Sparker section, *Calypso,* September 1966).

3. *Complex*

Other reflectors, clear-cut, strong, and with good characteristics, have a more complicated pattern.

The subbottom of the Etang de Berre (Horizon C of LEENHARDT and ROUX) shows an important series of sloping reflectors, as if knife-cut horizontally.

The substrata of Planier (near Marseilles) gives rise to undulations, and these also are cleanly sliced.

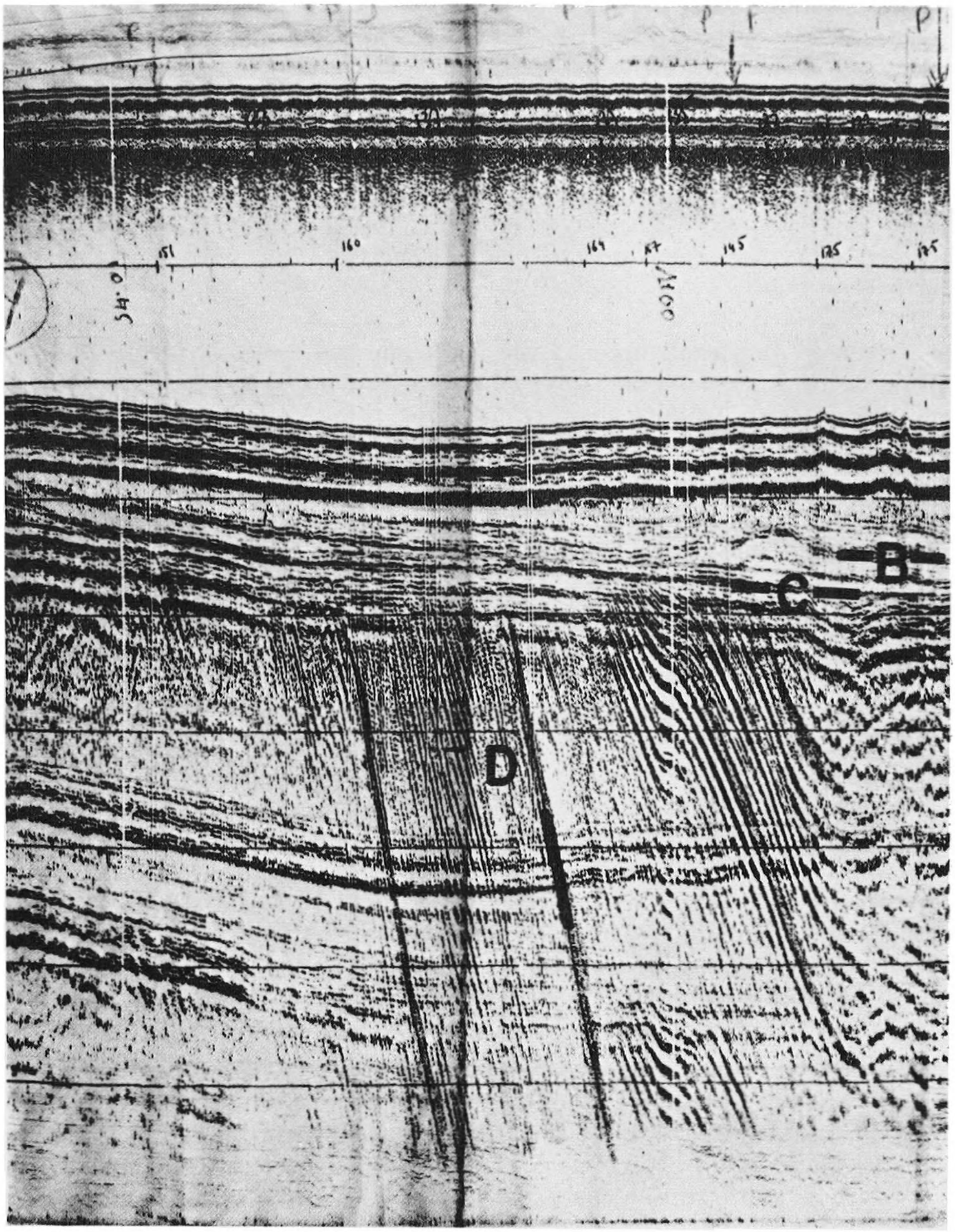


FIG. 11. — Slant of calcareous reflectors.

Here it is not a question of diffraction but of reflections over 180 ms. The apparent velocity is in fact of more than 2 500 m/s. The calcareous peak is about 170 m below the surface and the base at more than 500 m. If for this formation we adopt a 5 km/s velocity the slope will then be about 45°. The whole of the calcareous structure is levelled off.

(The Planier area, near Marseilles, sparker section 3 000 J, *Calypso,* May 1966, line Y).

In the Alboran Sea a hard and serpentine reflector shows up under the top sediments (figure 12).

