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THE FIRST DECADE OF GLORIA

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ABSTRACT

In 10 years of operation, GLORIA has been used on 26 cruises and has insonified more than 1% of the ocean floor. The paper reviews the scientific achievements of this new tool and assesses the contributions which it has made to understanding the geological features and the processes creating them. A complete bibliography of GLORIA papers is included in the references, and the best examples of sonographs obtained over different terrain are illustrated.

INTRODUCTION

After 10 full years of operation with the Geological Long Range Inclined Asdic (GLORIA) it is an appropriate time to stand back and review what has been achieved scientifically by the project and to consider what role in the future such long-range side-scan sonars might have. The Bullard Seminar is a particularly appropriate forum in which to do this since Sir Edward's pioneering work in the study of oceanic geology and geophysics stimulated the late Maurice HILL to make the Department of Geodesy and Geophysics at Cambridge a center of excellence for the new technology of marine geophysics and for generating new ideas about the evolution of the oceanic crust. HILL realized the importance of knowing the shape of the seafloor, and I was fortunate enough to work closely with him over many years and to further these particular studies.

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It became apparent in the early 1960's that conventional echo sounding from surface ships could never give the detail of morphology on the deep seabed that is available to geologists working on land and which is the starting point of so much geological understanding. The need for new methods of studying seafloor morphology with a higher resolution was emphasized by the IOC report in 1969 on a long-term expanded program of 'global ocean research' which gave it the highest priority (Advisory Committee on Marine Resources Research *et al.*, 1969).

The challenge has been met in various ways since then. Deep submersibles, deep towed vehicles, and long-range bottom photography have all played their part in studying morphology at relatively small scales. However, the area that can be covered is limited, and rigorously navigated surveys are both difficult and expensive. Two major new systems emerged that operate from near the sea surface and can be used at normal cruising speeds and with the navigational control that is normally available to surface ships. One of these systems is the multibeam swath sounding technique, first developed for the U.S. Navy as the Harris array (GLENN, 1970) and now available commercially as SEABEAM and installed in the French Research Vessel (RV) *Jean Charcot* (ALLENOU et RENARD, 1978). A fan of individual narrow acoustical beams obtains slant ranges to the seabed in a swath extending across the ship's track out to approximately 30° from the vertical. The signals are processed to give a continuous contoured strip of seafloor of width about equal to the water depth with a resolution of better than 10 m. Thus in a water depth of 5 km, surveys can be mosaicked together from tracks spaced about 3 km apart to give saturation coverage.

The other development was the translation of the side-scan sonar techniques which had been so successful on the continental shelves for geological studies (BELDERSON *et al.*, 1972) into the deep ocean. The National Institute of Oceanography embarked on this project in 1965. By 1969 it had developed GLORIA (Geological Long Range Inclined Asdic) Mk I and had demonstrated that acoustic pictures of the deep ocean bed (Fig. 1) could be obtained out to a range of nearly 30 km (STRIDE, 1970). The technical problems faced in the design of Mk I (Fig. 2) have been well-documented (RUSBY *et al.*, 1969; RUSBY, 1970; SOMERS, 1970, 1973; EDGE, 1974; RUSBY and SOMERS, 1977) so all that it is necessary to say here is that Mk I gave good service and was extensively used for 6 years before being paid off in order to allow Mk II to be built (LAUGHTON and RUSBY, 1970).

The need to develop a Mk II arose both from the lessons learnt about the acoustic performance of Mk I which enabled a more effective system to be developed and from the constraints imposed on the operation of Mk I by its size and inflexibility.

Acoustically we found that it was not necessary to use a beam which was limited (to 10°) in the vertical angle, and hence the vertical dimension of the transducer array could be reduced from 1.5 m to 0.5 m, enabling it to be put in a smaller body. Furthermore, an increased knowledge of the back scattering coefficients at low incidence angles together with improved signal-processing techniques allowed a reduction in the transmitted power and acquisition of sonographs from both sides of the ship simultaneously.

The size and weight of Mk I (10 by 1.75 m, 6 tonnes) necessitated special launching techniques that were lengthy (4 hours or more), hazardous in sea

