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PROJECT SWATHMAP: MILITARY SONARS IN SERVICE TO SCIENCE

by Peter B. HUMPHREY (*)

ABSTRACT

Project SWATHMAP (one of four deep-water, long-range sidescan sonars in operation today) is the low-cost peacetime application of a U.S. Navy anti-submarine warfare system utilized on routine ocean-wide combat vessel transists. While resolution is not sufficient to observe bathymetric structures in detail, the system is particularly adept at locating them and determining continuity. Routine observations include terraces, trench-crossings, fracture zones, abyssal hills, craters, seamounts (many of them new) often topped by craters, and abyssal hills (superb clues to plate tectonic motion).

> *'A great deal of efficiency can be gained in underwater surveys by increasing the data gathering ability of the survey tool and trading off resolution for survey speed whenever possible .... The highest survey efficiency will accrue to the system able to cover the territory in the least amount of time. Since the acoustic velocity in water places upper bounds on the rate at which survey data may be collected, it is often very useful to trade survey rate for resolution; a single broad view of an area is often sufficient.'*
>
> KASALOS and CHAYES (1983)

> *'In these financially strained times the scientific community cannot afford to pass up ship of opportunity data of significant value even if lower in quality.'*
>
> Peter VOGT (1986)

* * *

Project SWATHMAP is the geologic application of a combat vessel anti-submarine warfare system utilized on routine ocean-wide transits. It uses the United States Navy's 3.5 kHz bulbous bow-mounted SQS-26/CX sonar system in active bottom-bounce mode on ocean-wide combat vessel transits at times when

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(*) Hawaii Institute of Geophysics, University of Hawaii, 2525 Correa Road, Honolulu, Hawaii 96822, USA.

this apparatus is not serving the purpose for which it was developed: submarine detection. With the advent of sound-seeking torpedos, such detection is now generally a passive process, so SWATHMAP operates only on routine crossings where its blatant decibel level will not interfere with military operations. Currently there are four long-range sidescan sonars operating in the deepsea: one on either side of the North Atlantic (SeaMARC I and GLORIA II) and two based in Hawaii (SWATHMAP and SeaMARC II). All four systems have observed various sections of the Pacific; SWATHMAP was the first to do so (ANDREWS *et al.*, 1974).

SWATHMAP is a rapid bathymetric search technique for reconnaissance, survey and mapping of deepsea topography, and discerning changes in the texture and character of the seabed itself. Compared to the other three systems, it is a modest operation justified by its ease, speed and cost: U.S. Navy cooperation provides what is essentially free science. The hull-mounting of its transducer array accounts for its major advantages (all-weather capability, ease of operation, survey rapidity and low cost) at an order of magnitude cost in resolution (100's of meters compared to GLORIA's 10's of meters). Although its data acquisition and signal processing are still in their infancy, the project has successfully imaged deepsea trenches, seamounts (many of them newly discovered), craters, deep terraces and vast arrays of seafloor lineaments which are valuable keys to plate tectonic motion (particularly in regions devoid of otherwise essential magnetic anomalies). While hardly a comprehensive mapping system, these data have proven particularly valuable in two fields of endeavor: (1) pinpointing features (many new) whose gross appearance suggests they are worthy of detailed study, and (2) determining the character of the seafloor around them, particularly the long-range continuity of tectonic trends and sediment patterns. In its ability to quickly discern where outstanding features are and roughly what they look like, SWATHMAP has proved to be a most valuable tool with which to study the relief of the seafloor and the shape of the structures thereon. Seven trials have met these objectives: one down the Red Sea (publication pending), one in the Atlantic (published herein) and five across the Pacific (ANDREWS *et al.*, 1977; ANDREWS, 1980; ANDREWS and HUMPHREY, 1980; HUMPHREY, 1984).

Sidescan sonar is still lacking a comprehensive theoretical manual, but those who wish to understand the technique and its constraints in detail will be well served by studying LEENHARDT (1974), BERKSON *et al.* (1975), FLEMING (1976), SOMERS (1977), MALAKHOV (1978), RUSSELL-CARGILL (1982) and KLEIN (1985), all of which concern towed units. SeaMARC is well reviewed by KASALOS and CHAYES (1983). The following discussions on principles and interpretation comprise a guide for hull-mounted SWATHMAP.

GENERAL PRINCIPLES OF OPERATION

A sidescan survey's main concern are maximum sonograph clarity (resolution) and maximum possible range (minimum ship time). Each is a trade-off with the other. Table 1 shows the effect of these logistical balances in the three longest range sidescan sonar systems.

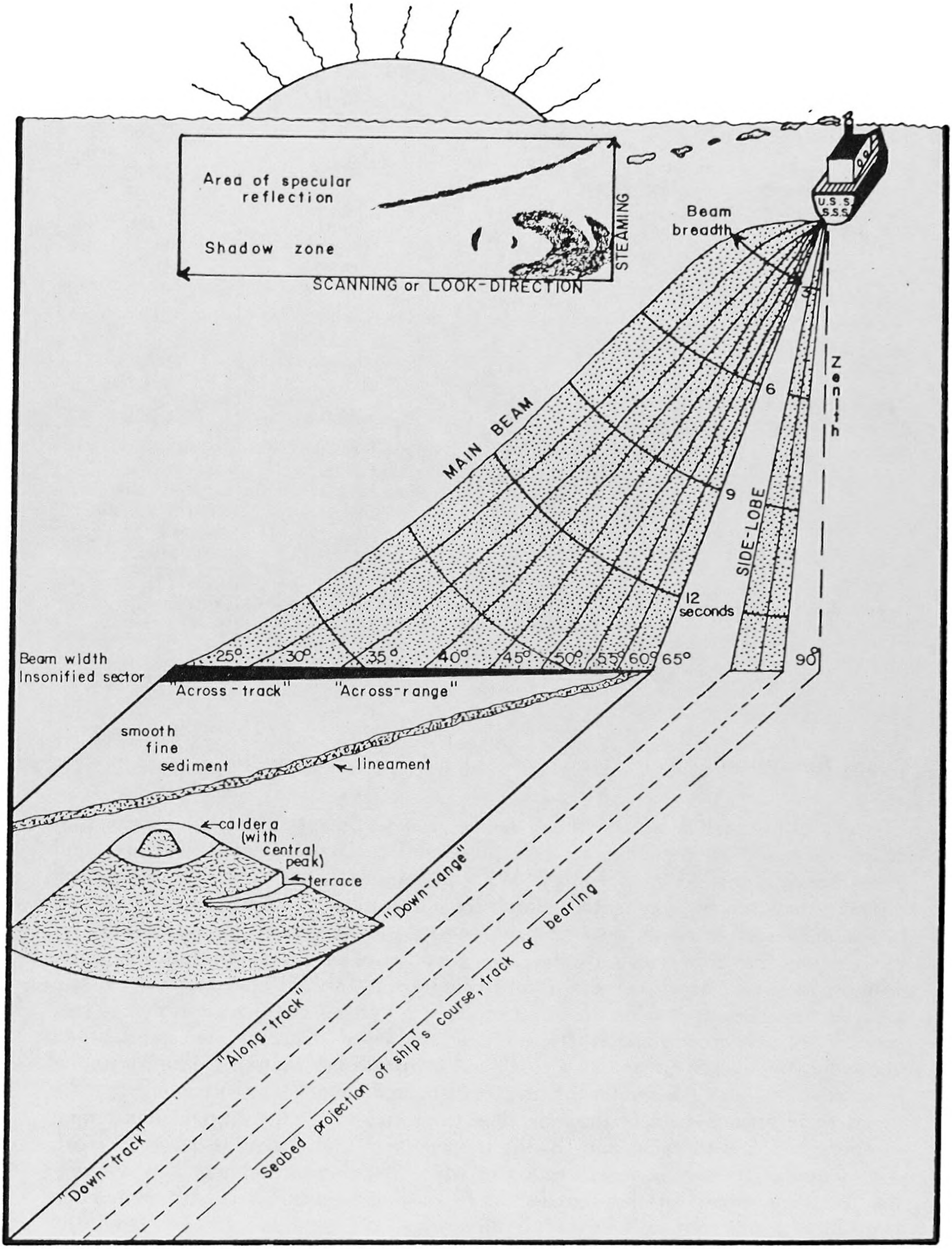
TABLE 1

Specifications of long-range deepsea sidescan sonar systems

	SWATHMAP	GLORIA II	SeaMARC II
Wavelength (centimeters)	43	25	13
Frequency (kilohertz)	3.5	6.5(6.3 & 6.7)	11.5(11.0 & 12.0)
Approximate tow depth (meters)	4	50-100	100
Survey speed (knots)	up to 20	∼7(up to 11)	10
Greatest possible deep ocean swath width or maximum slant range in minimally stratified waters (kilometers)	65 (less∼10 in center)	60 (less∼10 in center)	10 (less∼0.4 in center)
Time between pulses Two-way travel time (seconds) . .	40	30	15
Resolution (order of magnitude in meters)	100's	10's	1's
Maximum survey rate (kilometers^2/day)	58 000	30 000	4 000
Major advantages	ease great energy all-weather great rapidity economy	good stability good detail low refraction rapidity	great stability superb detail very low refraction bathymetry and sidescan advanced processing
Major disadvantages	hazy detail restricted access analog output only	expensive, unwieldy weather-restricted dedicated to one ship	expensive weather-restricted slow

Beam formation

A transducer is an electrical device which converts electrical energy into sound to create an outgoing acoustic pulse and reconverts incoming echo-sound into (monitorable) electrical energy. While a passive sonar system is one which merely listens for environmental or ambient noise, an active system (such as this) forces the issue, using its own acoustic energy to 'illuminate', or rather insonify, the seafloor on either side of the ship track. Unlike the more familiar echo-sounder whose transducer emits and receives a conical energy pattern, the arrayed transducers of sidescan sonar produce a vertical beam pattern that is fan-shaped: very narrow horizontally (only a couple of degrees) and quite broad vertically (to reach from the ship track out to maximum range). Beam formation from such an array demands highly sophisticated engineering involving (1) the geometrical arrangement of the individual transducers, (2) the amount and timing of energy applied to each, and (3) the frequency of that energy (transducer size). The shape of the beam and direction in which it points are changed by varying the electrical timing of the signals fed to different transducers. Although each transducer sends out signals in all directions, the signals radiated from the


Area of specular reflection
Shadow zone
STEAMING
SCANNING or LOOK-DIRECTION
U.S.S.
S.S.S.
Beam breadth
3
6
9
12 seconds
Zenith
MAIN BEAM
SIDE-LOBE
Beam width
Insonified sector
25°
30°
35°
40°
45°
50°
55°
60°
65°
90°
"Across-track"
"Across-range"
smooth fine sediment
lineament
caldera (with central peak)
terrace
"Down-range"
"Along-track"
"Down-track"
Seabed projection of ship's course, track or bearing

different transducers interfere constructively and destructively with each other. In one particular direction the interference effects are constructive, the signals add together, and the array's maximum response is transmitted in that direction. In all other directions the signals interfere destructively and cancel each other out so that very little energy is transmitted there. In sidescan, one seeks a beam that is wide enough in the vertical plane to allow proper insonification of the bottom out to maximum range, but as narrow as possible in the horizontal plane to obtain maximum along-track resolution at that extreme range.

Sonograph formation

From its high-powered transducers, a sidescan array emits short, regularly-spaced pulses of low frequency sound in the form of that vertical fan-shaped main beam or 'principal lobe' which reaches out at right angles from the ship track to sweep along the bottom: thus the sound will intersect the seafloor only in a long narrow strip that is similarly perpendicular to the ship track (see fig. 1). As the sound grazes the bottom at low angles and encounters rough features, it is scattered in many directions, but a small portion is reflected back to the transducers from which it came to let us know something is down there. These echoes are then amplified and transformed electrically into a recordable line of data (one for each sonar pulse) whose amplitude (darkness) depends on both (1) the strength of the energy received at any instant and (2) any boost added by the automatic gain control or time-varying gain. Since sound is incoherent energy, acoustic 'illumination' per unit area falls as a function of range. Increased amplification of increasingly distant echoes serves to compensate for attenuation and this unavoidable spreading loss. The intensity of the resulting signal controls the intensity of the recorded line, with near returns recorded first and echoes from more distant structures recorded progressively later (further across the line). As the vessel advances along its track, these successive closely-spaced lines of reverberation data — each representing the intersection of one acoustic pulse with

← FIG. 1. — United States ship *Sidescan Sonar* underway.

