NARROW-BEAM ECHO SOUNDING IN MARINE GEOMORPHOLOGY

by

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INTRODUCTION

The topography of the earth exists as a continuous spectrum in the scale of the features. Different scales require different methods of study. For deep-sea geomorphic studies, conventional echo sounding (wide-beam sounding) yields data from features on the scale of about one kilometre to features on the scale of the ocean basin. Deep-sea bottom photography yields data on the scale of millimetres to metres. This leaves a spectral gap of 1 - 1 000 metres about which, until recently, existed no satisfactory means of examination — yet this is the main scale on which terrestrial geomorphic interpretations are made. The information now available shows that this scale is equally as important to marine geomorphic interpretations.

This paper will discuss the relationship of marine geomorphology and echo sounding. It will show how narrow-beam echo sounding yields unique data about the spectral gap of 1 - 1 000 metres necessary for geomorphic interpretation.

MARINE GEOMORPHOLOGY

Much more of our geologic knowledge of the sea floor is based on geomorphology than is true of our geologic knowledge of the continents. This is due to several reasons. Firstly, the lack of erosion of the sea floor features relative to erosion of terrestrial features prevents the destruction of distinguishing geomorphic characters such as volcanic cones and linear fault scarps. Secondly, this lack of erosion leads to a simpler depositional history and hence to one more easily interpreted through geomorphology.

Even where the tectonic history of the sea floor is not simpler than that on land, the marine geomorphic features are far less modified by erosion and thus are more easy to interpret. Thirdly, the very nature of the medium requires that the marine geologists be much more dependent on geomorphic interpretation than the terrestrial geologist. Leaders in such studies have been Ph. KUENEN, F. P. SHEPARD, H. W. MENARD, B. C. HEEZEN and G. B. UDINTSEV. They have been very successful in applying geomorphology to problems of sedimentation and tectonics.

The marine geomorphic studies are dependent upon the methods used. The work to the present time is based on surveys and profiles made with the wide-beam echo sounder and with bottom photographs (geologic samples and geophysical studies, of course, are also necessary for good geomorphic interpretations). This means that such features as volcanic cones, the large linear fracture zones, and rift zones are well characterized, as well as features like ripple marks and animal burrows. However the scale between roughly 1-1 000 metres is very poorly known. This represents such features as terraces in turbidity current channels, individual fault scarps, margins of lava flows, and landslide scars. These are the features that are observed on land in interpretation of geomorphic processes and features. As a result, our detailed knowledge of the geomorphic processes on the sea floor is very meagre and/or generalized.

MARINE GEOMORPHIC PROCESSES AND FEATURES IN THE SCALE 1 - 1 000 METRES

I. Volcanism
  1. Lava flows
  2. Volcanic cones
  3. Craters
  4. Accumulative features
  5. Volcanic terraces
    a. Lava
    b. Palagonite
    c. Faulting related to volcanism
  6. Volcanic rifts
  7. Abyssal hills

II. Faulting
  1. Scarps
  2. Linear topography
  3. Rifts
  4. Abyssal hills

III. Folding, large and small
  1. Swells

  2. Elongated elevations
  3. Elongated depressions

IV. Landsliding (mass movement)
  1. Landslide scars
  2. Landslide masses, large and small
    a. Continental and island terrace
    b. Deep-sea

V. Sedimentation and erosion
  1. Turbidity currents
    a. Channels
    b. Terraces in channels
    c. Channel levees
    d. Submarine canyons
    e. Rills
    f. Cones, fans
  2. Terraces due to lowered sea level (eustatic or tectonic)
  3. Pelagic sediments
    a. Rounded topography
    b. Levelling of topography
    c. Ponds of sediment
  4. Deep currents
    a. Depositional ridges
    b. Sand waves
    c. Erosional swales and channels

These processes and their products are studied by (1) profiles, (2) detailed surveys, and (3) statistical studies of profiles and surveys (quantitative marine geomorphology). The geomorphic study is, of course, never independent of geologic sampling and geophysical studies.

EXISTING TECHNIQUES FOR DETAILED GEOMORPHIC STUDIES

Methods for studying the deep-sea topographic spectrum of 1-1 000 metres have only been developed within the past few years and have only just now begun to yield significant geomorphic data. Three principal methods exist :

1. Narrow-beam echo sounders mounted on surface vessels.
2. Instruments towed near the sea floor from a moving surface vessel.
3. Deep-diving research submarines.