In all these cases the reflector that we observed below the sediments is again visible on land or on the bottom itself. In the Alboran Sea we are dealing with volcanic structures, and this is confirmed by studies of the magnetism (GÉRARD) and of the geomorphology as well as by dredges (PFANNENSTIEL *et al.*).

These reflectors have not only undergone tectonic deformation but have also been subjected to sub-aerial erosion.

4. *Discontinuous*

Taken in the knoll area of the Ligurian Sea (zone A of GLANGEAUD), horizon H of ALINAT *et al.* is very broken, and only by its character can we interpret it (see figure 8).

Horizon C of EDGERTON, GIERMANN and LEENHARDT on the Monaco shelf has a sudden break. Its character is so clearly defined that I do not think that there is any doubt about its identification on both sides of the discontinuity. (See figure 10).

In the first of these two cases we are dealing with the effect of extrusive tectonics on a relatively horizontal horizon. In the second case we are, beyond doubt, dealing with a fault.

5. *Hyperbolic*

In certain areas, as for instance in GLANGEAUD's zone A, the hyperbolic reflections are legion and their character cannot be distinguished. Only the shape of the curves is noticeable : these are hyperbolas of diffraction. Produced by points, planes or "highlights", (see figure 8) they are due to the absence of instrumental directivity, and can be compared to hyperbolic reflections obtained from a bottom of broken rocks when echo-sounding. These reflections often provide evidence of fractures or of faults of varying importance.

Strictly speaking the signal does not propagate vertically, for the emitter is usually omnidirectional. As a result any mirror surface is to be found on the semi-ellipsoid of revolution, with the emitter and the receiver as focii. There is no geometrical means of determining the exact position of the reflector. In simple cases the analysis will enable the lateral echoes to be distinguished from the subbottom echoes. On steep slopes, however,

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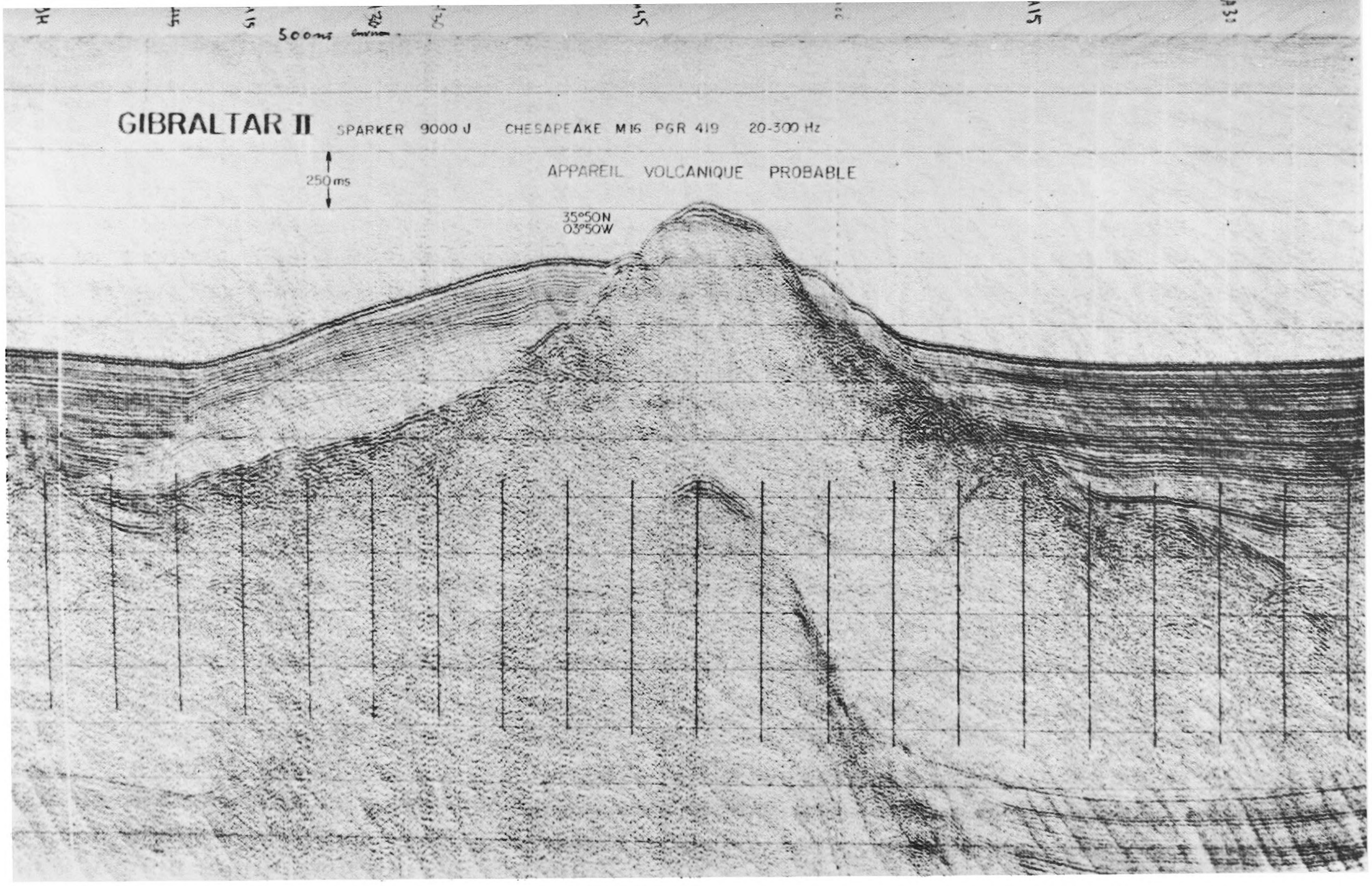
FIG. 12. — Probably a volcano.