This diagram illustrates many of the more important principles of the technique:

(1) Orientation of the main beam and side lobe(s) with respect to the ship and each other.
(2) Orthogonal nature of sidescan sonar and the terminology most commonly used to describe that nature in the scientific literature.
(3) Increasing acoustic refraction with distance due to density changes (generally temperature stratification) in the water column.
(4) Uncontrolled spreading of the beam (widening in plan view) across the track due to inherent incoherency — this means a signal loss resulting from fewer energy 'rays' per unit area.
(5) Controlled spreading of the beam (fanning in vertical view) across the track.
(6) Change in seabed incidence angle of the beam across the track.
(7) Schematic of an imaginary deepsea bottom bearing the features most commonly observed by SWATHMAP: seamounts and lineaments.
(8) Sketch of the sonogram which would result from that same bottom — note especially the two types of data voids:
  - those resulting from 'shadowing': areas which never received sound (e.g. behind the seamount or near the crater lip);
  - those resulting from specular reflection: areas which received the sound but reflected it away from the ship (e.g. bouncing off the flat terrace or smooth abyssal plain sediments).

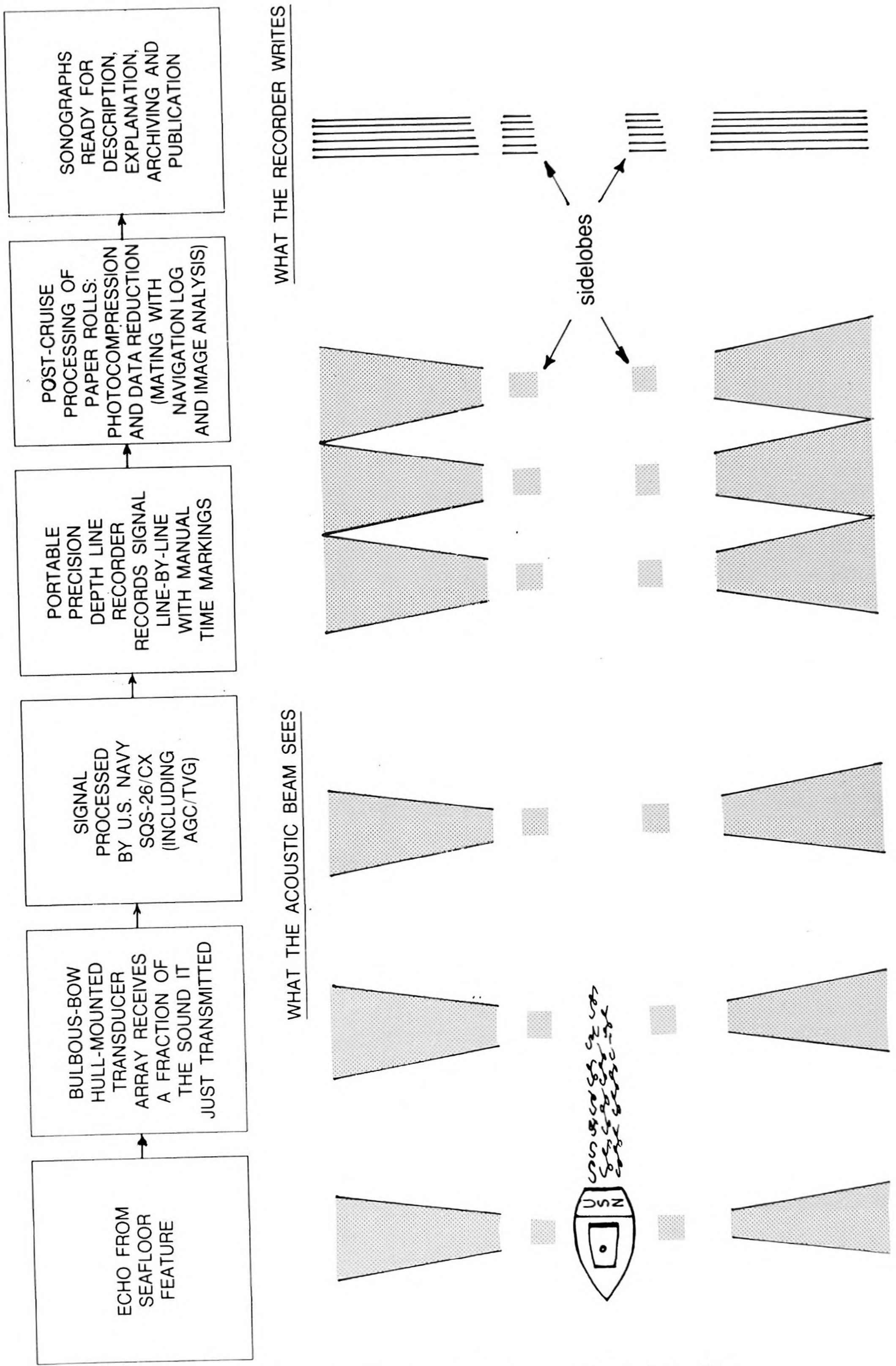


FIG. 2. — The transformation of an echo from seafloor to data archive.

the seafloor — are laid down one-by-one and side-by-side (just like television) to givea continuous coherent 'photographic' image known as a 'sonograph' or 'sonogram' (see fig. 2). The result is a map-like or aerial perspective display of acoustic reflective properties or scattering behavior of the terrain below — images of the shape, trend and texture of seafloor structures which indicate both their form and their location with respect to the ship.

Resolution

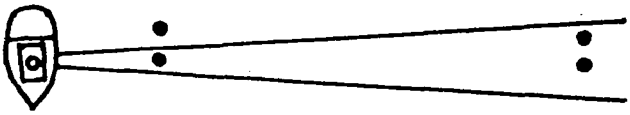
Sidescan sonar resolution (the minimum spacing necessary to discriminate two adjacent features as being distinct from each other) is unique in that along-track and across-track resolving powers can be quite different. Range resolution is completely dependent on the 'thickness' of our sonar pulse and can be estimated (assuming true range ≈ slant range) as:

Mean Sound Velocity × Pulse Length/2
(~ 1500 meters/second) (seconds)

Thus a discrete point acquires an artifact thickness proportional to ping length and two points within that length will not be seen as discrete. SWATHMAP's half-second pings suggest a 375 meter range resolution.

Along-track, at least three factors affect resolution:

(1) Foremost is *horizontal beam width*. In addition to vertical fanning by design across the track, there is unavoidable dispersion in the horizontal plane (see fig. 1) and concomitant deterioration of resolution with range. Even though a relatively narrow beam is used, each pulse insonifies (and therefore integrates) an even larger area of seafloor at ever greater distances away from the ship. Spreading with range destroys the resolving ability which is present closer to the ship: two objects distinguishable at short range may appear as one at long range.



Also affecting resolution is the accompanying decrease in signal-to-noise which results from attenuation and the energy per unit area decrease across track.

(2) While *high ship speed* allows rapid survey, resolution is degraded due to the decreased sampling rate along-track and 'smearing' of any long transmissions. The latter effect both increases beam width artificially and decreases the energy per unit area.

(3) *Yaw, roll and pitch* (usually in that order) can have devastating effect on along-track resolution. Yaw during transmission is particularly troublesome. Its effect is to artificially widen the horizontally narrow beam, averaging even

greater areas over distance and further elongating point targets in a direction parallel to the ship track. Since we derive distance from simple travel time (with no concern for arrival angle), ship roll has considerably less effect. At worst, a serious roll (giving acute arrival angles) will limit the maximum attainable range and affect signal-to-noise, but not resolution or distance estimates. SWATHMAP is quite fortunate in this regard. U.S. warships have a high 'fineness ratio' — *they are made long and thin so as to present a* minimum frontal target and consequently yaw is negligible. The price paid is high roll, for which many ships carry hydroplane-like 'fin-stabilizers'. Taken together, these ships prove impressively stable. Furthermore, their sonar systems can compensate electronically for yaw, roll and pitch. All told, SWATHMAP's down-track resolution at a typical cruising speed of 16 knots (assuming no currents) is delimited by a sampling density of about three pings per kilometer. Widening of the beam across track will degrade this one-third kilometer resolution somewhat further. In addition, objects appearing within only one ping are difficult to distinguish — targets should be large enough so that several echoes render them visible on the record.

Both axes taken together, SWATHMAP's total theoretical resolution is at best 300 to 400 meters, a value which seems to bear out in practice. Resolution could be improved through any of the following:

(1) decreased ship speed (more pulses per unit area)
(2) increased power (more energy per unit area)
(3) increased bandwidth (more energy)
(4) increased array length (narrower beam)
(5) higher frequency (narrower beam)
(6) decreased pulse duration (shorter ping)
(7) decreased range (less spreading, higher repetition rate)
(8) increased array depth (below pycnoclines, closer to subject)
(9) increased ship stability, and perhaps most important
(10) increased dynamic range.

The one factor that has the greatest effect on resolution is acoustic contrast: a target's ability to scatter energy relative to the adjacent seafloor (a function of rigidity, slope or acoustic impedance contrast). Unless it is tall enough to cast a shadow, its gray level must differ substantially from the overall shade of the surrounding field to be visible on a sonograph. Accordingly, the single greatest improvement would be enhancing our ability to record these contrasts. Quantification of echo strength or analog color would be optimal.

Range and coverage

The *area of the seafloor illuminated by a sidescan system* is a function of vertical and horizontal beam width, inclination angle, distance from the bottom and frequency. SWATHMAP's poor resolution is the price paid for its rapid coverage, a rate made possible by hull-mounting (high speed), great acoustic power and low frequency. The natural density (temperature and salinity) stratification of the ocean redirects vast amounts of energy which would otherwise aid both resolulution and range. This is particularly a problem in warm waters. Given the intensity of our decibel level and the open conditions in which we usually work (free of the radical stratification one finds in shallow or enclosed waters), achieving maximum range has not generally been a problem. Our maximum — 30 to 40 km depending on the depth and slope of the bottom — is at the theoretical ('grazing') limit imposed by refraction of sound away from the seabed, the bending becoming more pronounced at greater ranges:

> The steadily rising velocity at great depths gives the sound rays an upward curvature such that a ray launched at a shallow (or intermediate) angle becomes horizontal before it reaches the bottom. This gives rise to the so-called Deep Shadow Zone and limits the range, at any depth, at which sidescan sonar remains effective ... Of course, greater ranges can be obtained if the ground slopes upward. (SOMERS, 1977).

With scanning to only one side of the ship, our coverage is currently half the 60,000 plus km^2 per day that is possible when we overcome the problem of 'cross-talk': the confusing tendency of one side to receive the other side's echoes (on top of its own) and vice-versa. To avoid cross-talk, we must either (1) scan the two sides alternately (which means a concomitant reduction in resolution because of fewer signal pulses per unit of seafloor), or (2) somehow differentiate the two *arrays* — we can supply each side with a slightly different frequency and engineer each to ignore all except that which it broadcasts. Within the limits of the hardware's bandwidth sensitivity, these two frequencies can be quite close (so that the trade-offs inherent in a given frequency choice are little different from side to side), but the selection is still a delicate balance of parameters. In the GLORIA II system, for example, 'the pulse is impressed on two different carrier frequencies, the choice of which is a compromise between keeping them both near the optimum transducer frequency, and yet providing sufficient separation for efficient filtering to suppress cross-talk' (SOMERS *et al.*, 1978).

INTERPRETING SWATHMAP RECORDS

The factors one considers in sonograph interpretation are tone/intensity, texture/pattern, shadow, location, orientation, size and shape. The manner in which we derive this information is elaborated herewith.

Echo strengths and shadows

A relief feature will only show well if it gives a strong reflection or casts a significant shadow. Because it gives the illusion of sunlight on landscape, the GLORIA team has chosen to print sonographs such that features reflecting sound are light-toned, and those in shadow (or consisting of minimally reflective fine-grained sediments) appear dark, giving the appearance of illumination coming from the top of the sonograph (near the ship). (Two of GLORIA's best images appear in the seamount and abyssal hill sections which follow.) Because so much of the Pacific Basin appears smooth and featureless (like white paper), SWATHMAP records seem a bit clearer when printed so that steep topographic highs appear as dark areas, weaker reflections from gentler seafloor or smoothly sedimented areas appear gray, and acoustic shadows appear white (apropos to the data voids they represent). Such voids result primarily from (1) slopes facing away from the ship, (2) specular (mirror-like) reflection away from the ship, and secondarily from (3) refraction or (4) absorption into the seabed (a problem at these low frequencies).