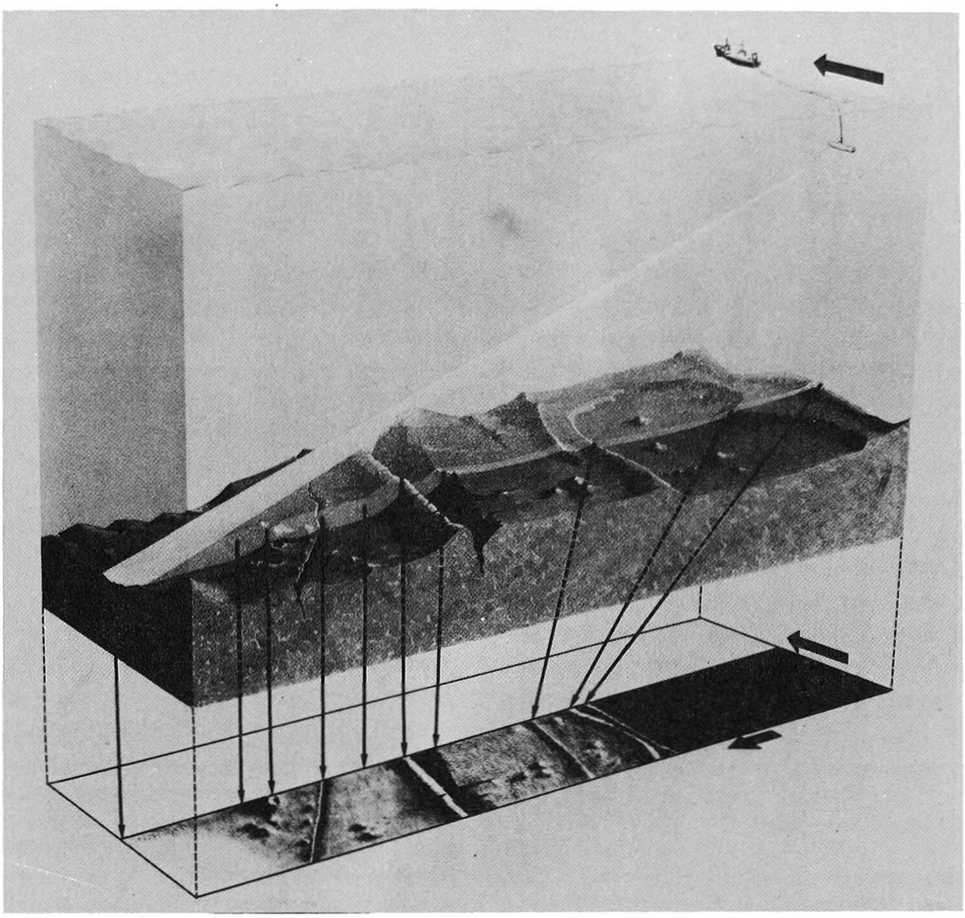


FIG. 1. – Operational and recording configuration of GLORIA Mk I. Maximum range is 30 km in 5 km water depth. The lower part of the figure shows the slant range distortion on the record that arises from high incidence angles on the bottom.
MK II insonifies to port and starboard simultaneously.

conditions more than a very gentle swell, required rubber dinghies and divers, and which could only be operated from RRS *Discovery*. The operating team could not be reduced below eight in number, thus limiting the number of other scientists on board. In order to reduce undue strain on the cable due to sea conditions the vehicle was suspended at a top towing point below a submerged float that was towed astern of the ship. Operations had to be limited to areas where recovery could be made if necessary within the shelter of land, and multiple launchings during a single cruise were not encouraged.

By contrast, Mk II was designed to be neutrally buoyant and to be towed from the nose on a flat catenary cable without fairing. The slimmer diameter (0.7 m) and lower weight (2.0 tonnes) enormously simplified handling arrangements, so that no personnel are required over the side of the ship and so that launch and recovery can now be made in sea conditions up to force 5 or 6 in less than half an hour. The GLORIA support team is now reduced to two. The integral launching gantry

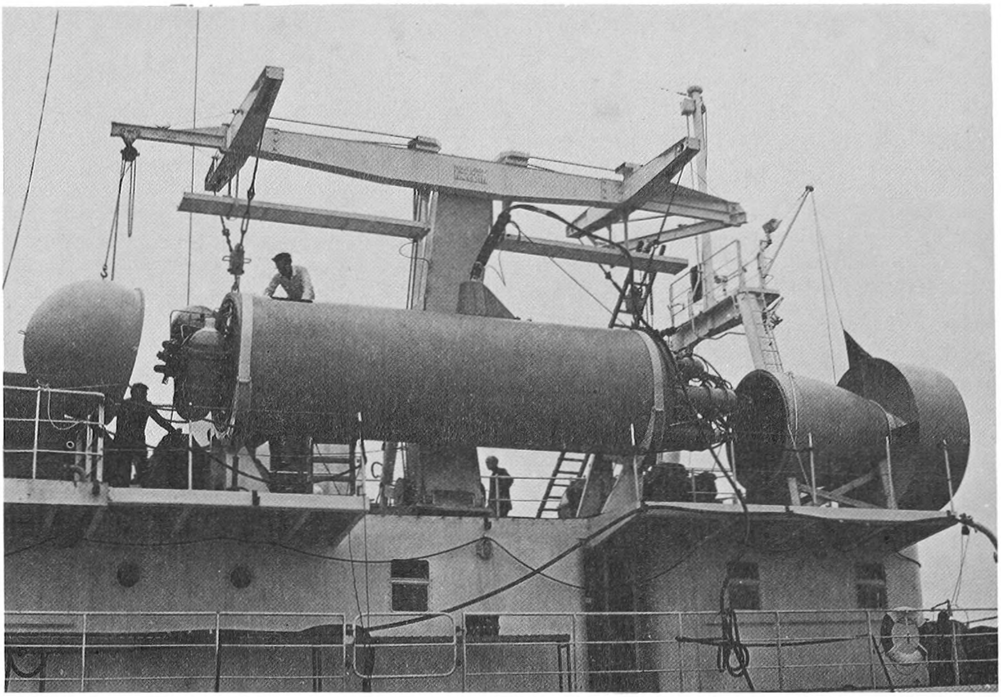


FIG. 2. – GLORIA Mk I in the launching davit on RRS *Discovery*, with the nose and tail sections removed.

(Fig. 3) and cable winch (13 tonnes in all including the vehicle) can be installed in many ships and has in fact already been used in two ships other than RRS *Discovery*. A detailed technical description of Mk II together with comments about its availability for use on other ships was published by SOMERS *et al.* (1978). Table I summarizes some of the principal specifications.

OPERATIONS

From 1969 to 1980, GLORIA has been used on 26 separate cruises, all but two of which have been on RRS *Discovery* (Table 2). The earlier cruises with Mk I were limited to the calmer waters of the Mediterranean or within easy striking distance of a windward shore or an island. Initially, the objectives were the larger targets of the continental margins, seamounts, and large fault scarps. However, since the recovery operation of Mk I was so difficult, the vehicle was left in the water between specific study areas, and data were obtained on passage across all types of sea floor terrain and a considerable range of features were seen. These tracks soon revealed that quite small and gently sloping sedimentary features could be seen and that bottoms of different sediment roughness could be distinguished.