The deep reflector is irregular both in detail and as a whole. Its multiple reflection is clear. The plioquaternary sedimentation is very regular on the right but slopes on the left side of the volcano and is rich in high frequencies.

(Sparker section, *Charcot,* October 1967).

GLANGEAUD, BOBIER and BELLAICHE show other volcanoes in the same region — the Alboran Sea.


GIBRALTAR II
SPARKER 9000 J
CHESAPEAKE M16 PGR 419
20-300 Hz
250 ms
APPAREIL VOLCANIQUE PROBABLE
35°50N
03°50W
500ms
15
30
45
15
30

confusion may arise. The sounding does not give an accurate representation of either the bottom or the subbottom.

The study of the bathymetric sounding illustrations published by KRAUSE in the *International Hydrographic Review*, Vol. XXXIX, No. 1, page 65, can be easily extended to the case of a "highlight" buried under the sea floor and giving rise to diffractive hyperbolas. It is easy to see that the asymptotes of these hyperbolas measure the velocity in the subbottom. This is the sole conclusion to be drawn from this method which in practice is of very little use in seismic work in view of the practical difficulties of plotting these asymptotes.

If we examine the diffractions and the curvature of the reflections close to the mirror surface we can say whether we are dealing with a direct or a reversed fault. This, however, is at the cost of sophisticated suppositions on the geologic sequence in question and on the respective velocity values in the various layers.

B. — Tectonic analysis

1. *Arrangement of the reflectors*

The arrangement of the reflectors gives the pattern of how the geological strata are disposed.

We can identifiy either conformities, or else unconformities, leading to bevels and to lenticular structures, as well as faults. The big advantage of the *raw document* — that is of the continuous profiling record — is that the tectonic history of the area becomes immediately apparent (figure 13).

We should merely add that as on land an analysis of the character of the reflections — in particular of the frequency — makes it easier to identify slight bevels and lenticular structures. Faults are often more difficult to detect. On the record the scale ratio — often 1 to 10 — almost entirely obscures the reflectors at angles of more than 45° (*).

2. *Tectonic analysis*

Geophysical analysis has already supplied the researcher with much information. Analysis of the tectonic style goes beyond this and very