With sufficient dynamic range, the stronger the returning signal, the darker will be the mark on the film or paper. Reflection strength or image intensity (gray level) confuses the effects of two different seafloor characteristics: topography (slope variation at numerous scales) and acoustic behavior (variation in surface material or texture). Surfaces inclined or oriented toward the sonar — or, more accurately, slopes perpendicular to the across-track-varying acoustic ray paths — provide the strongest returns. Slopes facing away yield shadow. The gray spectrum between these two extremes results from the balance between specular reflection away from the sonar and weak backscatter toward it. But variations in gray level can also result from differences in acoustic penetration between rock and sediments (though large grain size or high compaction can work to reflect sound as efficiently as rock). Both effects are frequency dependent: short wavelengths can image small surfaces with minimal penetration, but long wavelengths such as SWATHMAP's 43 cm will be reflected only by sufficiently large surfaces. Low frequency, moreover, also means great penetration. Consequently it is hard to distinguish between an unfavorable inclination or orientation and an absorptive seafloor. As a result, SWATHMAP theoretically has poor discrimination ability between slope and substance. Rather conveniently though, steep slopes tend to be formed of highly reflective rock and gentle slopes tend to accumulate poorly reflective sediments. Thus our desire to view SWATHMAP's returns as genuine topography is not nearly as corrupt as theory suggests. We need only be wary that the same smooth surface which reflects sound away from the ship would return ample sound if there is surface roughness on a scale comparable to the sonar wavelength used. Even flat bottoms give good returns if they have texture or incorporate slopes — smooth or rough — which face the ship.

Let us consider the signal return from a hard disk sitting on a typical smooth bottom. With the gain of the receiver set so that the backscattered return from the uniform flat bottom writes as gray on the graphic recorder, the reflection from the face of the disk is stronger than any others and writes as a curved black line. The disk casts a shadow that is outlined by the gray return from the uniform bottom. Holes or depressions also show as shadows, with the back of the hole reflecting sound quite well. Holes are distinguished from elevations by the position of the strong reflections relative to shadows. Figure 3 presents several permutations of shape and shadow that are commonly observed undersea. Throughout these discussions, the appearance of a small black arrow indicates the scanning vector or look-direction.

Even though shadows represent some loss of terrain information, their existence actually assists us in several ways:

(1) Dark returns accompanied by shadow are not merely strongly reflective lowlands, so topography can be confirmed.

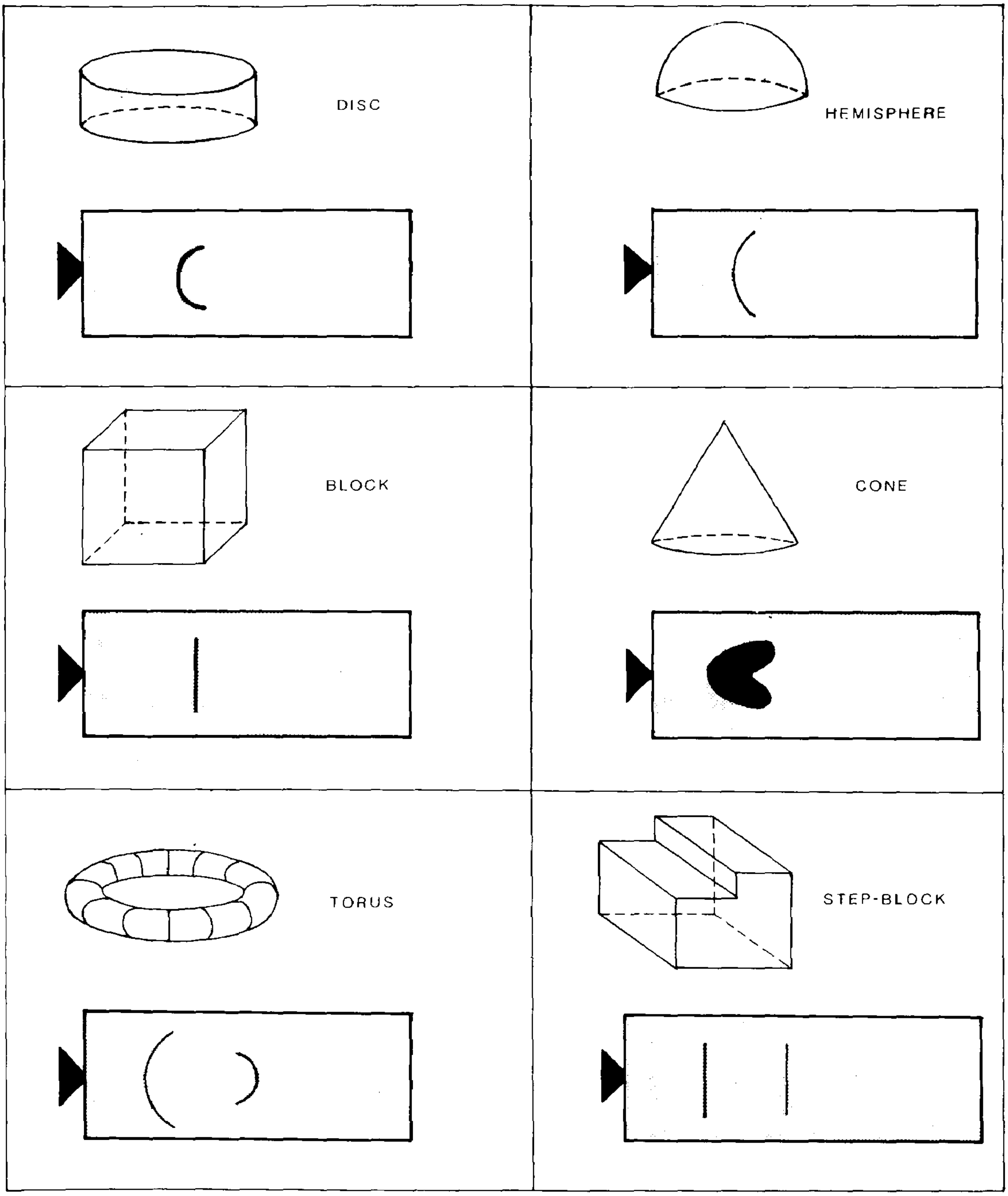


FIG. 3. — Approximation of sonograph appearance for some standard solids. Note relative echo-strengths and shadow shapes. The uniform gray represents specular reflection: an area where most of the sound energy is exported away from the ship.

(2) Even features which are poor reflectors may show up thanks to shadow.

(3) Linear geologic features (often low and long) are particularly enhanced by the shadow characteristics and synoptic view which sidescan offers.

(4) With an idea of the local ray paths, shadows even allow height estimates. Certainly the taller an object is, the longer a shadow it casts. More subtle, however, is the increase in shadow length across an image as the decreasing angle of incidence gives an increasingly horizontal approach to the sound. Thus one is cautioned that the exact same object will cast different shadows at different distances from the sonar — without any change in height.

Sidelobes and foreshortening

Between the near edge of the main beam and the floor directly below the ship, weaker secondary beams termed 'sidelobes' reach the seafloor at steeper inclination angles up to ninety degrees vertical (see fig. 1). LEENHARDT (1974) notes, 'the transducers will have either a single or several sidelobes according to the degree of care taken in their design. The best instruments are those where only one sidelobe is retained' — like SWATHMAP. Because of their short range and steep incidence angle, sidelobes can produce quite strong echoes, and despite the information inevitably lost in the dead spaces between them, they can confirm the existence or continuance of a trend suspected at greater range. When viewing a sonograph, one must keep in mind the change in ray angle from the ship track (vertical) across the sidelobe (steep) to the outermost reaches of the main beam (grazing). 'Where water depth is an appreciable fraction of the sonograph range, the resulting picture is distorted from a true plan view. At the closest range, the sonograph gives a narrow beam bathymetric profile beneath the vehicle, whereas at longer ranges it approximates a plan view of the acoustic highlights of topographic relief' (LAUGHTON and RUSBY, 1975). All first returns can be most valuable in providing an oblique profile of the seafloor adjacent to the ship and parallel to its track.

The portion of a sonograph resulting from both the sidelobe and the near edge of the main beam also exhibits foreshortening, a phenomenon better known with side-looking radar. Since these records are drawn strictly on the basis of time, and since it takes just that much more time for sound to reach down to the bottom of a seafloor pit and return, depressions occurring on sonographs will appear slightly displaced (away from the ship track) with respect to their true position. In a similar manner, a ship approaching a seamount may very well pass much closer to its peak than to its base. Naturally, any sound emitted will echo off that peak first and off its base moments later — uncorrected (unmigrated) sonographs will display these echoes in that same order. Accordingly, the image of a point rising above the general bottom is shifted toward the ship track (to a degree proportional to that elevation and its position relative to the ship). MALAKHOV (1978) elaborates:

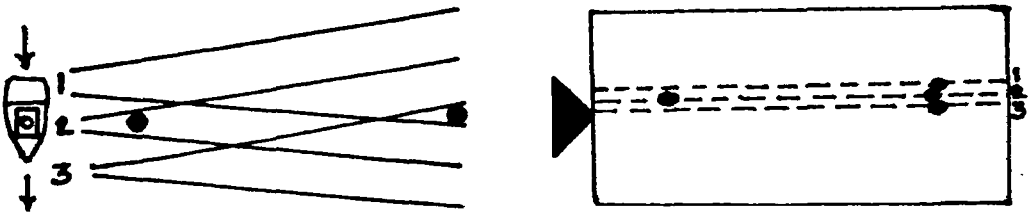
> The image of a point rising above the average surface of the bottom is shifted in the direction toward the sonar antenna; on the other hand, when the point is situated below the level of the average surface, its image is displaced in the opposite direction. As a result, the images of two neighboring objects in the sonar picture can approach one another, coalesce and even be positioned in the reverse sequence.

Taken together, foreshortening and the oblique profile nature of the early returns give all raw sidescan a most unusual anamorphic geometry wherein the near edge of the sonograph (the portion of the image closest to the look arrow or ship track) has the appearance (and to some degree the function) of a conventional reflection profile, while portions immediately below are close to plan view. Some are more comfortable viewing sonographs as if seen from an airplane: map-like in general with a horizon off to the edge.

Directional prejudice

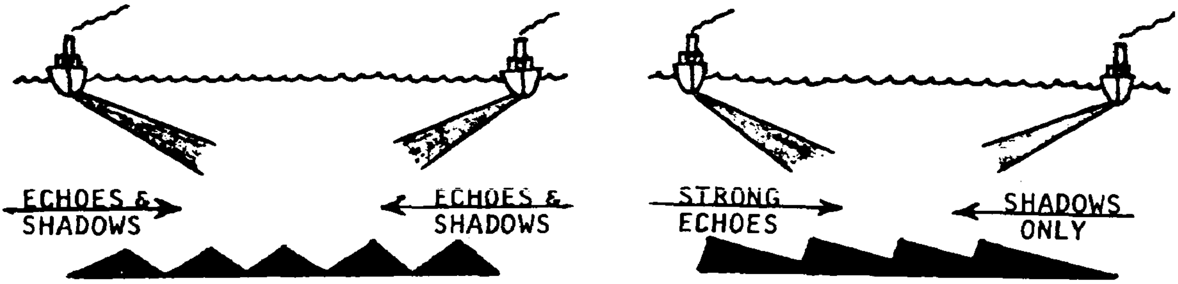
It is inherent in the nature of the sidescanning process that a bias will occur parallel to the track. Trends in this orientation are emphasized to the exclusion of those in any other. The very same seafloor can look very different from different look-directions. Undulating or corrugated bottoms, acting like a bank of mirrors, show far better when a course is run parallel to the crenulations than perpendicular to them. In a like manner, a feature (say a seamount) viewed downslope is much less distinct than a distant seamount whose upslope faces the wavefronts in a more orthogonal manner. Knowing this can greatly assist our choice of bearing during a survey over previously observed terrain. But it can also be a hindrance: single tracks over unknown areas can illuminate trends which are secondary to the geology of the region, leading us to inaccurate conclusions about tectonics. Primary trends running perpendicular to the ship track are so easy to miss that when they *do* show up, one is well advised to accept them only with the greatest caution.

The problem is compounded by simultaneous point-elongation along-track. A distant feature will scatter or reflect energy over a larger number of pulses than does a similar feature close to the ship track. Thus it will appear longer. Consider two points of the same size at different distances from the ship.



Notice that the near point will be seen by one sonar pulse, but the distant point can be seen by three or more. This results in artificial elongation parallel to the track. Adequate ping separation (by high ship speed or beam thinness) minimizes this effect.

Generally, sonographs taken from opposite sides of the same seafloor show a considerable degree of symmetry. Lineations which show well when insonified from one side can, however, appear very different — or not at all when seen from the other: occasionally only long linear shadows will record their existence.



One is cautioned, then, that different look-directions can give very different images for the exact same seafloor.

The change in angle of attack across track gives longer shadows and more of a plan view the further we get from our array. Simultaneous beam-fanning across-track gives weaker reflections and elongation of points parallel to the track. Taken together, these four range effects can give the very same objects very different appearances at different ranges. Given all of the problems inherent in point-of-view, the very best data are those which result from a synthesis of views taken across the same area at different orientations, look-directions and ranges. Such multiplicity is a luxury few can afford.