Each of the methods has its distinct advantages and disadvantages — each yields its own set of unique data. All are needed to completely characterize the marine geomorphology.

Briefly, some of the advantages and disadvantages are as follows :

1. Narrow-beam echo sounder. This instrument can be operated at normal ship speeds and in most weathers. It yields very accurate profiles. Very detailed surveys are required to utilize its maximum capability.

2. Deep-towed instruments. This instrumentation can be complex but many types of near-bottom underway measurements can be made (echo soundings, seismic profiling, side-looking sonar, magnetic, etc.) (Mudie, *et al.*, 1967). The towing is done at very low speed and very detailed surveys are required.

3. Deep-diving research submarine. The human observer can directly study the phenomena of interest with the submarine. At present, the submarine requires elaborate logistic support, is relatively clumsy, and limited by depth. The research submarines capable of diving to truly oceanic depths are too fragile for many types of geomorphic studies.

This paper deals only with the narrow-beam echo sounder.

ECHO SOUNDERS

The echo sounder periodically produces a short sound pulse which is reflected from the sea floor and recorded. The sound wave spreads roughly spherically as from an explosion, but the sound intensity is highly directional, and it is this directionality that is the topic of this paper. This directionality varies with the frequency of the sound-producing transducer and with the size and configuration of the transducer. To obtain a given beam pattern, the diameter of the transducer must be proportional to the wave length. Conversely the size of the transducer must be increased to obtain a narrower beam. Finally, the absorption of sound in sea water is a function of sound frequency, the higher frequency sound being absorbed more. Therefore the design of an echo sounder requires a balance between the size of a transducer and its frequency.

Thus the conventional deep-sea echo sounder (wide-beam) operates between 10 000 - 14 000 hertz (depending on design) with a transducer about 0.25 metre in diameter. This gives a beam pattern that is about 30° wide between half power points. The sound pulse will be reflected back in strength to the transducer from any reflector lying within 15° of the vertical angle from the ship, although 30° has been observed (Krause, *et al.*, 1967). For routine surveys and many studies, this is quite satisfactory. However this severely limits detailed examination of the sea floor. Many steep features cannot be observed and an accurate profile of the sea floor cannot be obtained in irregular topography. A narrow-beam echo sounder must be used to study such features. Such sounders operate at 20 000 - 30 000 hertz with transducers (or transducer arrays) larger than a metre in diameter. One such gyro-stabilized, narrow-beam sounder (constructed by the General Electric Co.) is on the U.S. Coast and Geodetic Ship *Oceanographer*. It operates at 20 000 hertz, has a transducer 1.8 metres in diameter and has a beam 3° wide. The transducer is vertically stabilized by hydraulically operated pistons. Other narrow-beam sounders of the U.S. Coast and Geodetic Survey use transducer arrays which are switched electronically to obtain a vertical beam.

PRINCIPLES OF ECHO SOUNDING

The basic theory of wide-beam echo sounding will be reviewed to show the advantage of narrow-beam sounding over wide-beam sounding. The sound wave front is assumed to be spherical, and the bottom is assumed to be a non-specular reflector.

The depth as measured by the wide-beam sounder is the true depth only directly over a peak or over a level sea floor, because the sound is reflected from the nearest bottom. For a sloping or uneven sea floor, the measured depth in general will be less than the true depth beneath the ship. The true depth (d) is related to the measured depth (s) by (see fig. 1) :