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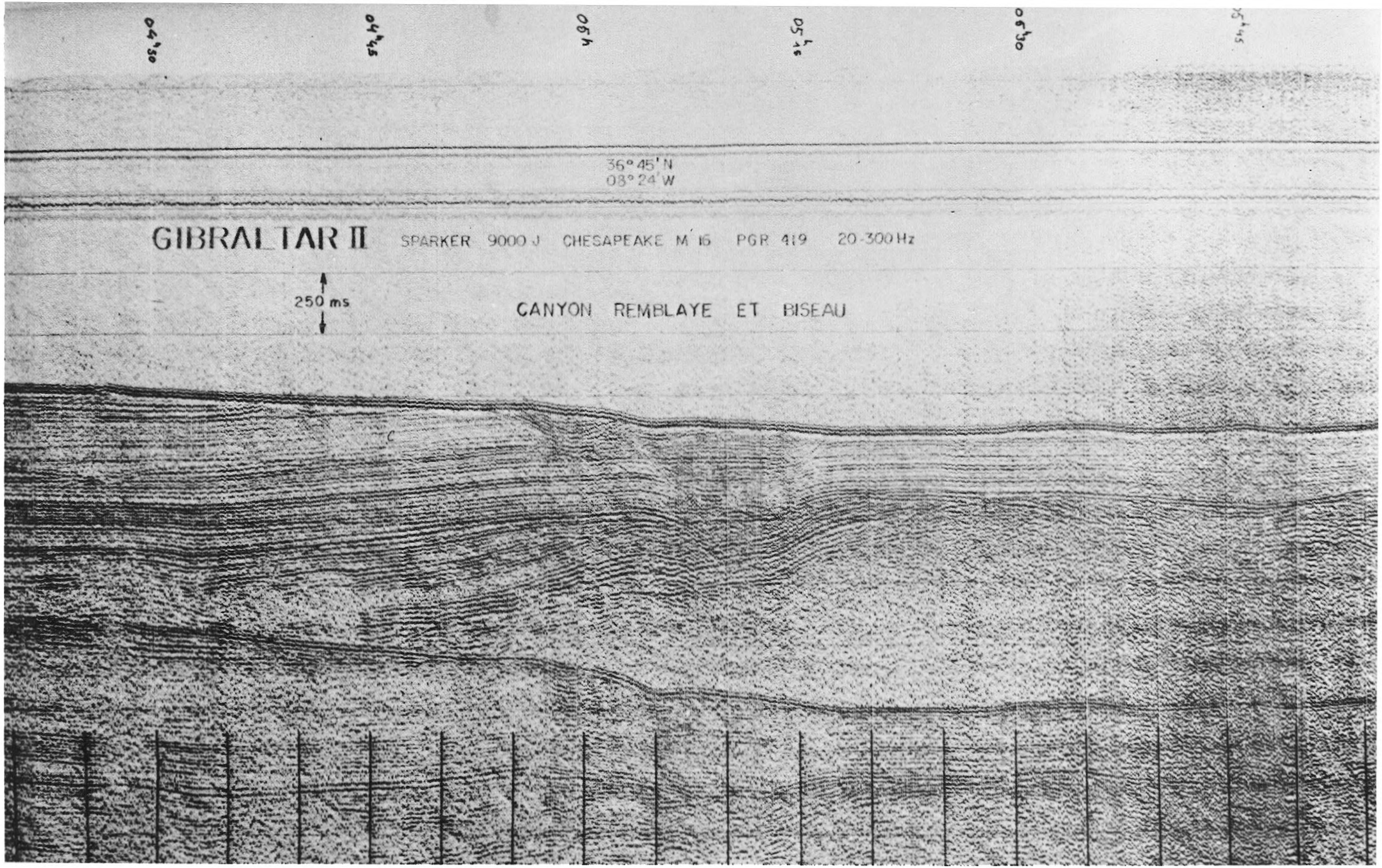
(*) This shows the advantages of a rapid rate of emission and of wide record paper with a rapid paper feed.

FIG. 13. — A buried canyon.

The plioquaternary sedimentation covers a relatively irregular substrata. A filled in scar caused by the passage of an old canyon can be observed. Below this canyon, a bevel. The section was taken on the continental slope parallel to the south coast of Portugal.

(Sparker section, *Charcot*, October 1967).


04h30
04h45
05h
05h15
05h30
5h45
36° 45' N
08° 24' W
GIBRALTAR II
SPARKER 9000 J
CHESAPEAKE M 16
PGR 419
20-300 Hz
250 ms
CANYON REMBLAYE ET BISEAU
C

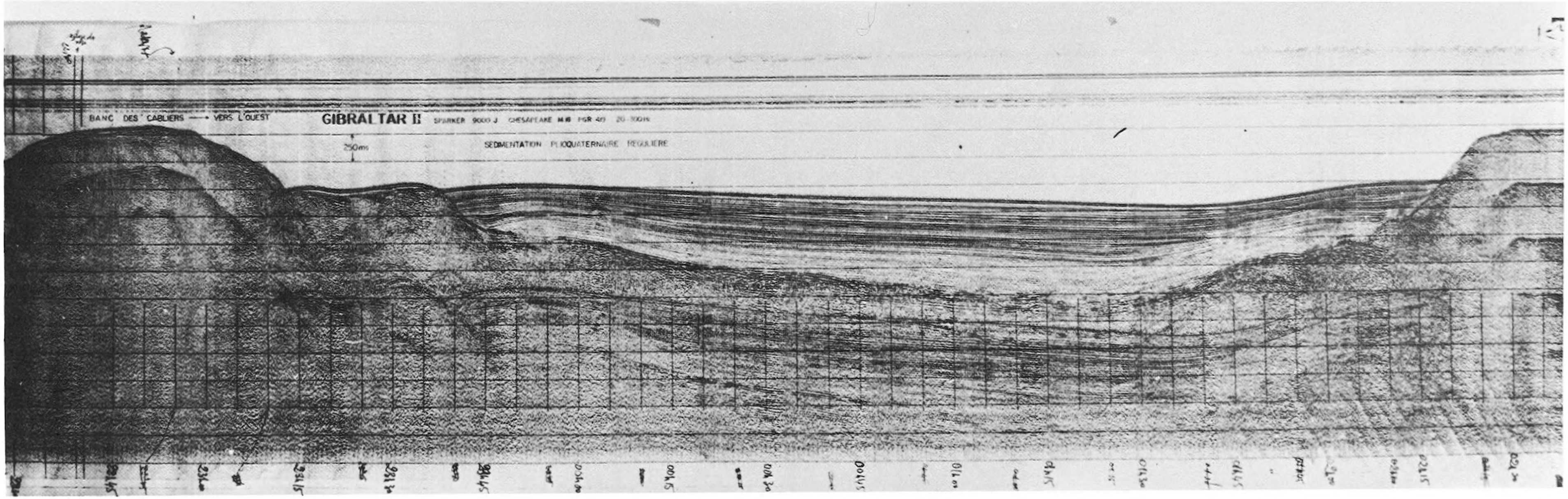


FIG. 14. — Regular plioquaternary sedimentation.