Estimating true co-ordinates: The slant range problem

The horizontal narrowness of a sidescan beam allows assumption of perpendicularity from the well-known shiptrack. Barring major navigation errors, the along-track co-ordinate is thus easily discerned. Obtaining the cross-track co-

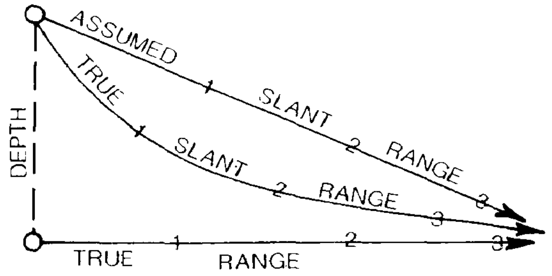


FIG. 4a

ordinate is a bit more of a challenge (see fig. 4a). A geometric problem common to all sidescan systems is the non-linear relationship between distance along an acoustic ray path (the triangle's hypotenuse) and the horizontal distance along the ground over which it passes (the triangle's base). Common line recorders register sonar echoes as a function of time, not distance. Consequently, one records slant range instead of true range, a projection discrepancy which is particularly severe close to the ship and in deep water. At low grazing angles, the difference between horizontal and slant range is small (and for most purposes negligible). Even so, the entire trace is shifted by the near-ship slant range problem: for low objects on the bottom (i.e. those whose position is not further corrupted by foreshortening), estimates of distance from the ship track based on simple travel time are overestimates, their actual position being slightly closer to the ship.

It would be most novel to have a recorder's stylus lay its data down differentially with range, but the easiest way to correct for those portions of the sonograph most affected by slant range — usually taken to be the first third of the record in deep ocean — is to assume the perfect triangle which would be present in isopycnic water conditions. If the terrain is smooth and not sloping, a fair estimate of true range will then be given by trigonometry (if the inclination angle is known) or Pythagorean theorem:

$$\text{true horizontal range} = \sqrt{\text{slant range}^2 - \text{nadir depth}^2}.$$

For SWATHMAP, such an estimate would be drawn from the dimensions shown in figure 4b. Generating a linear correction curve, table or graphic overlay from such data is a relatively simple way to produce estimates of distance from the ship track.

A higher order slant range correction than this would require water temperature and salinity profiles (or sound velocimeter data) to compute the actual ray-bending due to refraction. (Project SWATHMAP's founder, Dr. Wilton HARDY, did in fact do this.) Using an average sound velocity profile, we have drafted a correction overlay (or 'nomographic transparency') accurate enough that our off-track estimates are well within the resolution of our system. This elementary acoustic modeling is an essential part of our data reduction.

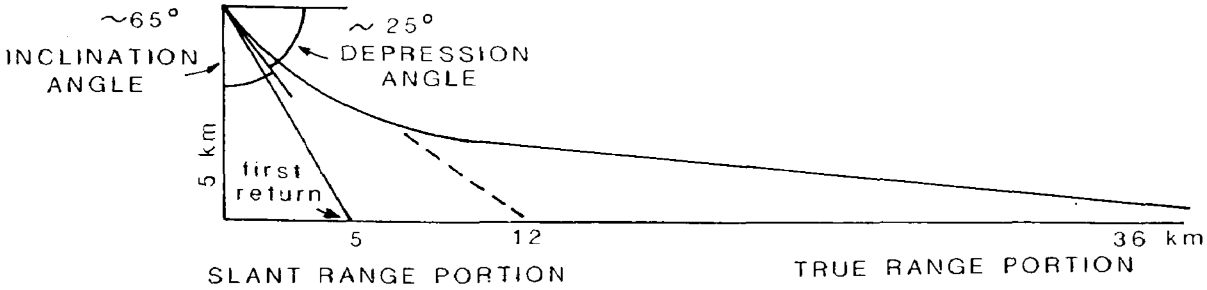


FIG. 4b

Estimating true shape: The ratio problem

Unprocessed sonographs never represent isometric maps of the seabed. True cartographic shape is distorted by four processes:

(1) the slant range variation problem discussed above
(2) differential along-track and across-track scales
(3) changes in ship speed without changes in recorder speed, and
(4) course changes.

One of the difficulties in interpreting sidescan records arises from the distortion of the sonograph caused by a difference in scale factor along and across the swath. It is possible to prevent this by (1) reducing ship speed, (2) radically reducing the printed scan length, or (3) accelerating the paper feed rate. One finds that ship time is costly, short scans give you little more than an undecipherable spaghetti strip of data, and fast feed uses excessive amounts of paper with intolerable amounts of space between scan lines (though one can repeat the previous line to fill such voids). Consequently, analog system live with this inherent nuisance and compress the image sometime later. While one may digitize the image with a microdensitometer and computer-manipulate it at will, photographic anamorphosis is far cheaper and the method of choice for low cost science such as this. As long as it is uniform, it is often useful to maintain some exaggeration, and on most images I've chosen to leave some of the distortion in. This may annoy the uninitiated, but full photographic compression to actual dimensions (like short scans) reduces the image to insignificance and eradicates detail. As with the early GLORIA records:

> A few of the sonographs represent an almost true plan view, but the great majority have a somewhat exaggerated width scale. This, while causing a loss of true shape and orientation, can have some advantages, not unlike the vertical width exaggeration of echo-sounder or sub-bottom profiler records ... Also, the width exaggeration makes shadows more dramatic by lengthening them (since these are always presented at right angles to the ship's track, and so extend in the width direction of the sonograph). A further aspect is that elongate shapes other than those parallel or nearly parallel to the ship's track will have their linearity exaggerated and so made more obvious, whereas the apparent angular changes in trend will be greater than their true angular change when parallel or nearly parallel to the ship's track, and less than true when approaching right angles to the ship's track. (BELDERSON *et al.*, 1972)

If one disagrees with the value of exaggerated scale, it is certainly possible to render an image fully compressed to true scale. A problem that is more difficult to fix is that which results from currents and changes in ship speed. Like the rubber currency one finds at a magic shop, it is easy to see what havoc differential stretching can wreck upon an image. PALUZZI *et al.* (1981) explain:

> Side-looking sonar imaging depends on the forward motion of the transducer to construct the image raster. Sonar pulses commonly recur at fixed repetition rates while underway. Hence, scans will be made at constant intervals in time and not in fixed intervals of distance along a track-

line. This results in an along-track or ship speed distortion when the scan line is written on a recorder with a fixed feed rate. Some recorders can alter the feed rate according to water speed; this too may distort the image if there are strong currents or drift.

The progressive shortening of the along-track component with increasing ship speed has no effect on the cross-track axis. The effect is exactly the same as the unequal ratios mentioned above — only the variability is particularly troublesome. SWATHMAP is unusually lucky in this regard: Navy transits tend to hit a cruising speed and stay there.

Ratio's greatest effect is on the determination of true submarine trends. Apparent angles must be anamorphosed optically, graphically, mathematically or digitally to obtain true global angles. Apparent angles (θ_A) are related to true angles (θ_T) by a simple relationship:

$$\text{tangent } \theta_T = \text{tangent } \theta_A \times \frac{\text{paper length across maximum range}}{\text{paper spent along track for the same distance}}$$

Estimating height and depth

Given their inclination or depression angle, the appearance of either a sidelobe echo or the first point of contact of the main beam allows an estimate of the depth a few kilometers off the track. These are the least refracted parts of the sonar field, allowing a simple calculation from trigonometry:

off-track depth = cosine of the inclination angle × slant range of first echo.

The accuracy of edifice height estimates from shadows depends on the excellence of our ray path estimates. Near the ship, as above, assumption of a simple triangle allows a fair approximation from trigonometry or Pythagorean theorem (see fig. 5a):

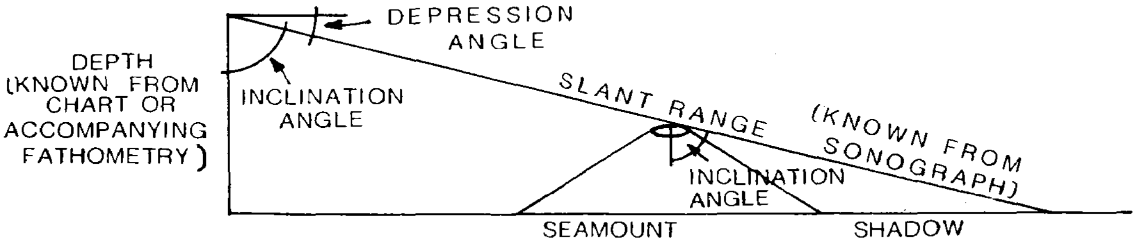


FIG. 5a

$$\text{edifice height} = \frac{\text{shadow's slant length} \times \text{nadir depth}}{\text{shadow's slant length} + \text{range to edifice center}}$$

edifice height = cosine of inclination angle × shadow's slant length.

Such height estimates are not possible in the far field where rays parallel the seabed or anywhere that shadows run off the paper's edge.

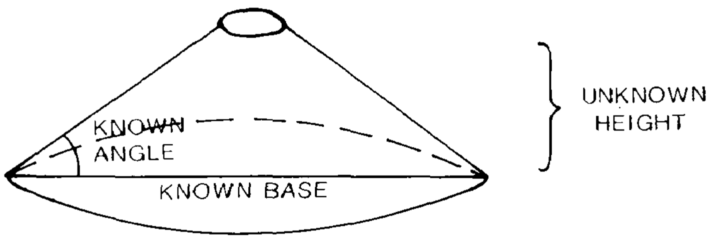


FIG. 5b

Seamounts approximate a standard slope of 15° frequently enough that one may also estimate their height via trigonometry, knowing only the size of the base, a piece of information readily discernable on a sonograph (see fig. 5b). Convergence of estimates from both slope and shadow provides the most certain quantitative readings of these qualitative data. More systematic methods of depth determination are under study.

RESULTS

Seamounts

Comprehensive knowledge of the world's most abundant volcanoes is important to several fields of human endeavor. Economic interests include their association with fishing grounds and ocean mining (hydrothermal polymetallic sulfides at the top or ferromanganese crusts on their sides). Military interests include (1) avoidance of uncharted navigational hazards, (2) concern over uncorrected gravitational influences on inertial navigational systems, (3) barriers to acoustic propagation, and (4) convenient basing of acoustic navigation beacons or anti-submarine warfare hydrophones. Earth scientists are interested in their effect on benthic currents, ability to reveal tectonic clues and the degree of mantle homogeneity.

One of the most profound discoveries in marine geology is the ever-increasing estimate of the world's seamount population. Covering 10% to 20% of the seafloor (MENARD, 1969), and comprising at least 5% and possibly 25% of the seafloor volcanic layer (BATIZA, 1982), up to one quarter of the oceanic crust may be accounted for 'not by the near horizontal sheet usually envisioned but by the volcanic features superimposed on it' (SMITH, 1983). Even on young crust, 'seamounts occupy about 6% of the seafloor area and constitute 0.4% of the oceanic crustal volume' (JORDAN, MENARD and SMITH, 1983). Estimates of Pacific Basin seamounts taller than one kilometer have ranged from a low of 4200 on Soviet charts (LARINA, 1975) to a high of 12000 on the ca. 1970 Scripps charts (BATIZA, 1982). Current rates of discovery suggest a Pacific total of 22000 to 55000 (ibid.). Unlike the size/frequency spectrum on land (FRANCIS and ABBOTT, 1973), low mountains predominate undersea (LARINA, 1975; UDINTSEV *et al.*, 1976), and in fact seamount distribution is 'Poisson-like' (BATIZA, 1982; BATIZA and Vanko, 1983/4) or very nearly exponential (Jordan, Menard and Smith, 1983), with small mountains far more common than large ones. Size increases with distance from a mid-ocean ridge (Menard, 1969), with the maximum size generally increasing as a function of lithospheric age (Vogt, 1979). Volcanoes can erupt on lithosphere of any age, so the density (and average size) of seamounts increases into the past simply because older lithosphere has been around longer.