$$d = s/\cos\theta \qquad \text{where } \theta = \text{true slope of bottom}$$

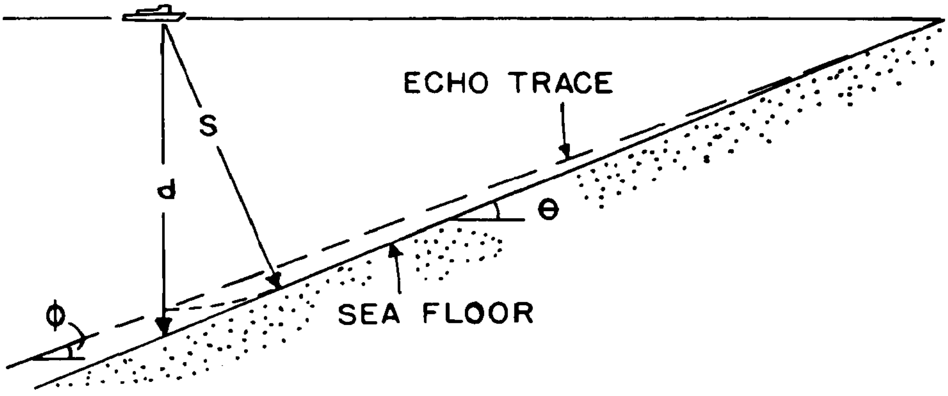

Fig. 1. — Relation between observed echo trace and true sea floor.

The true slope (θ) is related to the measured slope (φ) by :

$$\sin\theta = \tan\varphi$$

The characteristic echo trace from a sharp feature on the sea floor is a hyperbola (Hoffman, 1967, Krause, 1962). For a very sharp peak (fig. 2), the equation of the echo trace is :

$$\frac{s^2}{p^2} - \frac{x^2}{p^2} = 1$$

where s = measured depth at distance x from crest
p = depth of peak.

If the peak is crossed to one side, the hyperbola becomes :

$$\frac{s^2}{H^2 + p^2} - \frac{x^2}{H^2 + p^2} = 1$$

where H = minimum horizontal distance of the ship from the peak's crest.

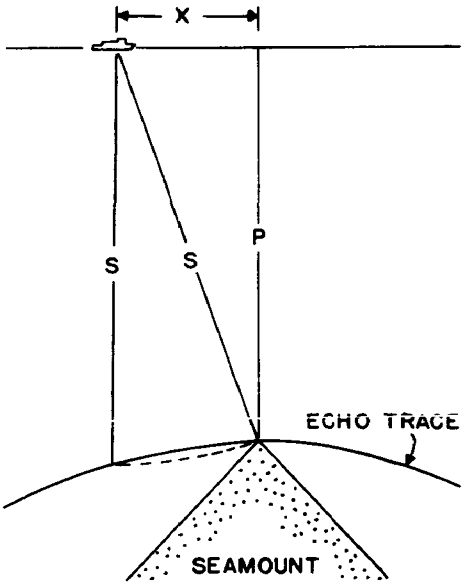

FIG. 2. — Echo trace of a steep seamount.

In the case of a seapeak with a gentle or moderate slope (θ) which is crossed to one side, the echo in general will not be reflected from beneath the ship's track but from a point to one side (fig. 3). The echo trace is still a hyperbola :

$$\frac{(s - p\cos\theta)^2}{H^2 \sin^2\theta} - \frac{x^2}{H^2} = 1$$

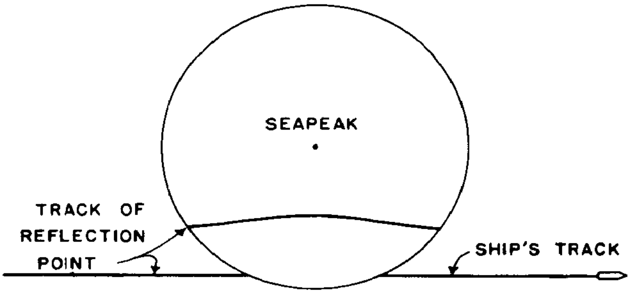

FIG. 3. — Plan view of a ship track across a sea peak showing displacement of the track of the reflection point from below the ship track.

A sharp edge or corner will give half a hyperbola. In the case of a submarine canyon or channel, the echo envelope from the upper edges can hide the true bottom which shows up as a second or third echo trace (fig. 4). Furthermore steepsided features smaller than a certain size will always be completely hidden by the echo envelope, and their features cannot be determined (table 1). Even their heights will not be known if the crests are not under the ship's track. KRAUSE (1962) and AGAPOVA (in press) have discussed these and many other examples in detail.

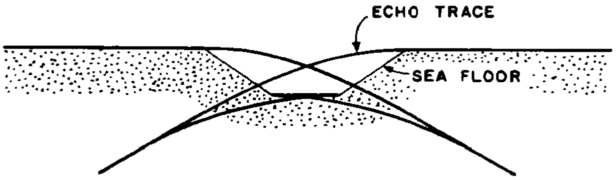

FIG. 4. — Echo trace of a depression showing multiple echoes above and below true bottom.