To the west of Cabliers Bank in the Alboran Sea, in a depression we observe a relatively untroubled layer of recent sedimentation resting on an antepliocene substructure. I interpret the upper layer, which has contrasted sedimentation, as quaternary and the layer immediately below which is paler and of more homogeneous sedimentation as pliocene.

Below, two layers may be clearly distinguished. The lower one is partially hidden by the double echo.

(Sparker section, *Charcot*, October 1967).

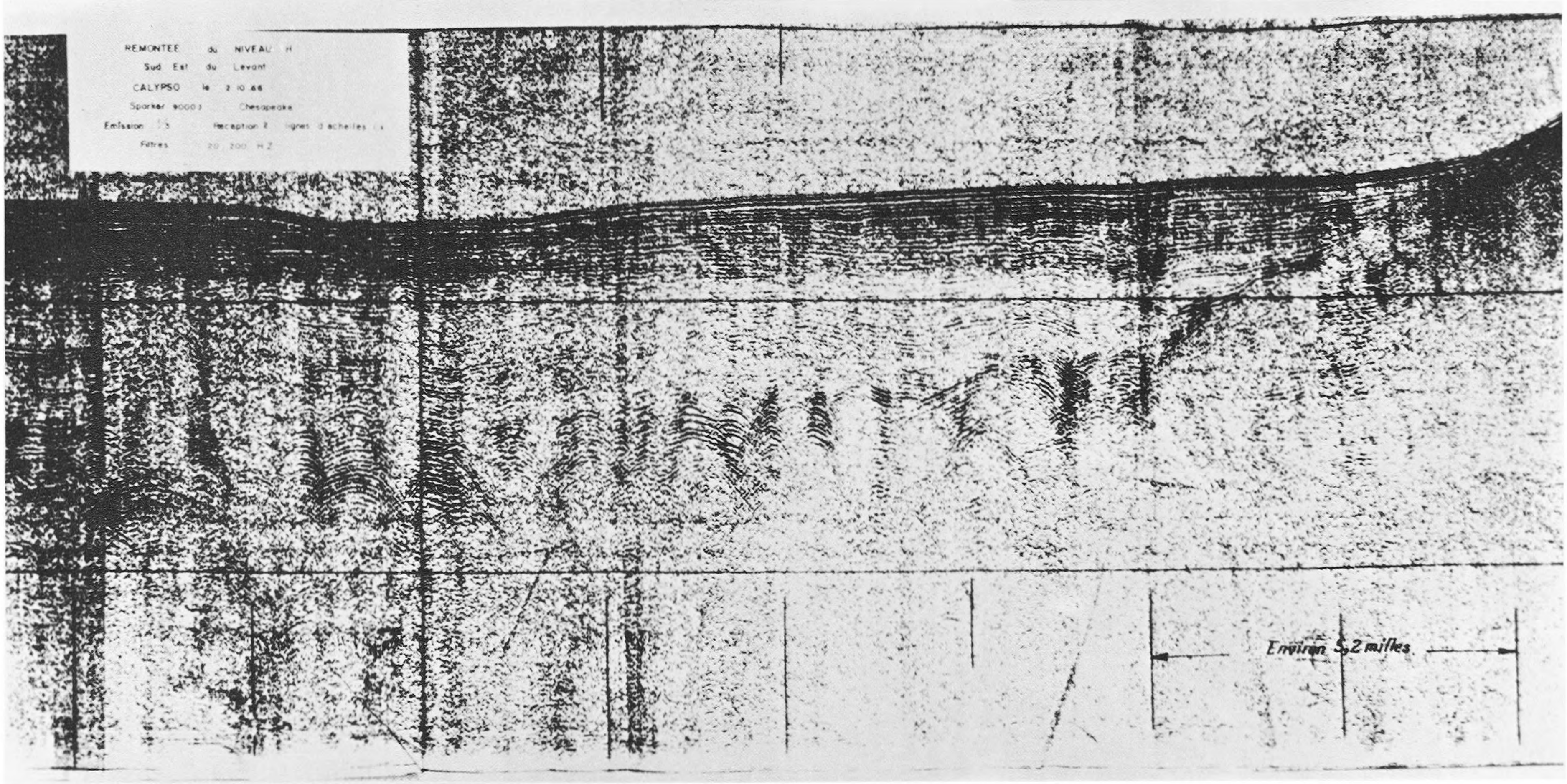


Fig. 15. — Antepliocene substrata.