Table 1
Principal specifications of Mk II GLORIA

	Specifications
Vehicle	7.75 by 0.66 m, nose towed 2.04 tonnes in air
Transducer	Two rows of 30 elements each side (ceramic stack to IOS design) Operating frequency within range 6.2-6.8 kHz Pulse 100 Hz swept frequency Active length, 5.33 m Horizontal angular beam width 2.5° (to half-power points) Vertical angular beam width 30° at fixed inclination of 20° below horizontal Peak electrical power per side, 12 kW Peak power into water per side, 10.5 kW
Operations	Speed 6 to 10 knots Range 7, 15, and 30 km, each side Depth of tow : 50 m at 8 knots with 400 m cable scope
Launching Gantry	Deck space 2.5 by 6.0 m Overall weight (including cable and vehicle), 13 tonnes
Additional Installations	Portable cabin, deck power pack; console and tape decks in laboratory
Power Supplies Required	For the launcher, 220 V d.c., 140 amps (for ships with three-phase 415 V 50/60 Hz a.c., a transformer rectifier is available) For operations, 230 V a.c., 50/60 Hz, 35 amps

With Mk I, different along-track resolutions could be chosen by altering the pulse repetition rate giving approximate ranges of 22 and 11 km to one side of the ship only. However, the beam could be rotated remotely to give port or starboard insonification. At the surveying speed of 6 knots (11 km/h), the coverage was therefore 240 or 120 km^2/h.

With Mk II, however, ranges of 30, 15 and 7 km are available to both sides simultaneously, and the surveying speed can now be as high as 10 knots (18 km/h) so that the coverage can be increased to 1,100, 540, or 270 km^2/h. The speeds are now limited by the seismic profiling system.

Since the surveying speed is now too different from the normal cruising speed of *Discovery*, it is customary to obtain GLORIA sonographs on passage whenever the equipment is on board, thus building up a bank of data outside those areas which are being specifically studied. However, since recovery time with Mk II has been reduced to about 20 min, it is now feasible to combine GLORIA studies with some station work during which GLORIA is recovered.

The total coverage to date is shown in figure 4. In over 9,000 hours of operation, an area of 6.5 million km^2 has been insonified, equivalent to 1.8% of the area of the world's oceans. However, the actual area examined is about half of this since many sonographs overlap.

Table 2
Cruises on which GLORIA has been used

Date	Cruise	Description	Reference
		Mk I	
April-May 1969	*Discovery*, Cruise 26	Trials in Loch Fyne	
June-July 1969	*Discovery*, Cruises 27 and 28	First deep sea trials in western Mediterranean	Rusby *et al.* (1969), Belderson *et al.* (1970), Rusby (1970), Somers (1970) and Stride (1970)
August-October 1969	*Discovery*, Cruise 29	Fisrst ocean trials south of the Azores	Whitmarsh (1971)
July-August 1970	*Discovery*, Cruise 35	Gulf of Cadiz and Mediterranean	Kenyon and Belderson (1973) and Belderson *et al.* (1974b)
June-July 1971	*Discovery*, Cruise 40	Eastern Mediterranean	Belderson *et al.* (1974a), Kenyon *et al.* (1975) and Stride *et al.* (1977)
September 1971	*Discovery*, Cruise 42	Herring studies west of Scotland	Rusby *et al.* (1973) and Rusby and Revie (1975)
October-November 1971	*Discovery*, Cruise 43	King's Trough and Azores-Gibraltar Rise	Laughton *et al.* (1972) and Laughton and Whitmarsh (1974)
June-August 1973	*Discovery*, Cruise 54	Mid-Atlantic Ridge (FAMOUS) and Azores-Gibraltar Plate boundary	Laughton and Rusby (1975), Whitmarsh and Laughton (1975, 1976), and Laughton and Searle (1979)
September-October 1973	*Discovery*, Cruise 55	Eastern Mediterranean	Belderson and Kenyon (1977), Kenyon and Belderson (1977), and Stride *et al.* (1977)
November-December 1973	*Discovery*, Cruise 57	Herring studies west of Scotland	Rusby and Revie (1975) and Rusby (1977)
May 1975	*Discovery*, Cruise 71	Continental slope north of Biscay	Belderson and Kenyon (1976) and Kenyon *et al.* (1978)
July-August 1975	*Discovery*, Cruise 73	Mid-Atlantic Ridge (Kurchatov Fracture Zone) and ocean basin north of Azores	Searle and Laughton (1976, 1977), Laughton and Searle (1979), and Searle *et al.* (1979)

Table 2 (cont.)

Date	Cruise	Description	Reference
		Mk II	
May-June 1977	*Discovery*, Cruise 83	GLORIA Mk II trials	Somers *et al.* (1978)
June-July 1977	*Discovery*, Cruise 84	Rockall Trough, Charlie-Gibbs Fracture Zone, Reykjanes Ridge, King's Trough	Laughton and Searle (1979), Laughton *et al.* (1979), Roberts and Kidd (1979), Searle (1979, 1981), and Searle and Laughton (1981)
August 1977	*Discovery*, Cruise 85	Eastern Mediterranean	Belderson *et al.* (1978)
January-March 1978	*Discovery*, Cruise 90	European and North African continental margin	
March 1978	*Discovery*, Cruise 91	Azores triple junction and Azores-Biscay Rise	Searle (1980)
November-December 1978	*Discovery*, Cruise 96	Equatorial midocean canyon and Romanche Fracture Zone	Belderson and Kenyon (1980)
January-February 1979	*Jean Charcot*	Walvis Ridge, south Atlantic	
April-May 1979	*Discovery*, Cruise 101	North Mascarene Plateau, Indian Ocean	
July 1979	*Discovery*, Cruise 103	Gulf of Aden and Red Sea	
July-August 1979	*Discovery*, Cruise 104	Eastern Mediterranean	
September-November 1979	*Starella*, 1/79	NW Scotland, east Greenland continental margin, east Canada and U.S. continental margin, Blake-Bahama Drifts	
March-April 1980	*Discovery*, Cruise 109	Lesser Antilles, Barbados Outer Ridge	
April-May 1980	*Discovery*, Cruise 110	Cocos-Nazca spreading center, Galapagos triple junction, East Pacific Rise, and Peru Trench	Searle *et al.* (1981)
June-July 1980	*Discovery*, Cruise 111	Blake-Bahama Drifts and Grand Banks	