Table 1 gives (see fig. 5) :

1. Depth (A) of crest of conical sea peak;
2. Height (Z) of sea peak above surrounding plain;
3. Width (K) of hyperbolic echo trace of sea peak where hyperbola intersects echo trace of plain;
4. Width (M) of sea peak of height (Z) whose hillside echo trace will be hidden below the plain's echo trace. The echo trace of width (K) above the plain's trace will be only the hyperbolic trace from the crest of the sea peak.
5. Minimum slope (θ) of sea peak completely hidden by its crestal hyperbolic echo trace. The echo trace of a sea peak of slope (θ) just changes from the crestal trace above the plain's trace to the hillside's trace below. The echo trace above the plain's trace from sea peaks with slopes of θ or larger will consist entirely of the hyperbolic trace from the crest. The echo trace from the peak's sides will lie below the plain's echo trace. For peaks progressively less steep than θ, the echo trace of the side will gradually appear above the plain, but the entire trace never will appear above. The width of the peak's trace at the plain's trace will always be wider than the peak itself. Slopes greater than 30° theoretically will not be recorded because of the sound cone width.

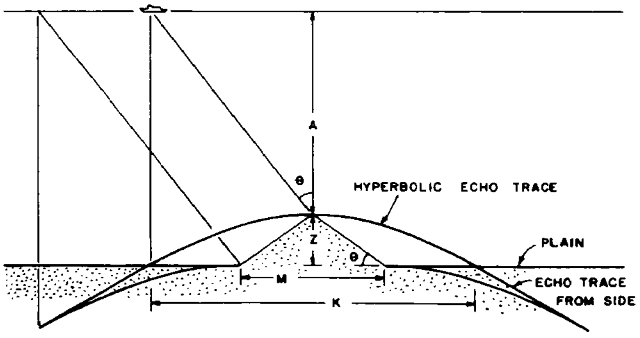

FIG. 5. — Echo trace over a seapeak.

However in actual practice, echoes will be returned from steeper slopes in moderate depths by non-specular reflection at the effective edge of the sound cone (at roughly 30° vertical angle from the ship) (KRAUSE, MENARD and SMITH, 1964). In table 1, slopes of greater than 30° are shown boxed.

TABLE 1

Characteristics of sea peaks and their crestal hyperbolic echo traces

Depth of peak in km A	Height of peak in km Z	Width of hyperbola in km K	Maximum width of hidden peak in km M	Minimum slope of hidden peak θ
1	0.1	0.92	0.44	24°37′
	0.2	1.33	0.62	33°39′
	0.4	1.96	0.82	44°25′
	0.5	2.24	0.90	48°11′
	1.0	3.46	1.16	60°00′
2	0.1	1.28	0.63	17°45′
	0.2	1.84	0.87	24°37′
	0.4	2.65	1.20	33°39′
	0.5	3.00	1.33	36°52′
	1.0	4.47	1.91	48°11′
4	0.1	1.80	0.89	12°42′
	0.2	2.56	1.25	17°45′
	0.4	3.67	1.75	24°37′
	0.5	4.12	1.95	27°08′
	1.0	6.00	2.67	36°52′
6	0.1	2.20	1.08	10°29′
	0.2	3.12	1.53	14°39′
	0.4	4.45	2.16	20°21′
	0.5	5.00	2.40	22°36′
	1.0	7.21	3.33	31°01′

In ideal cases where the geometry of the sea floor is well known, the true topography can be constructed from the echo trace (KRAUSE, MENARD and SMITH, 1964) (fig. 6). In steep topography, the differences in depth can be more than a kilometre, and the point of reflection can be more than a kilometre from the point beneath the ship. Although the topography can be constructed, mainly only the reflection highlights are found, and the bottom must be extrapolated between them.