Given their relative size distribution, it is at the small end of the scale that most seamount discoveries remain. While the next generation of satellite altimeters will soon fix the number and location of all large seamounts, that myriad below about half the ocean depth or isostatically compensated by virtue of genesis soon after crustal formation are generally not amenable to detection from space. Given the difficulties inherent in magnetic, gravimetric, altimetric, passive (e.g. Johnson, 1970, 1973, 1976; Johnson and Norris, 1972; Norris and Hart, 1970; Norris and Johnson, 1969) and horizontal (e.g. Dyer *et al.*, 1982; Erskine *et al.*, 1984, 1985, 1986; Schifter *et al.*, 1986) detection of low edifices through a couple kilometers of sea water, most seamount detection will continue to depend on the excellence of the acoustic surveys upon which the bulk of our knowledge of bathymetry is based. Lambeck and Coleman (1982) note, 'With the exception of some of the large volcanic islands, submarine seamounts rarely exceed about fifty kilometers in diameter at their base and for them to be located by conventional bathymetric surveys, the ship tracks must lie within a few tens of kilometers of each other. This is seldom achieved.' Consequently, many of these features are yet to be discovered, particularly by wide swath sonars. SWATHMAP, for instance, routinely finds a few new seamounts on each cruise over a data base thought pretty reliable by virtue of its location under common shipping lanes (see table 2). One can surmise that the discoveries awaiting us in the largely unexplored polygons of territory between these well-known strips are indeed substantial. All four deepsea sidescan systems have observed seamounts and published their images:

TABLE 2

Some significant new seamounts found by SWATHMAP
(against 1970 Scripps charts)

Cruise	Latitude	Longitude	Diameter	Estimated Height	Figure
II	13°28′ N	140°08′ E	7.5 km	1000 m	7
II	12°10′ N	134°14′ E	22 km	2950 m	not shown
II	13°01′ N	134°23′ E	15 km	2000 m	not shown
IV	19°23′ N	176°32′ E	11 km	1500 m	not shown
IV	15°45′ N	152°56.5′ E	13 km	1750 m	8
IV	14°63′ N	149°45′ E	16.5 km	2200 m	8
V	5°50′ N	165°16′ W	9 km	1200 m	6

1. GLORIA in the Tyrrhenian section of the Mediterranean (Belderson, Kenyon and Stride, 1974), upon the Mid-Atlantic Ridge (Laughton and Rusby, 1975) and Walvis Ridge (Laughton, 1981), across the Nazca region of the East Pacific (Searle *et al.*, 1981; Searle, 1983), and along North America's west coast (publication pending).

2. SeaMARC I on the East Pacific Rise (FORNARI, RYAN and FOX, 1982, 1984).
3. SeaMARC II on the Mariana forearc (HUSSONG and FRYER, 1983).
4. SWATHMAP throughout the Pacific (ANDREWS and HUMPHREY, 1980; HUMPHREY, 1984).

Two seamount morphologies commonly appear on SWATHMAP sonographs: (1) seamounts large enough to appear foreshortened toward the ship track (like fig. 6) and (2) cones seen close to plan view (like fig. 7). Less commonly one observes guyots (fig. 8) which, by virtue of their large size would indeed be expected less frequently. These images are cross-track exaggerated — the viewer is invited to 'sidescan' the image himself (by placing the tip of the nose upon the look arrow) for a more realistic perspective. Dashed lines show the author's interpretation.

Figure 7 illustrates two seamounts along 13°28′ N on either side of 140°24′ E (between Guam and the Palau-Kyushu Ridge). Both are exaggerated across track, roughly conical in actual appearance and apically depressed. Neither of the structures casts much of an acoustic shadow, which confirms that they are relatively small seamounts — anything much larger would produce more appreciable shadowing by blocking part of the sonar beam. The west (left) cone (about 7.5 km wide and 1.3 km high) appears to have a summit caldera. The right (east) cone is about 11 km in diameter with a trigonometric height estimate of 1.5 km (also the value shown on the 1970 Scripps charts). Most intriguing is the appearance of what appears to be a summit peak here. ANDREWS (in ANDREWS and HUMPHREY, 1980) suggests there is a small parasitic cone on the southern flank, like California's Mt. Shasta. I interpret this return as the inner side of the caldera's far wall which turns the intermediate echoes into a central peak, looking very much like Crater Lake, Oregon.

Trench crossings

SWATHMAP has had several opportunities to image deepsea tectonic trenches. A particularly fine example is figure 8 (along about 14°30′ N, see fig. 9), shown at 11X and 3X exaggerations, both of which show even smaller exaggerations for half the trace. Recall that the unusual geometry created by foreshortening and proximity to the ship track (nearest the look arrow) gives the image's lowermost portion the appearance (and to some degree the function) of a conventional reflection profile while portions immediately above are close to plan view. The oscilloscopic wanderings of the thin black 'depth profile' line of first returns demonstrates an outer slope (down-going side) that is steeper than its inner slope (arc side) counterpoint to the west. Numerous conventional bathymetric observations (e.g. MROZOWSKI and HAYES, 1980; HUSSONG and UYEDA, 1981; KARIG and RANKEN, 1982) frequently confirm the existence of the ridges we observe on figure 8's arc slope (MOORE and KARIG, 1976).

Four seamounts appear on the section of seafloor adjacent to the trench in figure 8, separated by very uniform expanses of what appears to be smooth sediment. The Magellan pair furthest from the trench may well be related genetically, but only one grew to heights sufficient for subaerial erosion: it is a guyot (MENARD, 1984). Most interesting is the Mariana Basin peak nearest the trench — so near, in fact, that it has almost begun descending. The proximity of this seamount to the trench has in some way given this slope a greater steepness than it would otherwise have had steeper, in fact, than its forearc counterpart to the west. This may be a lopsided guyot, but one side bears a (fault-generated?) scarp, sharper than those on either side of the guyot to the east, an edge so abrupt it may well be due to initial breakage on the way into the trench (50 km away from the 9000 m deep axis). Given a convergence rate of 10.7 cm/year (MINSTER and JORDAN, 1978), we may estimate the time of total breakup for this 40 km wide seamount as 370,000 years, and if perchance a seamount can maintain its integrity all the way to the trench axis, it will still last less than half a million years.

Abyssal hills

Abyssal hills are the most common morphologic feature on the face of the earth, covering about 85% of the Pacific Basin floor (MENARD, 1964). Numerous studies have shown widths ranging from 1 to 20 km and relief of 50 to 1000 m. With no statistical studies to date, it is difficult to declare their mean, but 5 km wide and 200 m high is probably not too far off. Lengths are highly variable, but always on the order of several tens of kilometers. Size variance aside, abyssal hills share several remarkable geometric traits: (1) they are low, long and thin, (2) they are mutually parallel to an extraordinary degree, (3) they closely parallel the local magnetic anomalies, and (4) they parallel the associated mid-ocean rise from whence they came. Seen from plate tectonic theory, it is no surprise that elongate abyssal hills parallel linear magnetic anomalies and the ridge from whence they came. What is most intriguing is our ability to infer the direction of any two given only one of the three. In their Nazca survey, SEARLE *et al.* (1981, see fig. 10) note, 'Throughout this plate the seafloor is characterized by linear, parallel ridges that are bounded by faults formed at and parallel to the spreading axis so one can, in general, infer paleo-spreading directions to have been perpendicular to this observed topographic and tectonic fabric.'

Sidescan sonar, by virtue of its acute 'illumination' or grazing angle, emphasizes the form of the seabed, and the large area that can be surveyed under almost constant conditions serves well the recognition of extensive features. The aforementioned tendency of sidescan to accentuate features parallel to the track can work very much to our favor here, provided the proper direction is chosen (or stumbled upon), or a general orthogonal survey is carried out. One is particularly impressed by the relative ease with which tectonic trends can be recognized in the West Philippine Basin, compared to the large amount of echo-sounding which would be needed to attempt the same job (see fig. 11).

Figure 12 shows one such image under the central Philippine Sea along about 13°30′ N. We know they are hills instead of channels because the white shadows appear behind the strong dark echoes (with respect to the ship) and not

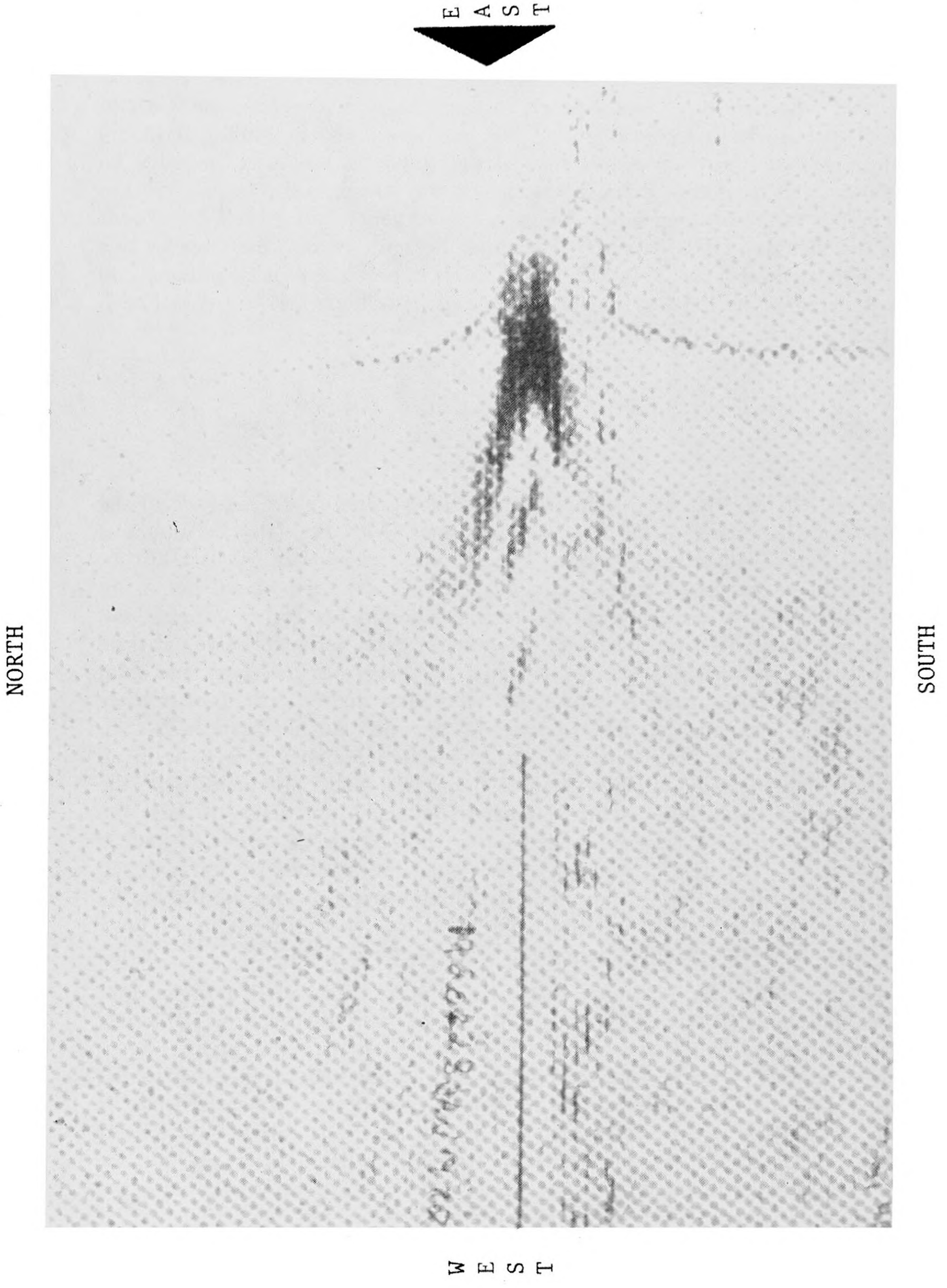


FIG. 6a. — Sonograph of a severely foreshortened Central Pacific seamount.