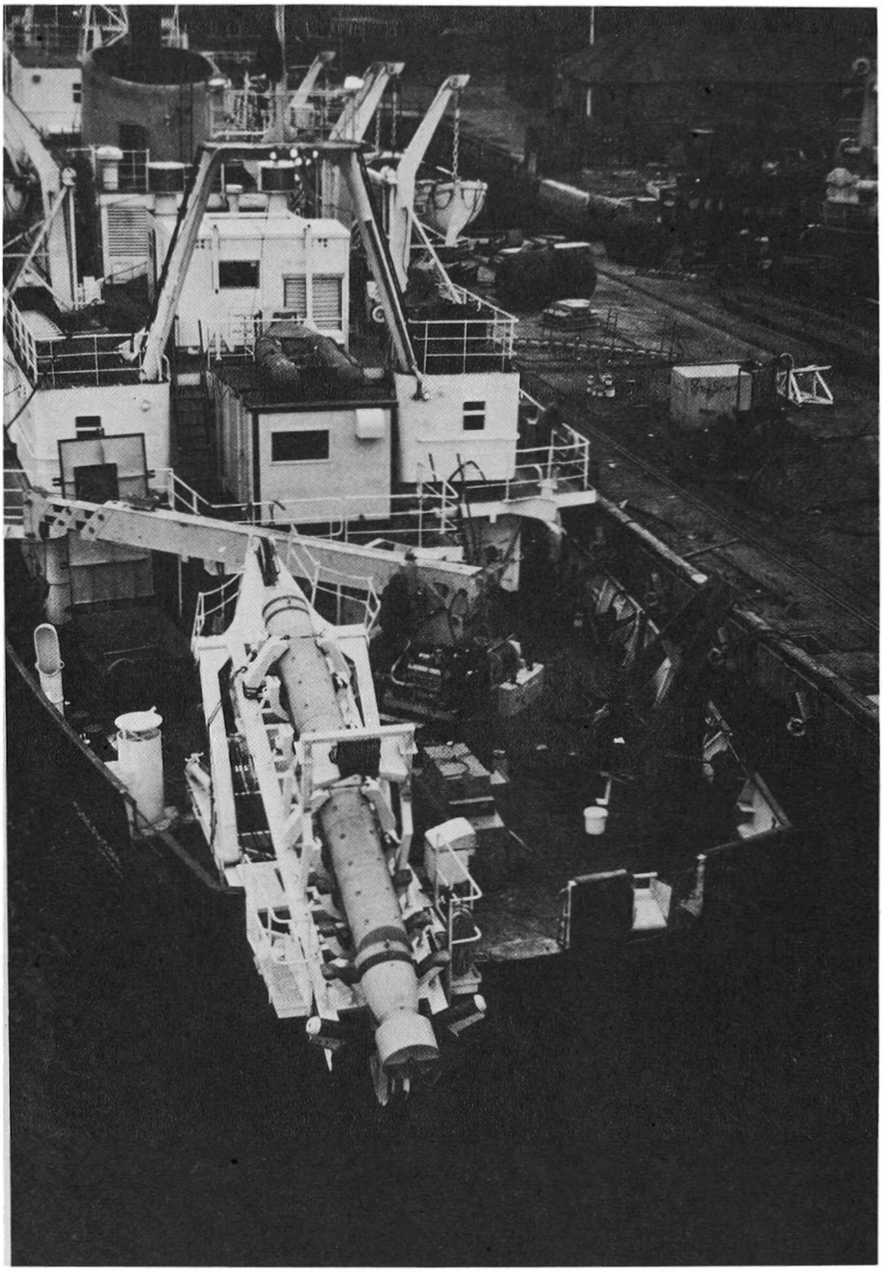


FIG. 3. – GLORIA Mk II on its launching gantry on the stern of RRS *Discovery*.

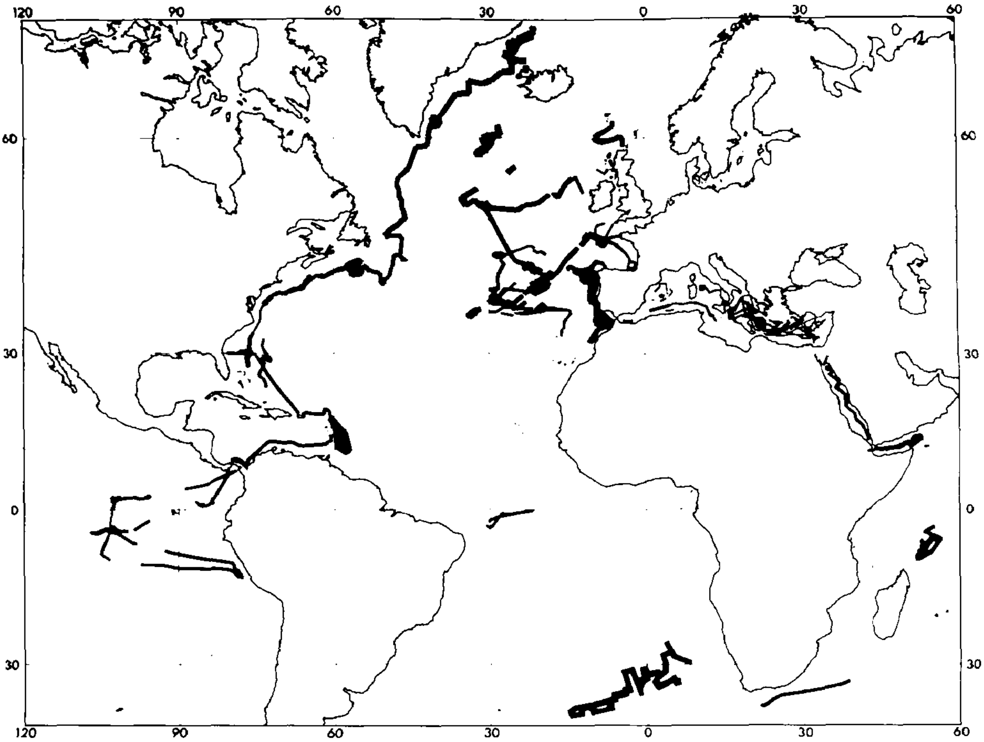


FIG. 4. – The total coverage of sonographs from 1969 to 1980. The black areas accurately represent the area insonified.