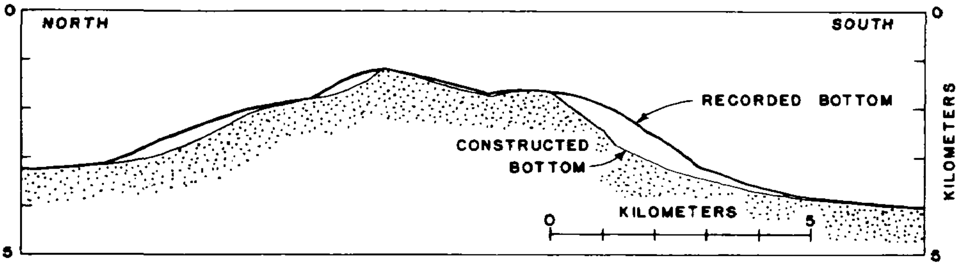

FIG. 6. — Mendocino Ridge in the northeastern Pacific Ocean showing the true sea floor as constructed from the echo trace (from KRAUSE, MENARD and SMITH, 1967).

Most of these problems become insignificant if the narrow-beam sounder is used. The hyperbolic echo trace is then very short (only a few seconds long, depending on the ship's speed).

NARROW-BEAM ECHO SOUNDER — THE DATA AND ITS USE

The narrow-beam sounder will provide information on the following :

1. The exact profile of the sea floor;
2. The exact depth under the ship;
3. The actual slope of the sea floor (depending on the sampling interval and on the ship's course relative to the slope direction);
4. Sub-bottom echoes of the sea floor directly under the ship (dependent on the frequency of the sounder);
5. Reflectivity of the sea floor in a given spot (a clue to bottom composition and/or roughness);
6. Detection of geomorphic features hidden in wide-bottom echo sounder records such as narrow sub-marine channels which for example are very common in the *Thresher* search area (HURLEY, 1964).
7. The direction and the angle of the bottom slope from a stationary ship (with a rotating beam sonar).

This information is necessary for several different problems in several different professions :

1. Many types of marine geomorphic studies, both descriptive and quantitative;
2. Transmission of underwater sound, both vertical reflection and long range reflection;
3. Deep-water navigation of deep-diving research submarines;
4. Installation of engineering structures on the sea floor requires data on bottom slope for sediment stability studies, exact depth, sub-bottom data, and ruggedness of the bottom; submarine telephone cables are the principal installations at present.

RECENT RESULTS

A few papers have outlined the advantages of narrow-beam sounding (HOFFMAN, 1957, COHEN, 1959). Immediately obvious is the increase in detail and the clear presentation of depressions (plates 1, 2, 3).

In the northeastern Pacific Ocean, the wide-beam sounder gives the impression that the sea floor is composed of irregular but rounded abyssal hills. However research with the deep-towed sounder at the Scripps Institution of Oceanography (ATWATER and MUDIE, 1968) has shown that this apparently rolling topography consists of rather flat areas bounded by steep linear scarps. The narrow-beam sounder of the U.S.C.G.S. Ship *Oceanographer* has shown that this phenomenon is widespread in the southern Pacific Ocean between New Zealand and Chile along 35° S latitude (plates 3, 4). It is also apparent in the North Atlantic (KRAUSE and SCHILLING, in press). This probably is the general case for most of the abyssal hill provinces of the sea floor. That is, most abyssal hills probably consist of gentle slopes bounded by steep scarps rather than have a generalized rounded shape. Such a form develops through tectonism and volcanism combined with sedimentation.

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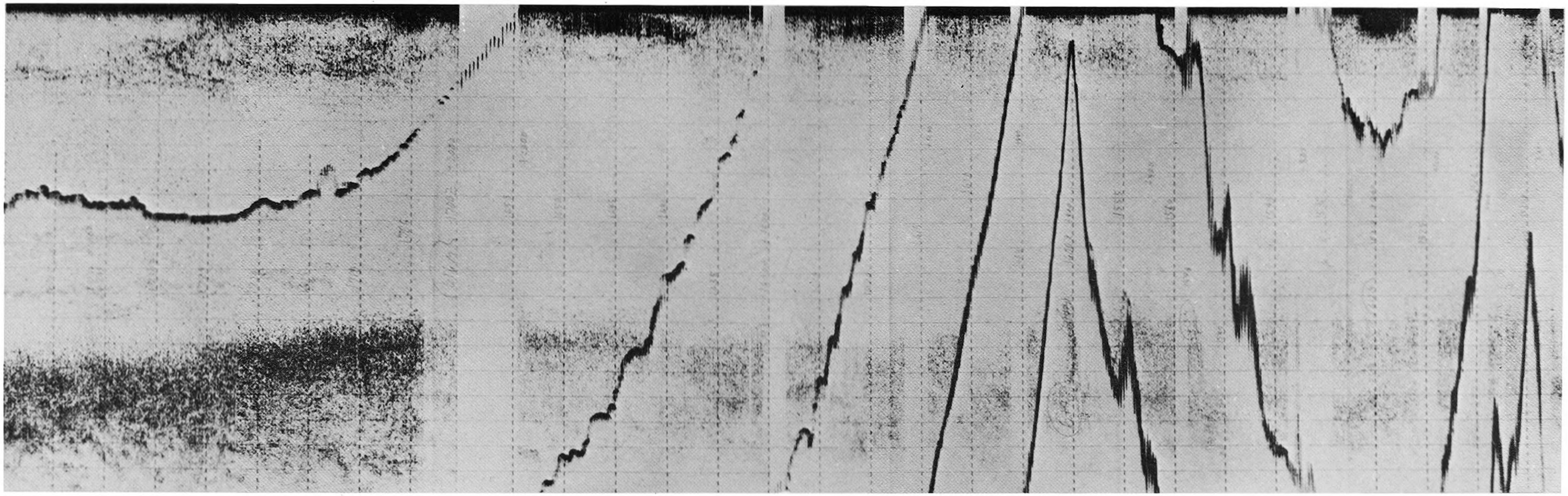