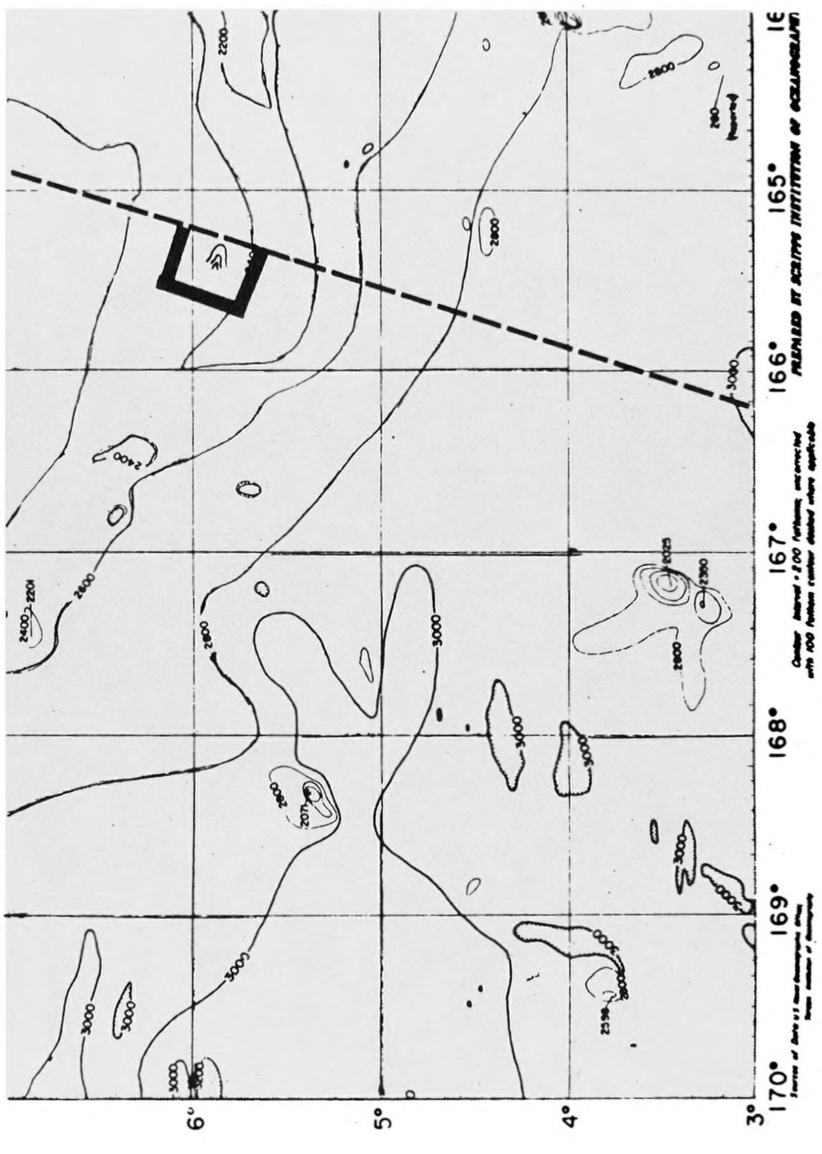


FIG. 6b. — Location of the new Central Pacific seamount shown in Figure 6a.

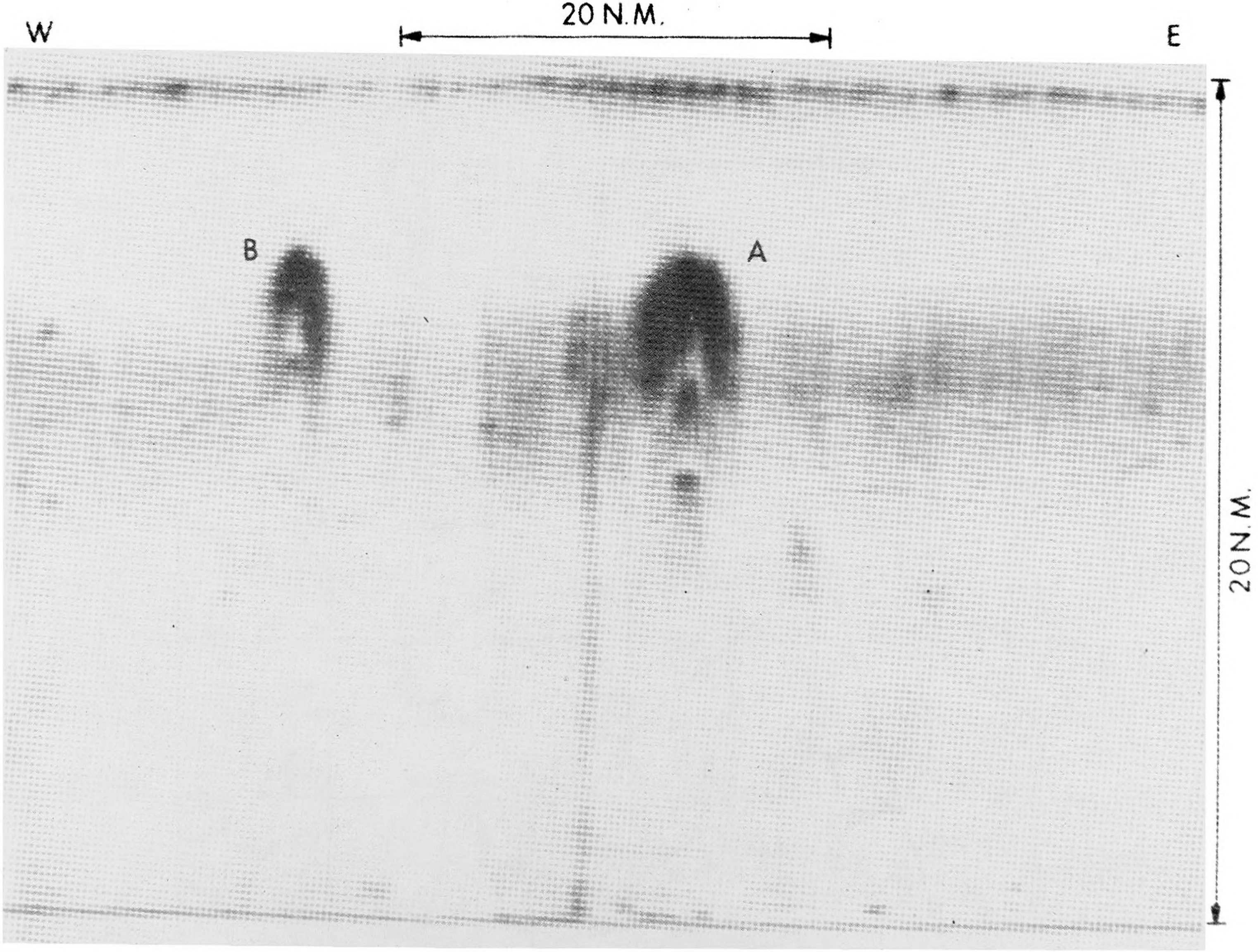


FIG. 7a. — Pair of cratered volcanic cones under the Philippine Sea.

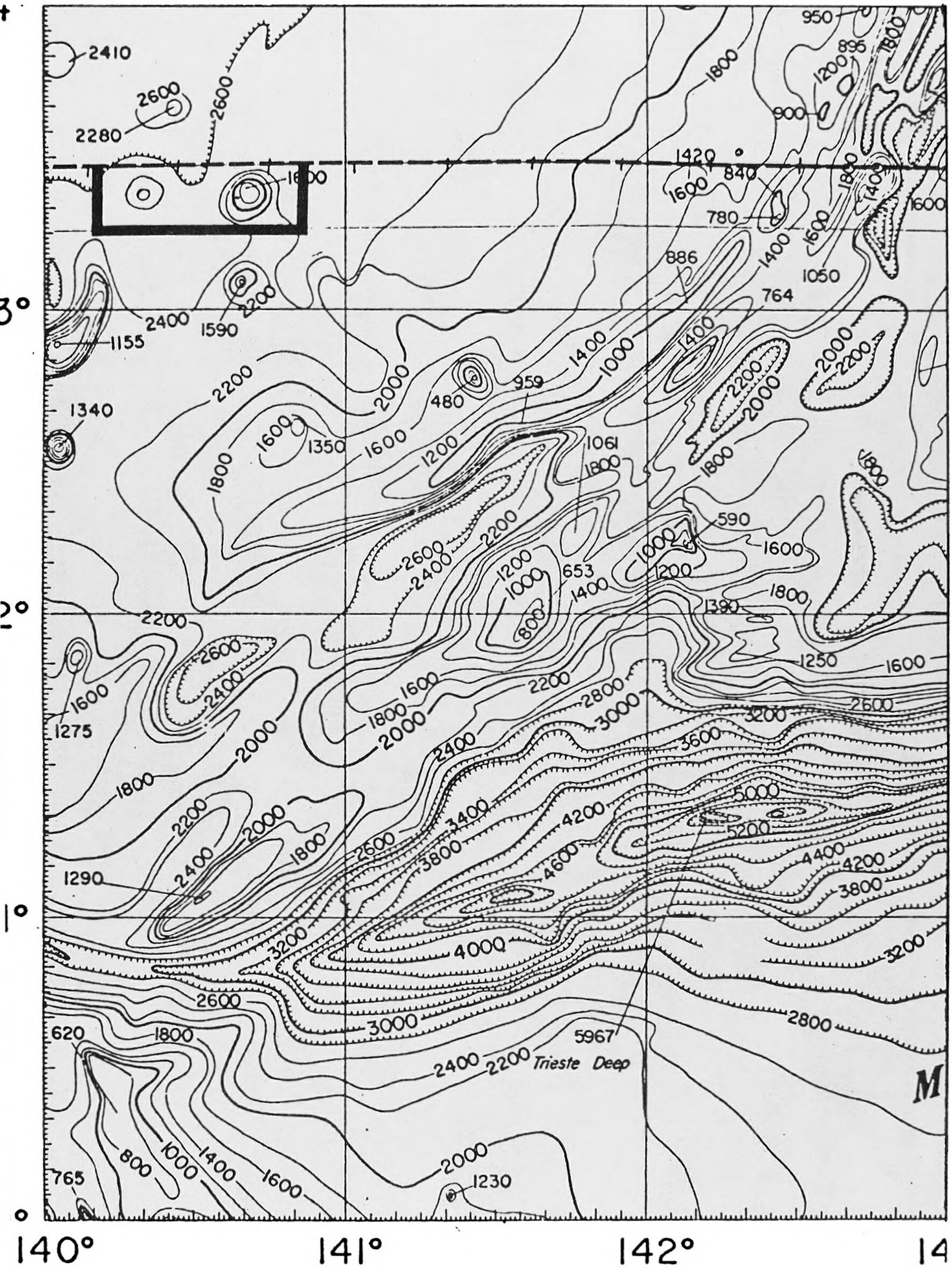
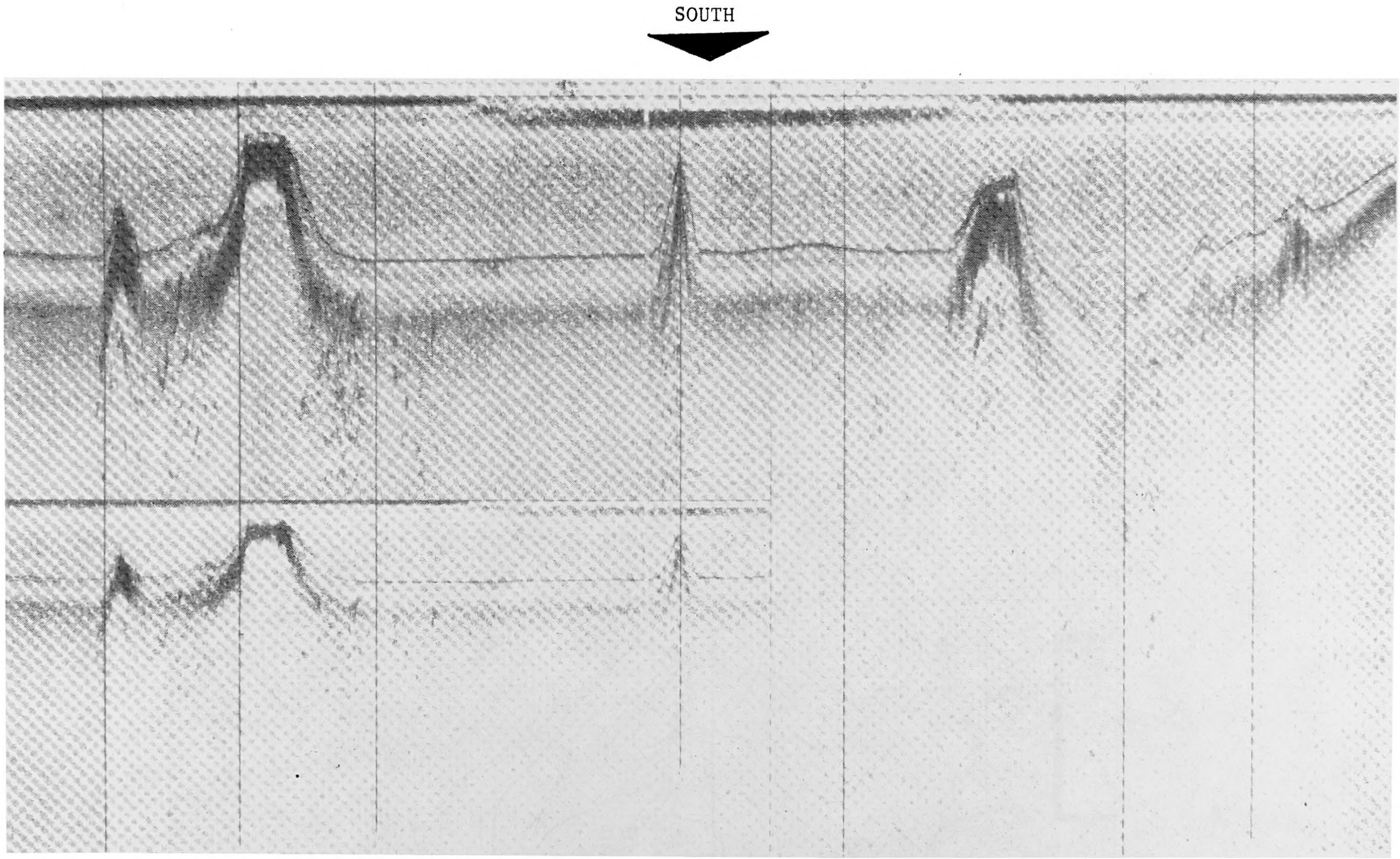


FIG. 7b. — Location of volcanic cones seen in figure 7a.