PROBLEMS OF INTERPRETATION

On reception, the processed signals are recorded on magnetic tape, played out on a photographic recorder, photographically anamorphosed (stretched) to take into account the actual speed of the ship over the ground, and printed at appropriate scales as sonographs. This procedure has a dynamic range considerably less than that of the signal, and hence two recording methods are used; one with fixed gain chosen in the center of the range and one with automatic gain control. The two types of resulting sonographs give different information, and interpretation requires both to be examined.

Although sonographs have many of the appearances of ordinary pictures, there are subtle factors that can confuse and mislead the unwary, and it takes some time to get familiar with interpretation. Whereas an eye resolves different objects by angular differences, sonar resolves them by range differences. Thus in order to obtain the correct pseudo-perspective on a sonograph, one must look toward the source of sound (i.e., the zero range line) rather than away from it (cf. LAUGHTON and RUSBY, 1975, p. 280). The profile beneath the ship's track then appears as the horizon line.

In deep water the near-range field is severely distorted by the angle at which the sound rays reach the bottom. For mosaicking purposes this must either be corrected or else eliminated by sufficient overlap between adjacent sonographs.

Artifacts can be introduced (BELDERSON *et al*, 1972) by echoes off the sea surface (such as a ship's wake), by multiple path echoes from very highly reflecting surfaces, by side lobe reception of echoes from strong reflections, and by focussing and smearing due to the yaw of the vehicle during the passing of a target (COOPER, 1974). The method of signal processing currently being used (SOMERS *et al.*, 1978) indroduces slight artificial shadows both in front of and behind targets which can be confused with real shadows. Thermal stratification in the water distorts ray paths and produces focussing and cut-off effects (BELDERSON *et al.*, 1972). All these effects need to be recognized and taken into account in the interpretation.

SURVEY OF SCIENTIFIC RESULTS OF GLORIA SURVEYS

The justification for developing GLORIA was that we should be able to learn something new about the seafloor and the geological processes that have shaped it. With such a wide variety of seafloor types to examine, work has concentrated on those areas in which particularly interesting scientific problems were known to exist. Except for the most recent cruises the results of these studies have been published in the scientific literature, and it is the intention of this paper to provide a guide to these publications. Since GLORIA sonographs are half-tone pictures, the number that have been reproduced in papers is relatively small, and the quality of reproduction is often limited by the journal itself. Opportunities have therefore been taken by authors to use different sonographs in different publications on the same subject, and therefore all significant papers will be referenced in this paper. It is convenient to start from the continental shelves and to move oceanward, assessing the role of GLORIA in a number of different morphological regions.

Continental Margins

Although GLORIA was specifically developed for deep ocean work, trials have been made of its potential capability on the continental shelf. Long-range sound propagation on the shelf is at times inhibited by the seasonal stratification that develops, and the best results were therefore obtained when the water column was well mixed. During studies of the reflectivity of fish shoals (see later), it was found by RUSBY and REVIE (1975) that geologically useful sonographs could be obtained to a range of at least 13 km if there were suitable targets (Fig. 5). However, at the resolution available, much of the continental shelf, at least around the United Kingdom, is acoustically dull and is probably better studied by shorter-range higher-frequency sonar methods. On the outer part of the continental shelf in northern waters, furrows generated by icebergs grounding on the shelf edge are revealed by short-range sonar studies (BELDERSON *et al.*, 1973) and have been studied also using GLORIA.