PLATE 1

Narrow-beam echo trace of a seamount about 1 000 kilometres west of the crest of the East Pacific rise.

Note the pronounced steps on the eastern side of the seamount. Note also the extreme sharpness of the peaks and inter-peak valleys. The minute jaggedness of the trace to the right is due to rocking of the ship sweeping the sound beam up and down the slope (the stabilizing mechanism was locked). The vertical scale is 750 metres (400 fathoms). The seamount lies between 800 and 4 400 metres depth. The length of the profile is 70 km. The position of east end (left) : 35°00′ S, 117°55′ W; west end (right) : 34°59′ S, 118°42′ W.

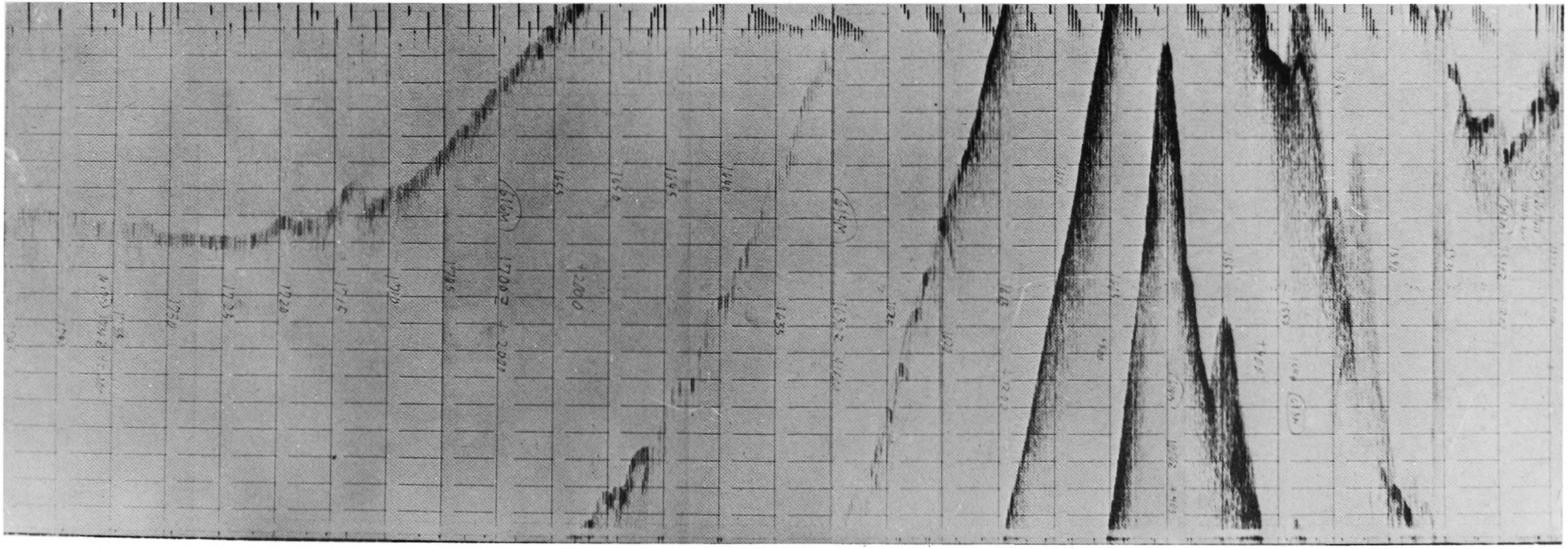

PLATE 2

Wide-beam echo trace of the seamount of plate 1 recorded simultaneously (long ping). Note the transformation of the eastern steps into small hyperbolae. Note also the broadening of the peaks including the introduction of side echoes and the narrowing or disappearance of the depressions. The profile is slightly shorter than that of plate 1.

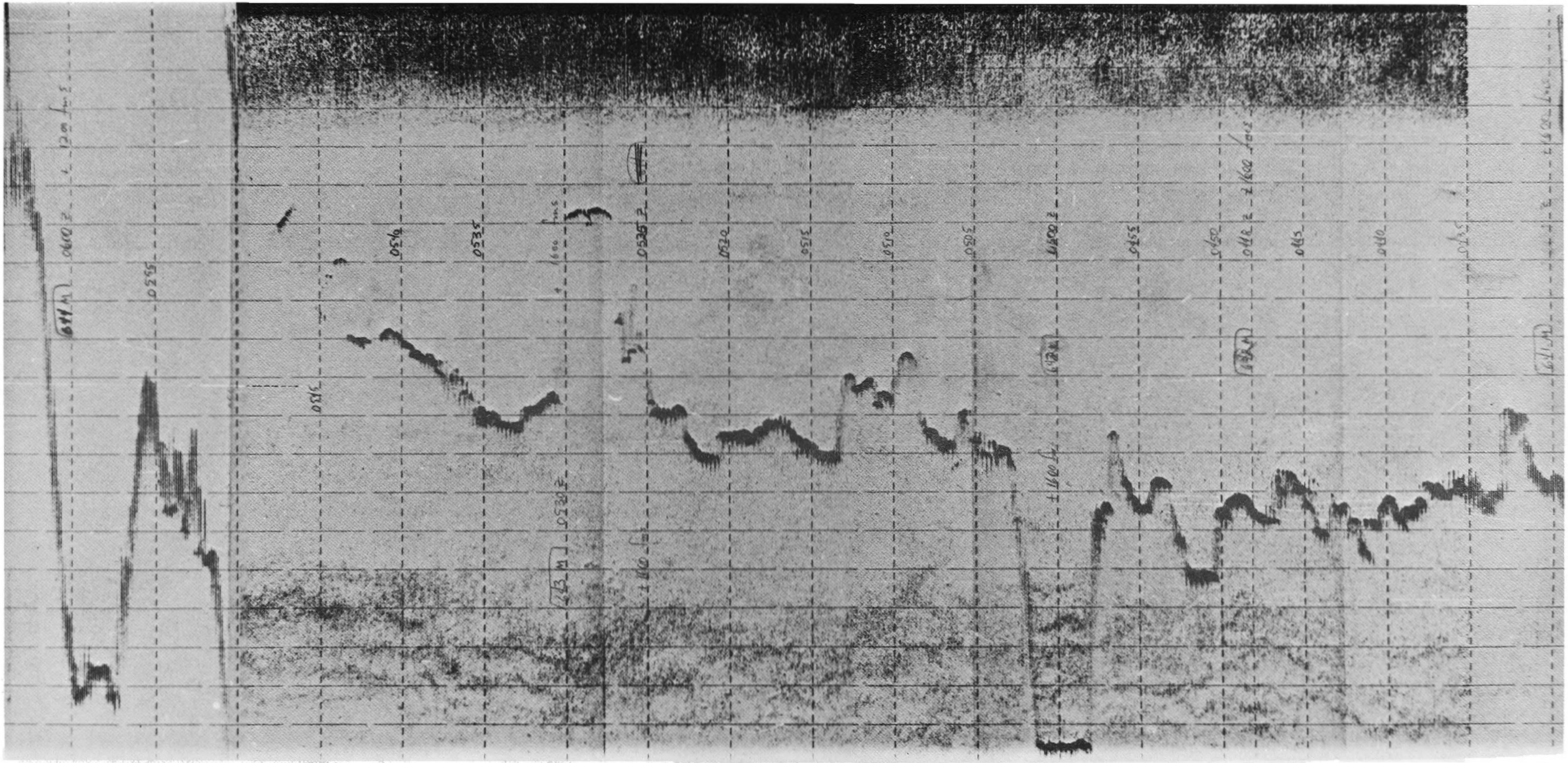

PLATE 3

Narrow-beam echo trace of blocky sea floor about 500 km west of the crest of the East Pacific rise.