The upward movement of layer A, to the southeast of the Ile du Levant, shows clear traces of erosion (i.e. the discontinuities in the reflector details).

(Sparker section, *Calypso*, October 1966).

frequently enables us to identify the main geologic outlines. This analysis is not made on the same level as the geophysical analysis for it studies the broad outlines and characterizes them.

Surface horizons that are regular, finely stratified, good reflectors and rich in high frequencies lie above a more transparent zone that has fewer reflectors, and is of fairly equal thickness throughout the abyssal plain of the west basin of the Mediterranean. Here we are confronted with an uniformly homogeneous whole, both consistent and little distorted, which is of the Plio-quaternary (figure 14).

Many echo-free passages on the record represent steeply sloping domes that deflect the sediments upwards on contact defining a pronounced perimeter. Here we have extrusive phenomena that are spread over a distinctive zone in the Ligurian Sea. They are interpreted as being salt (*) domes of the Ligurian anteclise era.

Analysed from the bathymetric point of view, the northern end of zone A has similar characteristics but the domes are larger. We (ALINAT *et al.*) at first linked this zone to the salt dome area. However attention to the tectonic style revealed by a good seismic profile and the study of the environment (GLANGEAUD, ALINAT *et al.* 1966) led to a reassessment of the phenomena as a tectonic contraction due to the Corsican/Sardinian block being pushed westward, giving rise to a genuine beginnings of overthrusts.

The numerous sediment-covered or simply submerged formations, of large but uneven shape, with diffracting reflectors allowing no penetration, are identified as volcanoes. There are many such volcanoes in the Alboran Sea. Fairly warped deflectors, that are sometimes faulted and always covered with plio-quaternary sediment, and which give rise to firmly characterized reflections are to be interpreted (figure 15) as concealed evidence of antepliocene tectonics.

In practice, by combining an analysis of character and a study of the geometry of reflectors with morphologic observations we are able to put forward a theory for the geologic character of a given reflector.

Carefully analysed, continuous seismic profiling documents provide a remarkably full account.

CONCLUSION

Analysis of the time sections enables us — for each reflection identified and followed throughout a particular study (figure 16) — to chart isochrones representing the surface of this reflection (figure 17).

To interpret the record we must first pass from isochrones to isobaths, that is we must know the velocities in the environment above the recorded reflections. This question is complex and the problem is not always entirely

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(*) Salt in the broadest sense of the word.

solved. It is usual to employ the seismic refraction method, or else the wide angle reflection method. Afterwards the seismic data have to be expressed in geologic terms. We do this by sampling the mud whenever possible as this enables identification of the reflecting layer. For deeper layers, but still however close to the hard ground, we can use geological extension in our deductions (*). In other cases only morphologic or tectonic considerations can be used to advance a theory (salt domes for instance) for explaining the structures observed.

Whatever the complexity of the geologic interpretation, a well-balanced study, one that is carried out in detail with instrumentation carefully adapted for the particular purpose and recorded with attention, will always supply documents whose methodic analysis will allow us to arrive at sound conclusions.

REFERENCES

ALDEN J. and FARRINGTON L.A., 1962 : High resolution direct graphic recording of underwater sound. *Int. Hydrogr. Rev.* **XXXIX**, No. 1, pp. 125-137.

ALINAT J., GIERMANN G. and LEENHARDT O., 1966 : Reconnaissance sismique des accidents de terrain en mer Ligure. *C.R. Acad. Sci., Paris,* (A-B), **262**, pp. 1311-1314.

EDGERTON H.E., GIERMANN G. and LEENHARDT O., 1967 : Etude structurale de la baie de Monaco en sondage sismique continu. *Bull. Inst. océanogr., Monaco,* **67**, n° 1377, 4 p.

GÉRARD A., 1967 : Etudes magnétiques en Méditerranée occidentale. Diplôme Ing. géophys., Strasbourg.

GLANGEAUD L., 1966 : Les grands ensembles structuraux de la Méditerranée occidentale d'après les données de Géomède I. *C.R. Acad. Sci., Paris,* (D), **262**, pp. 2405-2408.

GLANGEAUD L., ALINAT J., POLVECHE J., GUILLAUME A. and LEENHARDT O., 1966 : Grandes structures de la mer Ligure : leur évolution et leurs relations avec les chaînes continentales. *C.R. Soc. géol. Fr.,* p. 381 (résumé) and *Bull. Soc. géol. Fr.,* **8**, (7), pp. 921-937.

GLANGEAUD L., BOBIER Cl. and BELLAICHE G., 1967 : Evolution néotectonique de la mer d'Alboran et ses conséquences paléogéographiques. *C.R. Acad. Sci., Paris,* (D), **265**, pp. 1672-1675.