SOUTH

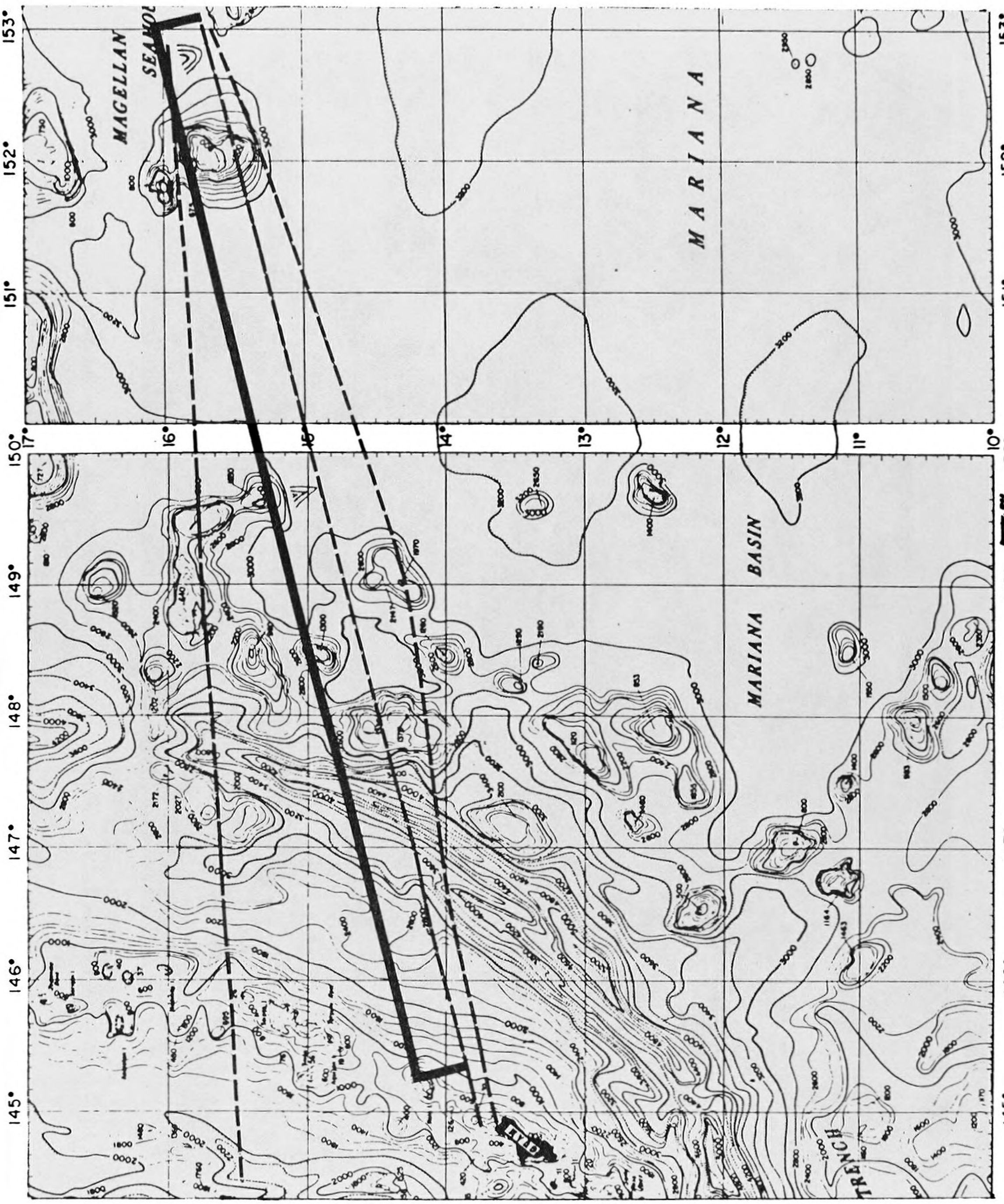


FIG. 9. — Location of Mariana Trench crossing shown in figure 8.

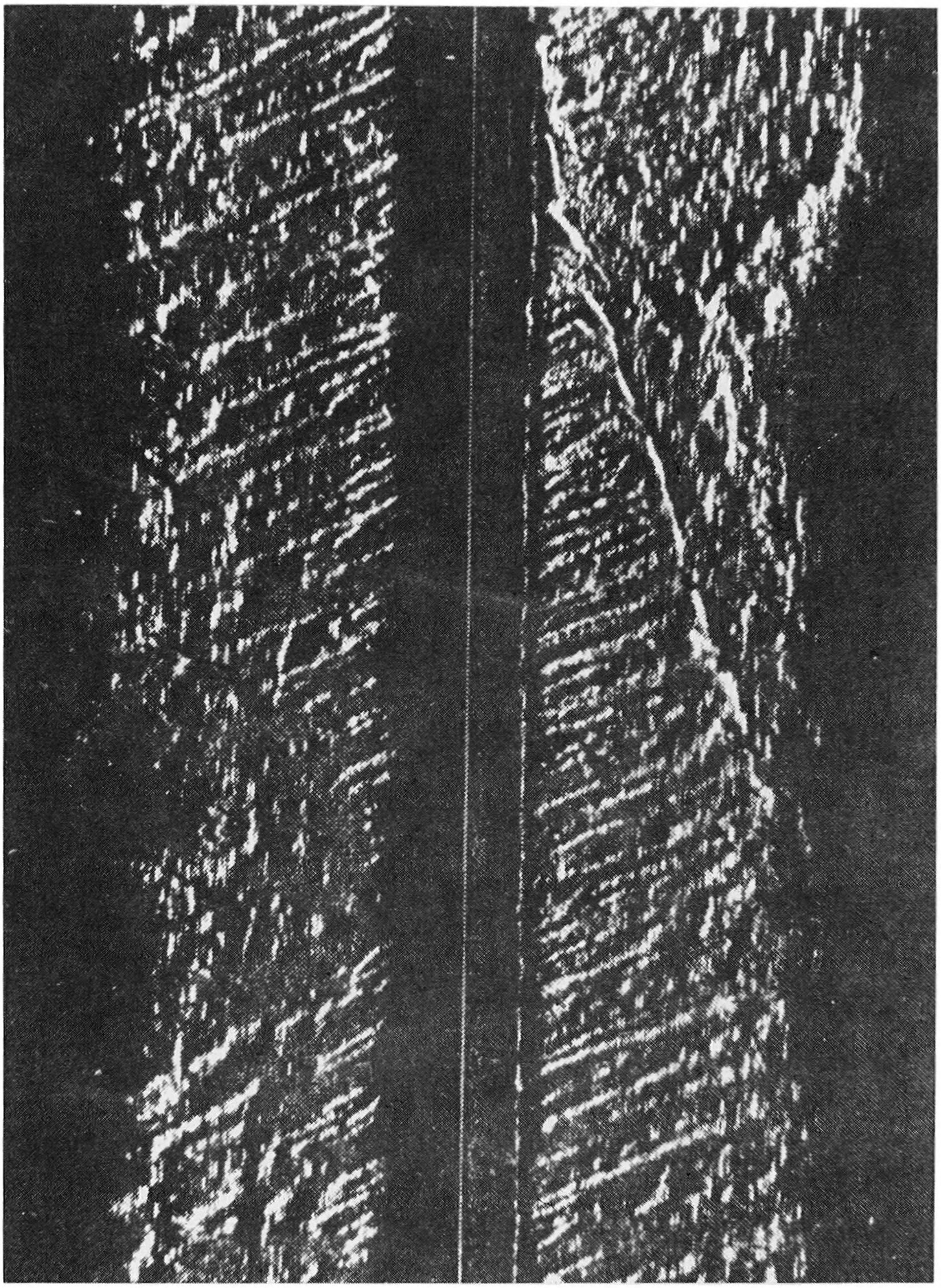


FIG. 10. — Analogous GLORIA image of abyssal hills, crosscut by a fracture zone, on the flank of the East Pacific Rise (from SEARLE *et al.*, 1981). (Used with permission.)

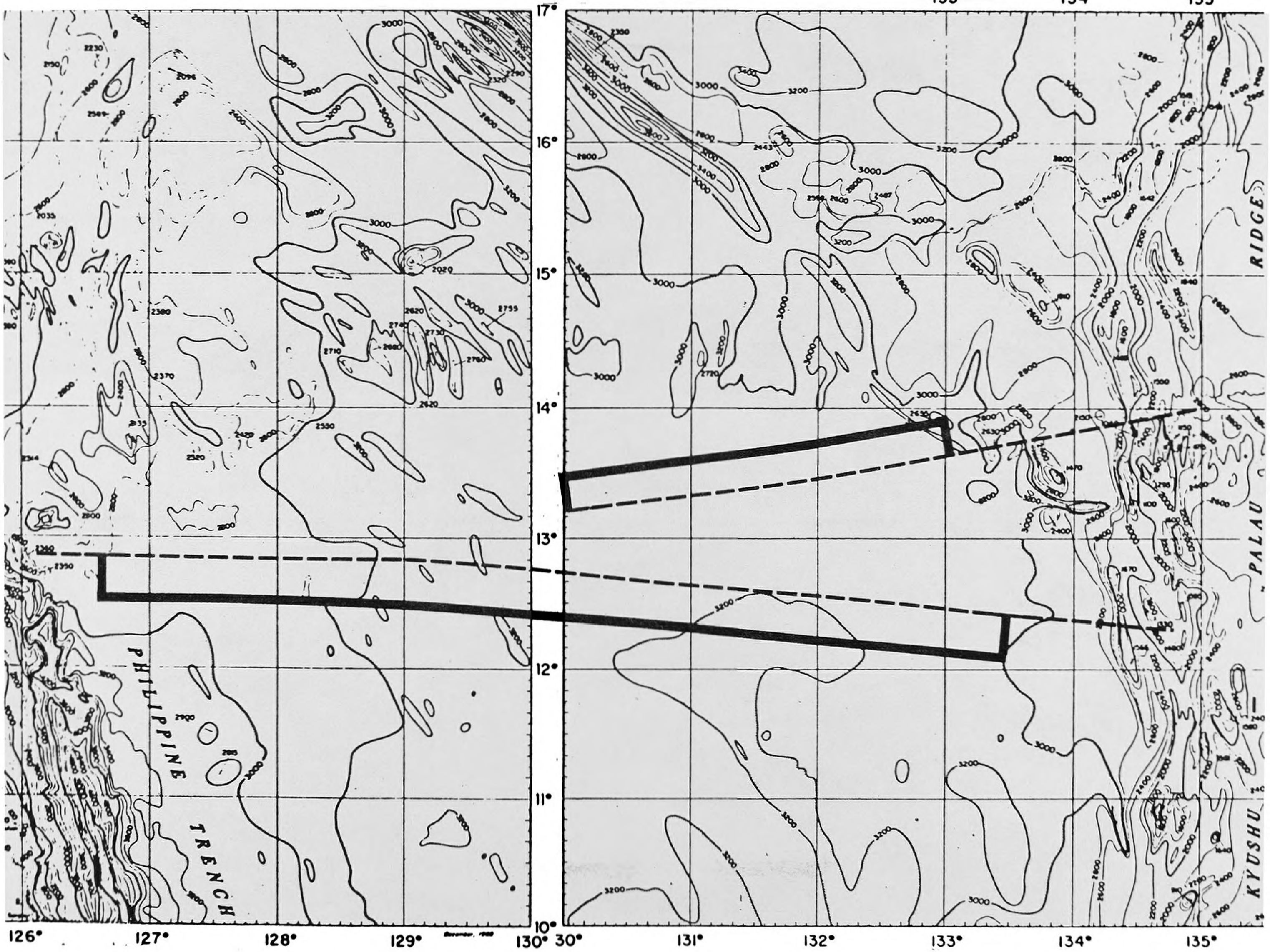


FIG. 11. — Location of abyssal hills appearing in figures 12 and 13.