Note the steep scarps bounding flat troughs and hills. Note especially the pronounced trough. The main part of the sea floor lies near 3 450 m depth. Length of profile : 48 km. Position of profile : east end (left) : 34°59′ S, 113°50′ W; west end (right) : 34°59′ S, 114°20′ W.

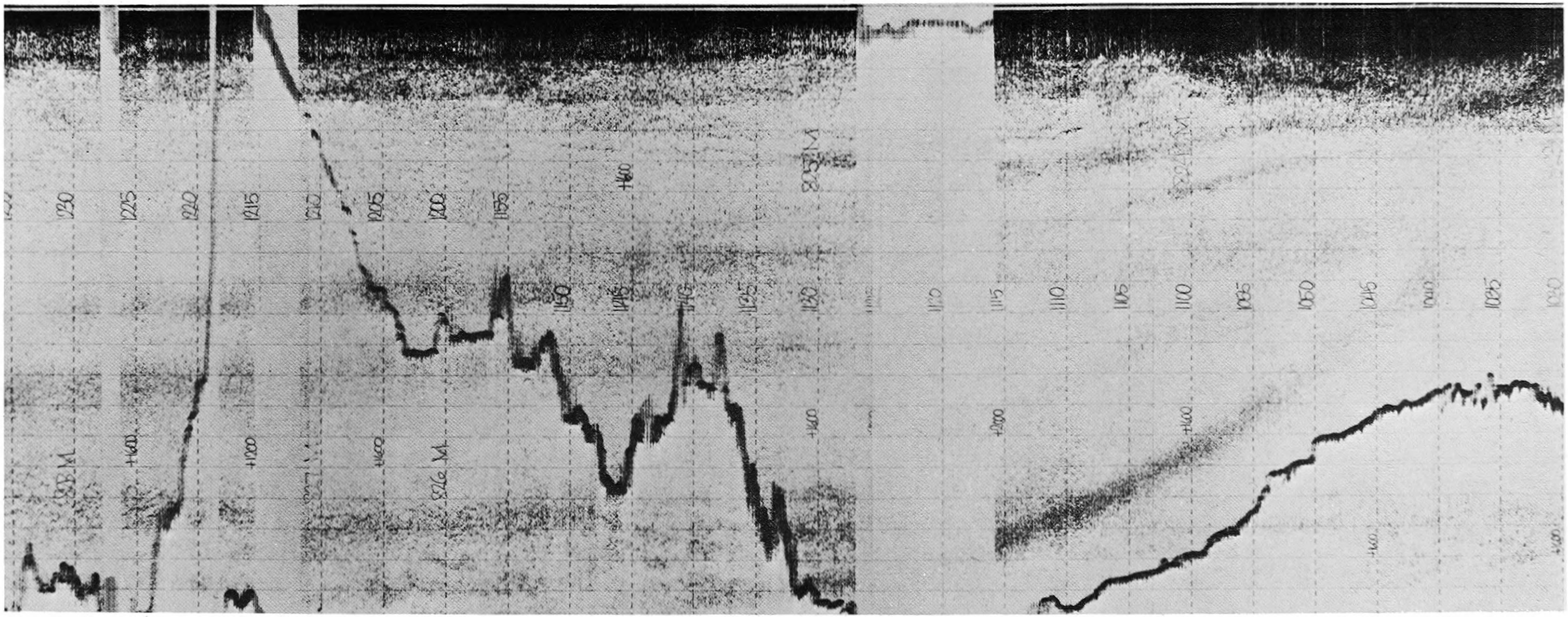

PLATE 4

Narrow-beam echo trace of blocky sea floor of the Chile rise.
Profile lies between 2 200 and 3 000 m depth. Length of profile 51 km. Position of profile : east end (left) : 32°28′ S, 91°31′ W; west end (right) : 32°32′ S, 92°04′ W.