GUIEYSSE L. and SABATHE P., 1964 : Acoustique sous-marine. Dunod, Paris, 251 p.

HERSEY J.B., 1963 : Continuous reflection profiling, *in* : *The Sea,* **3**, pp. 47-72. — New York, London, Interscience publishers.

(*) Thus in figure 11 the horizons are designated limestone by reason of the continuity, for the coast nearby has cretaceous formations.

KRAUSE D.C., 1962 : Interpretation of echo sounding profiles. *Int. Hydrogr. Rev.* **XXXIX**, No. 1, pp. 65-123.

LEENHARDT O. and ROUX M.R., 1967 : Morphologie du substratum de l'étang de Berre. *C.R. Soc. géol. Fr.*, **2**, p. 65 (résumé) et *Bull. Soc. géol. Fr.*, (7), **9**, pp. 88-92.

MAUFFRET A., 1968 : Etude des profils sismiques obtenus au cours de la campagne Géomède I au large des Baléares et en mer Ligure. Thèse 3^e Cycle. Paris. 95 p.

PFANNENSTIEL M., GIERMANN G. and WIMMENAUER W., 1968 : Relations entre morphologie, tectonique et volcanisme dans la mer d'Alboran. (Résultats préliminaires de la campagne *Jean-Charcot*, 1967). *C.R. Soc. géol. Fr.*, **4**, pp. 116-118.

QUARLES M.W. Jr., 1958 : Interprétation des enregistrements de sismique réflexion. Rapport interne C.E.P.

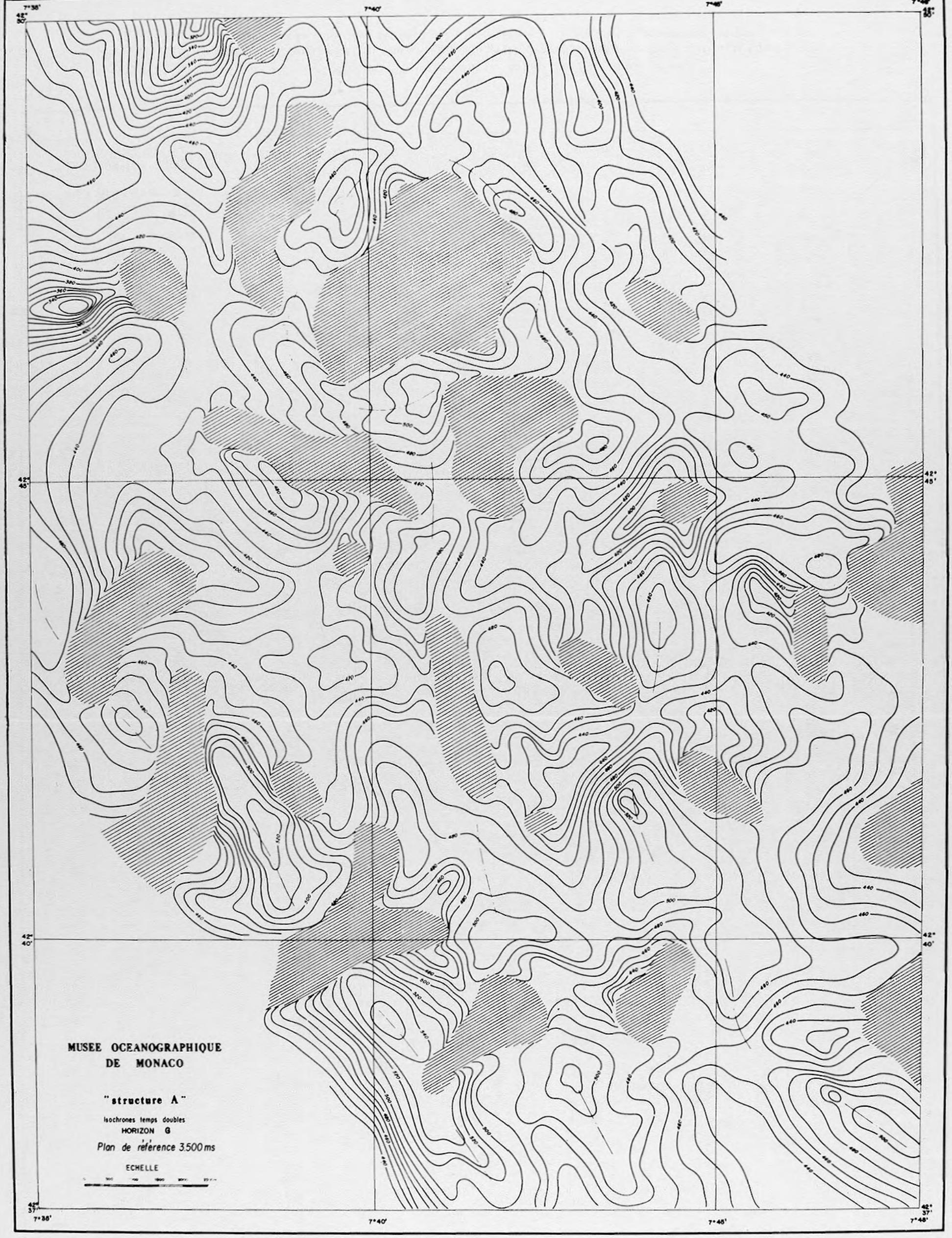

FIG. 16. — Position plane for the seismic study of structure A.