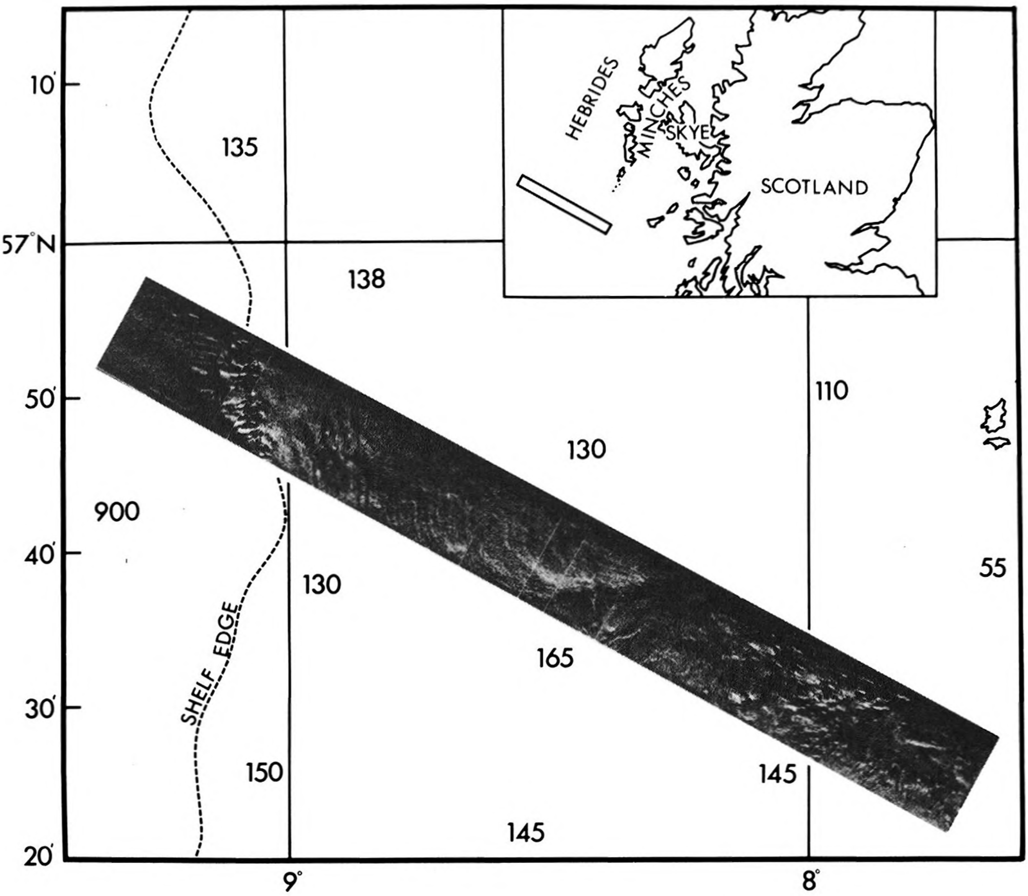
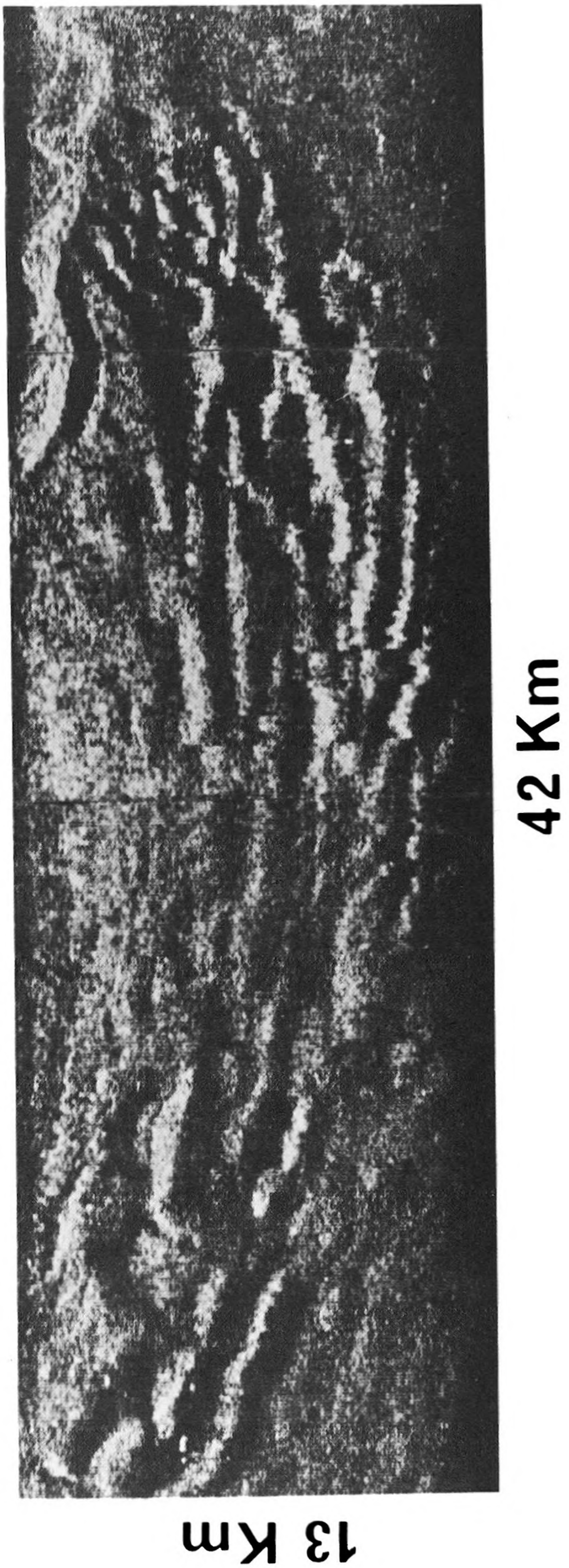


FIG. 5. – The 13 km range sonograph crossing the continental shelf edge west of Scotland. Insonification is toward the NE. Rock outcrops are seen at 8° W, sediment transport patterns of 8 1/2° W and the shelf break near 9° W. Depths are in meters (RUSBY and REVIE, 1975).

By contrast the continental slopes, especially where there are canyons, channels, faults, and slumps, have provided a rich field for GLORIA (BELDERSON *et al.*, 1970; KENYON *et al.*, 1975; BELDERSON and KENYON, 1976). The highly dissected slope to the north of the Bay of Biscay has been intensively surveyed by conventional means. But the sonographs (Fig. 6) have shown many of the contour charts to be in error and have demonstrated the strong control on the canyon directions exercised by the tectonic fabric. KENYON *et al.* (1978) have further shown slumping on slopes as low as 5° to the west of the Celtic Sea, slump folds on slopes down to 3° on the borders of the Landes Plateau in SE Biscay (Fig. 7), and sinuous channels crossing the continental rise with slopes of half a degree. The exploitation of any hydrocarbons on the continental slopes will have to consider the stability of the slope in relation to the engineering structures that might be placed upon it, and conversely, the geological structures that can be deduced from the sonographs can undoubtedly guide exploration.

Data, so far unpublished, on the continental slope of the eastern Atlantic as far south as North Africa and the eastern margins of Greenland and the eastern

FIG. 6. – A view down the continental slope north of Biscay, showing canyon axes in places controlled by faulting and intercanyon secondary gullies. Insonification is from top to bottom, the upper part of the slope being at the top (BELDERSON and KENYON, 1976).



margin of North America have all been obtained in connection with the search for and possible exploitation of hydrocarbons. These show frequent occurrences of diapirism, of slumping, of complex canyon erosion, of continental rise channels and of current moulded sedimentary bedforms (see below). The slump associated with the 1929 Grand Banks earthquake south of the Laurentian Channel has been mapped in detail (D.G. ROBERTS, personal communication, 1980).

Sedimentary Bedforms in the Deep Ocean

Echo sounding profiles have long revealed the existence of a variety of sedimentary bedforms in the deep ocean at a wide variety of scales, ranging from giant ripple marks to sediment drifts hundreds of kilometres long. GLORIA surveys have been able to provide unambiguous mapping of these features and their trends even though the slopes involved are sometimes very low indeed. Abyssal sediment wave fields were mapped on the Feni Drift in Rockall Trough (ROBERTS and KIDD, 1979), showing the wave crests to be subparallel to the drift axes and hence to the current direction and that the net migration of crests has been upslope toward the drift crest and down-current (Fig. 8). More spectacular fields of mud waves and of an intersecting set of erosional furrows were mapped (D.G. ROBERTS and R.B. KIDD, personal communication, 1980) on the Blake-Bahama Inner Drift (Fig. 9), where extensive studies have previously been made with Deeptow (HOLLISTER *et al.*, 1976). The sharp crest of the drift is clearly visible on GLORIA sonographs.