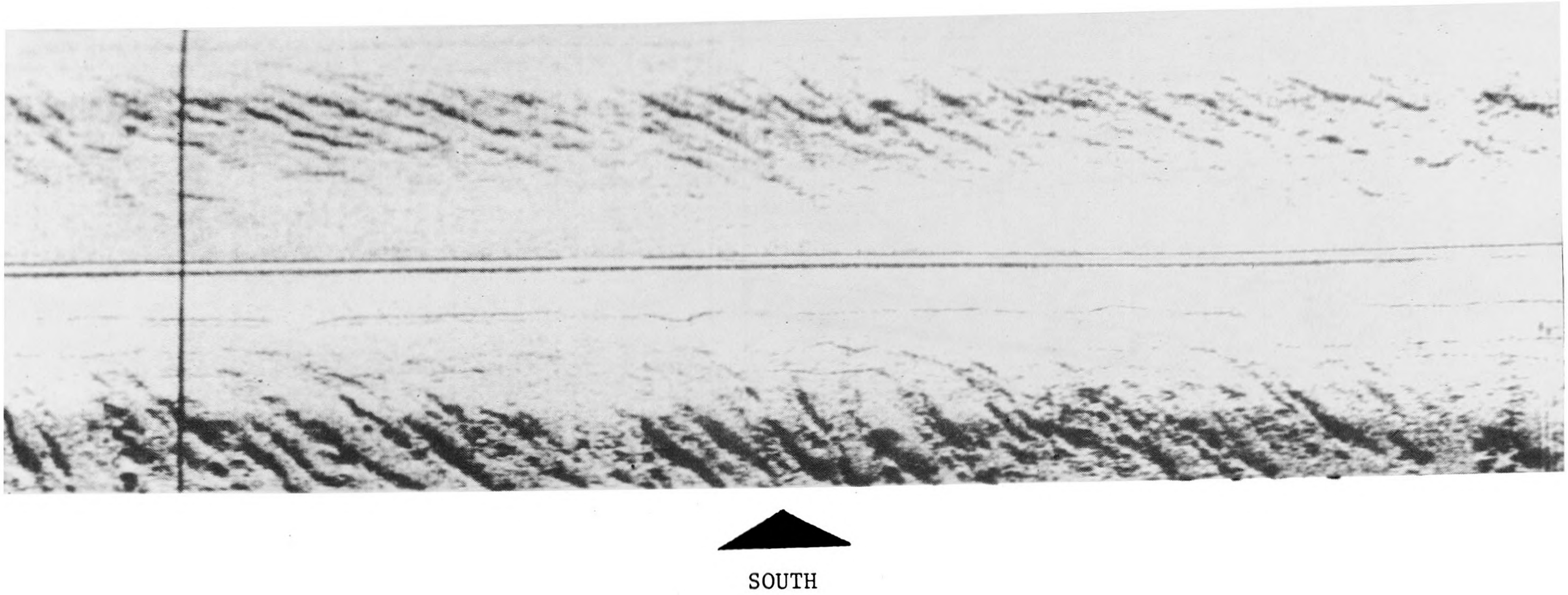


FIG. 12. — 440 km-long Western Philippine Sea abyssal hill series along about 13°13′ N (shown at two different compressions).

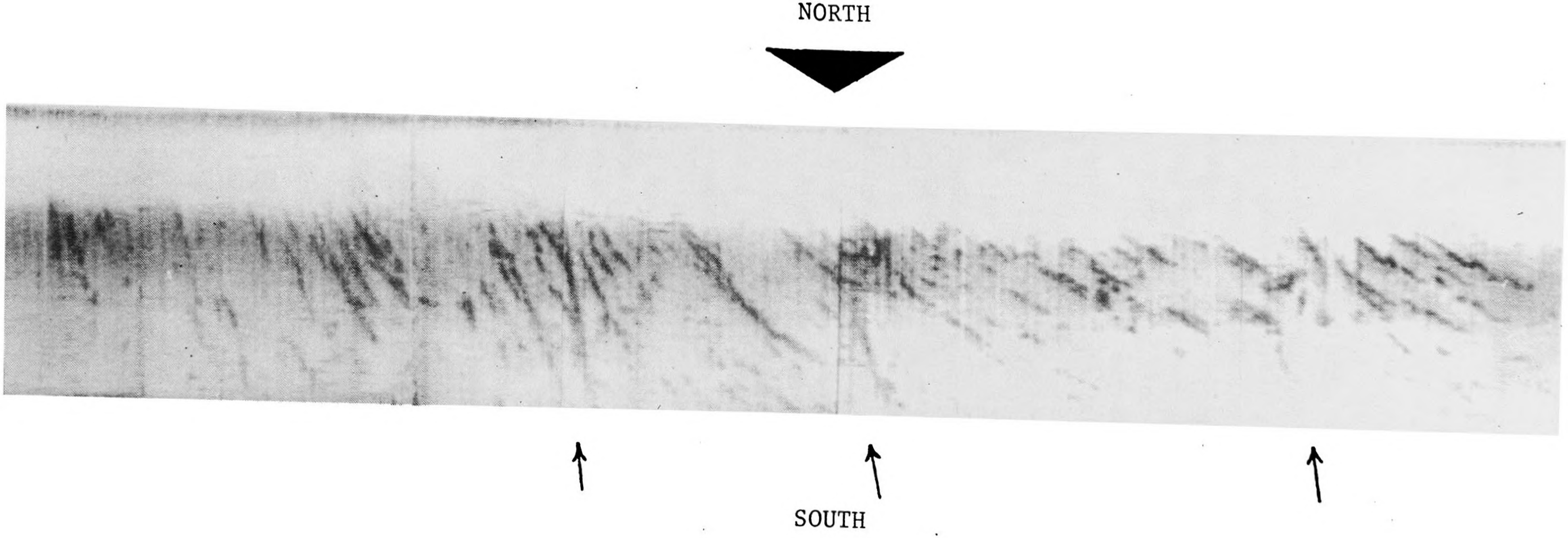


Fig. 13. — 760 km-long Western Philippine Sea abyssal hill series along about 12°30′ N. Small black arrows indicate possible fracture zones.

in front, as would be the case of a rille showing off its far wall. This remarkably parallel series of abyssal hills (shown at 3X and 1.5X exaggerations) was formed by the extinct spreading center located exactly at the northeast corner of the image. Roughly twenty-five hills appear in the space of 440 km, implying one about every 17 km (much finer detail than magnetic anomalies).

Further south, figure 13 shows a hill series similarly parallel to the Central Basin Rift (LEWIS and HAYES, 1980) from whence it came. The area is deformed into a regular pattern of linear abyssal hills which dramatically illustrate (in a manner even superior to the local magnetic anomalies) the evolution of this tectonic plate — note the change in orientation (and hence spreading direction) along the track. About forty hills appear within the 760 km shown, yielding a mean spacing of 19 km. Two or three slightly thicker lineations (indicated by small arrows) crosscut these hills and appear perpendicular to them at full compression — perhaps they are north-south fracture zones. One notices a marked dichotomy between east and west:

(1) Western hills appear closer together than eastern hills.

(2) We'd anticipate that progressively thicker sediments would smooth and then obliterate abyssal hills with increasing age, and this does appear to be the case: assuming some constancy of relief, the older western hills do seem somewhat muted compared with the younger and darker series to the east.

(3) Most significant is the change in orientation across the image. Given the parallelism between abyssal hills and the ridge systems from which they came, rotation of the plate is strongly indicated by this change in strike. This reorientation is something even most charted magnetic anomalies (BEN-AVRAHAM *et al.*, 1972; LOUDEN, 1976; WATTS *et al.*, 1977; SHIH, 1980) fail to show. SWATHMAP's image seems to give a paleo-motion vector even more precise than the magnetics, all of which agree on azimuth while disagreeing on dating. Here then, we have a geomorphic tool for inferring spreading directions, even in places where otherwise essential magnetic anomalies are absent (see POEHLS *et al.*, 1973; NAUGLER and REA, 1970). In fact, the number of hills per unit time may allow a rough estimate of spreading rate in regions devoid of magnetic clues.

Ridges and fracture zones

Figure 14, running along about 30° N, depicts the 2000 km long Atlantis Fracture Zone which offsets and scars all crust produced since the Cretaceous. Such geomorphic endurance could well prove invaluable to our understanding of lesser known crust elsewhere in the world. Fracture zones are also superb clues to ancient plate tectonic motion — indeed Atlantis itself has been used for this purpose (PHILLIPS and LUYENDYK, 1970). Like figure 8, this is an example of the imagery possible with our latest technology. To avoid photocompression, the image was artificially stretched along track by serial repetition of each data line.

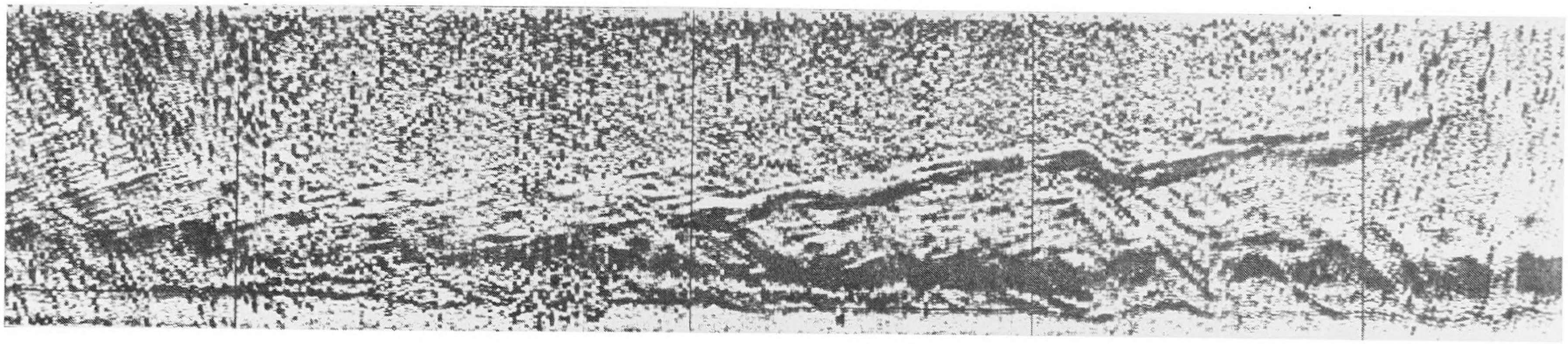


FIG. 14

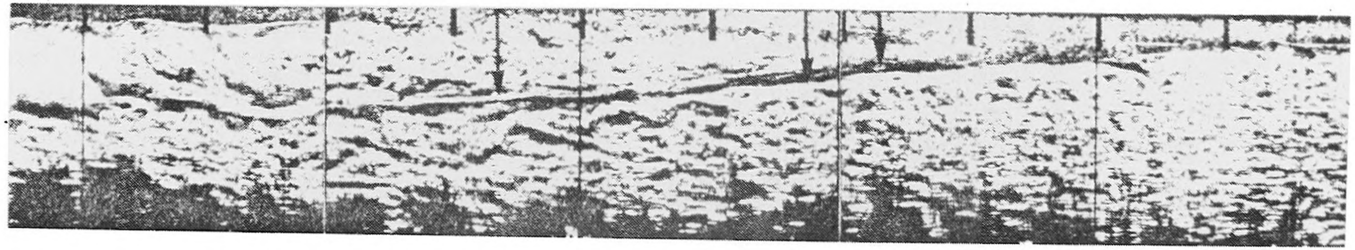


FIG. 15

The result is quite satisfying and bears a striking resemblance to GLORIA images of other Atlantic fracture zones (especially Charlie-Gibbs, reproduced here as figure 15, from SEARLE (1981)).

FUTURE PROSPECTS

Certainly there are sidescan systems that do a better job of seafloor mapping than American battleships, but their cost is extraordinary by comparison, reaching hundreds of thousands — even millions — per expedition. It is, of course, no surprise that funding allows them only a couple of expeditions per year. U.S. military vessels, however, make routine ocean crossings several times a week and they often do so in places largely untouched by research expeditions. Steps could be taken to automate the system so that it can be sent out 'on autopilot' any time a U.S. Navy commander is willing to contribute to this most fundamental knowledge of the seafloor.

Despite our modest success and the improving quality of our most recent imagery, Project SWATHMAP is still in its infancy. Possible system upgrades include: (1) two-sided scanning for maximum coverage, (2) stereo image production from parallel transducer rows, (3) digital magtape recording for subsequent image manipulation and enhancement, and (4) decipherment of parallax across the array to determine the acoustic arrival angles one utilizes for estimates of bathymetry. Improvements not withstanding, one does well to utilize such existing systems for low-cost survey, particularly in poorly-known areas. Given the exploration that remains to be done and the often prohibitive cost of today's excellent seafloor imagery, even low resolution systems have a great deal to offer.

Acknowledgements

My fondest appreciation is extended to the overwhelmingly co-operative captains and sonar technicians of the United States Navy. Abundant thanks go to the officers and personnel ashore who paved the way for these explorations. Above all, I am particularly inbedted for the constant encouragement of mentor Dr. James ANDREWS and the early support of the United States Office of Naval Research.

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