The bathymetric structure in ms double-way time has been overprinted, and shows against a very flat background two humps rising above the bottom. These humps are interpreted as salt domes. (See figure 8).

The regularity of the ship's tracks can be noticed : this is due to the Rana system, the only one to permit first rate positioning at this distance from land and both by day and at night.

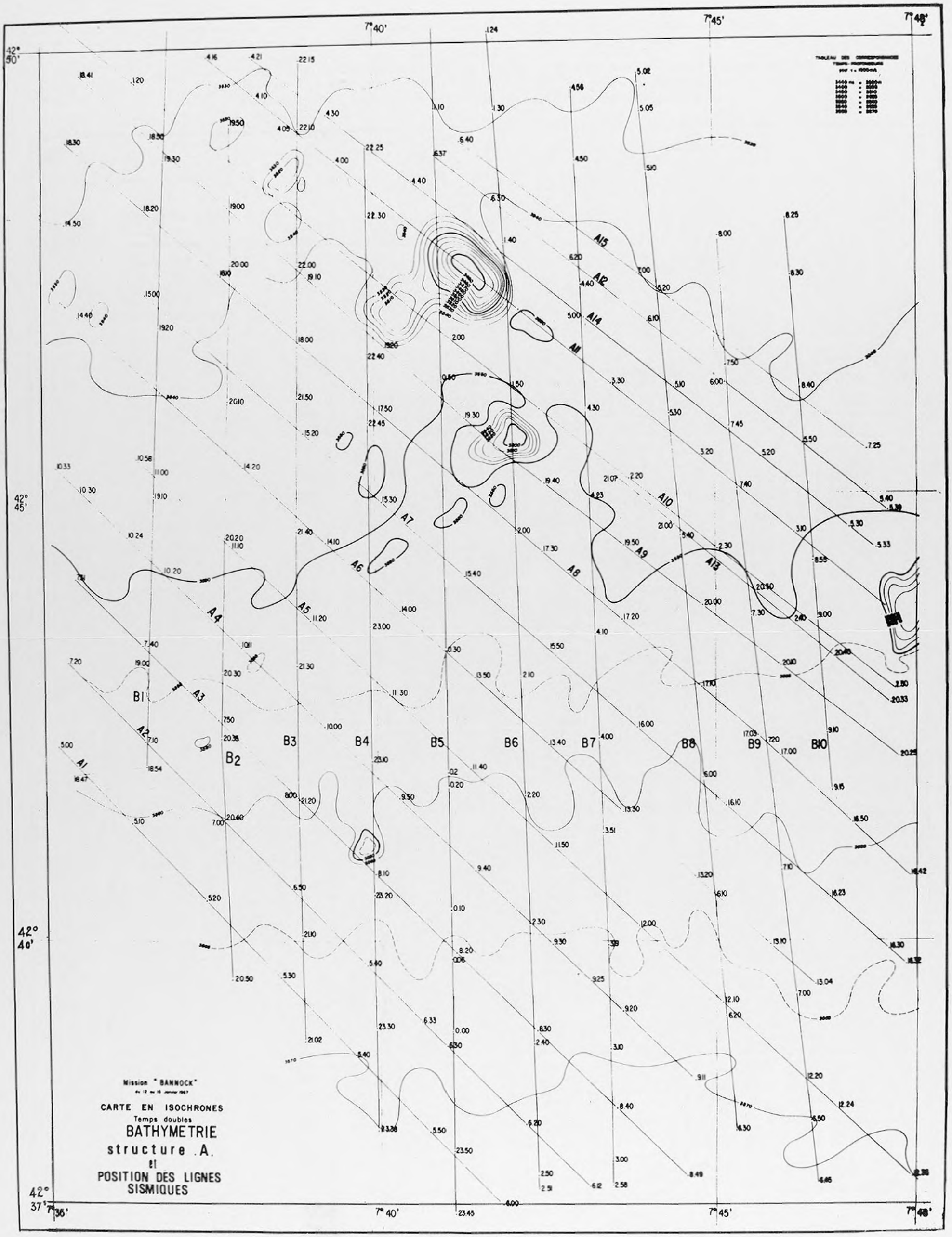

Fig. 17. — Isochrones of horizon G, taken in the dome area.

The surface of horizon G in the same area as figure 16. Domes arising through the horizon are observed, and the surface of the reflector G is softly undulated around these domes.