Current related bedforms in the Gulf of Cadiz were studied by sonar by KENYON and BELDERSON (1973) and showed the strong influence of the Mediterranean undercurrent on eroding, transporting, and depositing sediment. These studies were valuable in advising on the routing of a submarine cable across the Gulf.

Submarine channels are particularly good targets for GLORIA because of the steep slopes generally associated with their banks and have been mapped both on the Lower Nile Cone (KENYON *et al.*, 1975), where their course is partly diverted by fault scarps on the cone, and in the equatorial Atlantic (Fig. 10), where the burial of the upper end of the channel by sediment indicates that it has been inactive for the last 1 m.y. (BELDERSON and KENYON, 1980).

A more unusual bedform caused by local submarine salt-karst formation was identified on the Hellenic Outer Ridge in the eastern Mediterranean by BELDERSON *et al.* (1978). These features generally appeared as sharply defined patches of rough ground in oval or elongated craters several kilometers in size and probably consist of collapse breccia above salt diapirs. Specific sites chosen from the sonographs were later investigated by the Scripps Deeptow (SPIESS and MUDIE, 1970) and sampled by precision coring.

Compressional Tectonics in Regions of Thick Sediments

Extensive studies have been made of the Hellenic, Calabrian, and Cyprus outer ridges in the eastern Mediterranean where the sedimentary sequences of the seafloor have been subjected to compressional forces (BELDERSON *et al.*, 1974*a*;

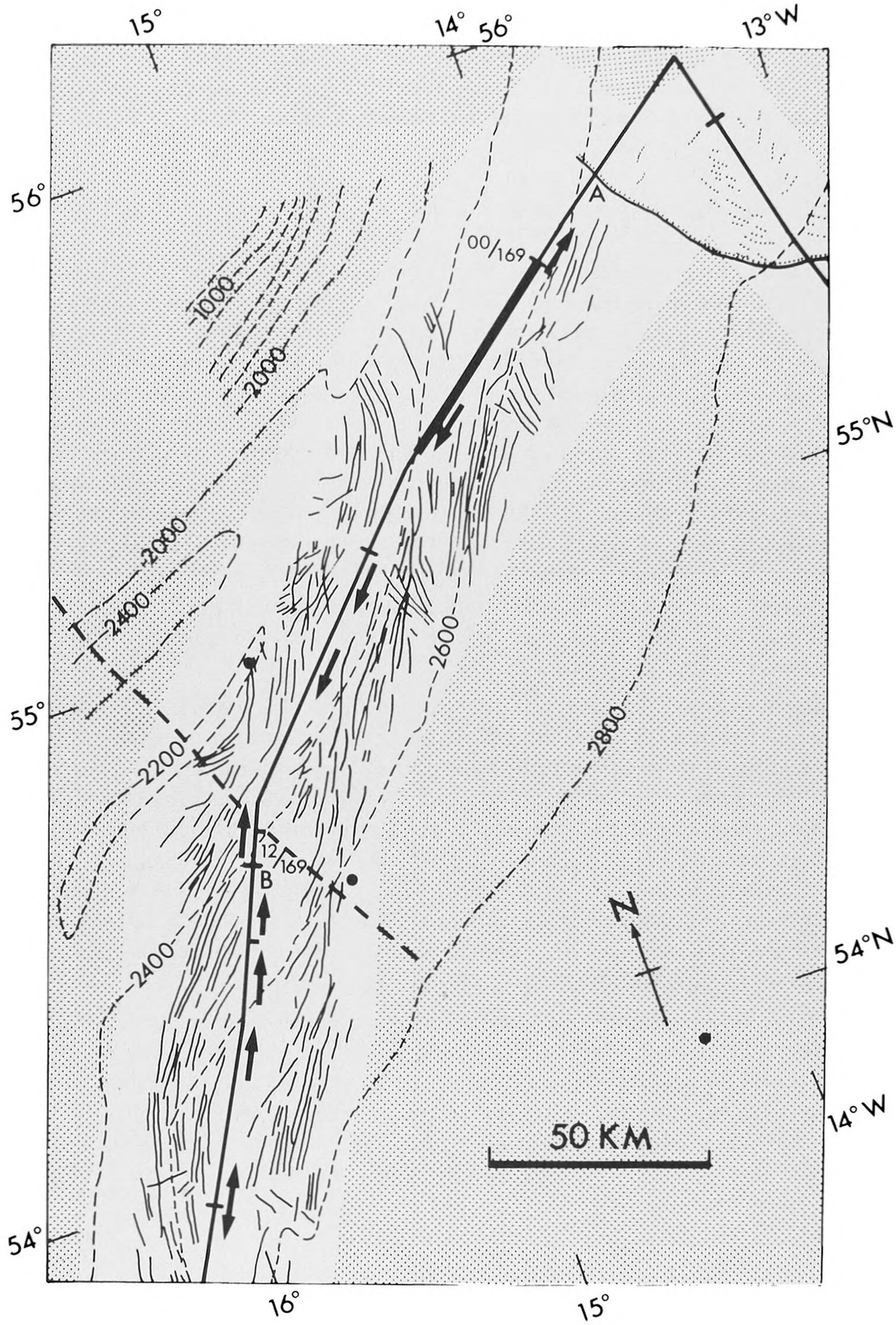


FIG. 8. – Map of principal sediment wave trends derived from GLORIA traverse over the Feni Ridge in Rockall Trough. Depths are in meters. Heavy arrows show along-track component of wave crest migration determined by 3.5 kHz profile (ROBERTS and KIDD, 1979).

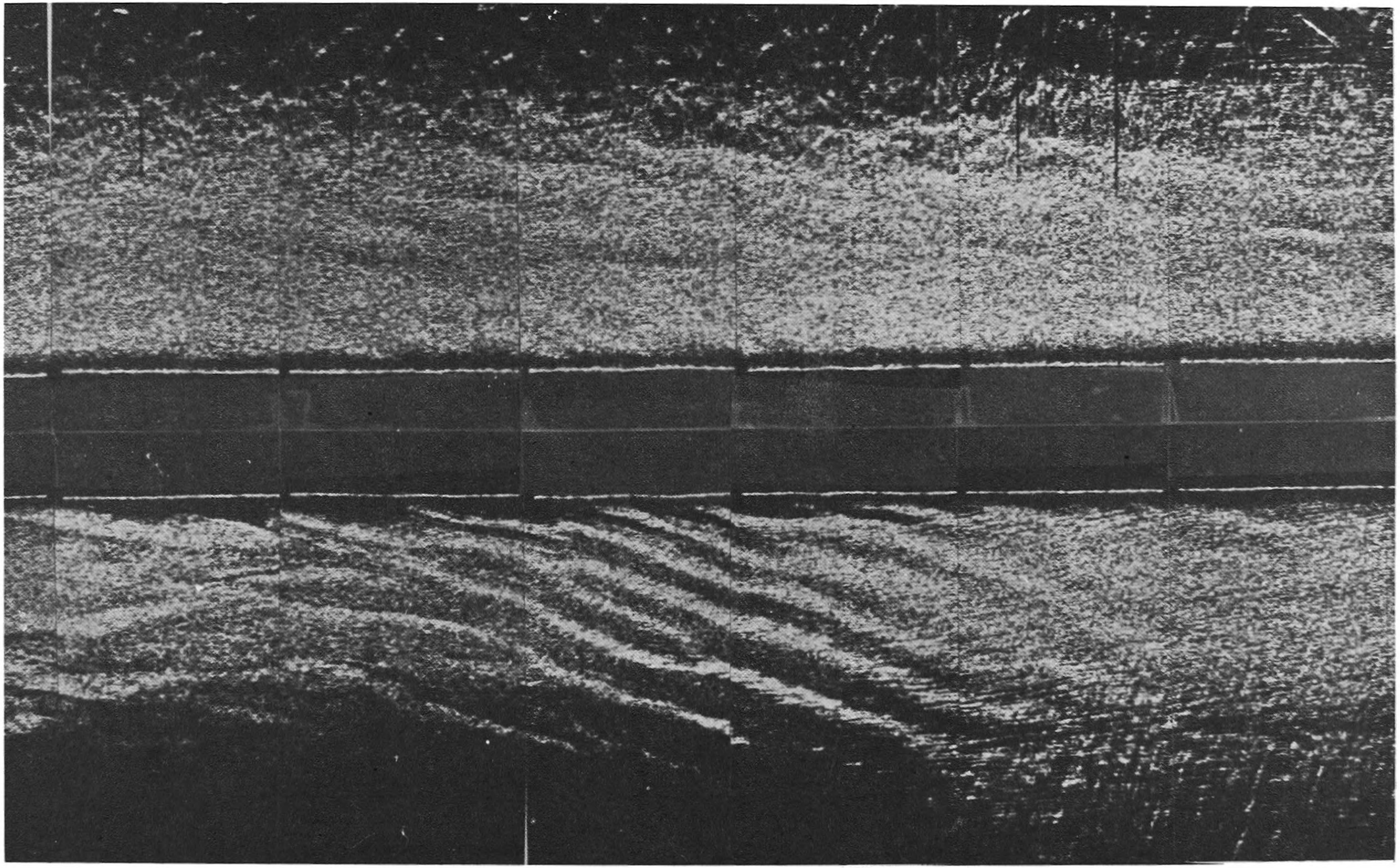


FIG. 9. – Sediment waves crossed by a fine pattern of furrows subparallel to the track on the Blake-Bahama inner drift between 30° N, 75 1/2° W (left) and 29° N, 74 3/4° W (right). The track is along the centre line of the figure. Interruptions to the thin white lines (the bottom) occur every hour. Total sonograph width 60 km.

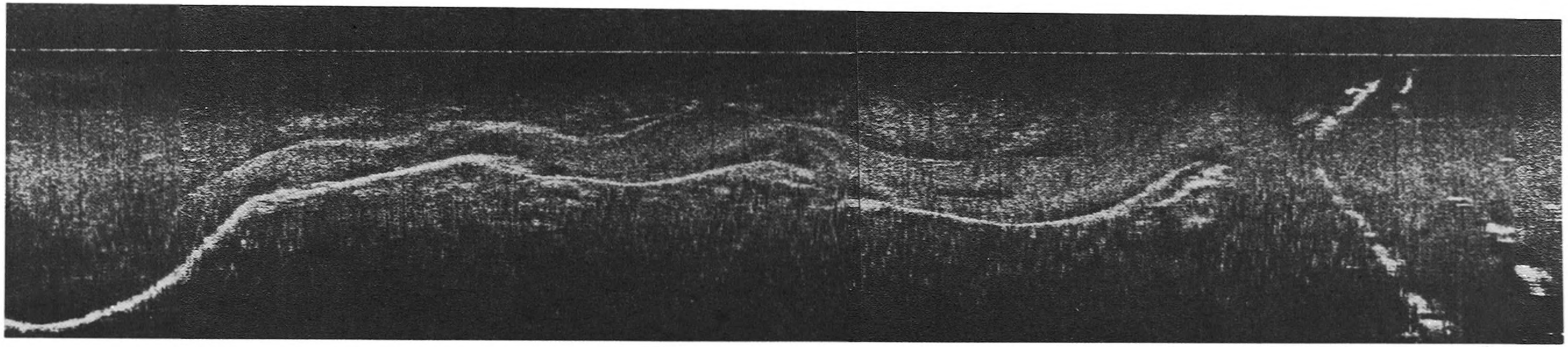


Fig. 10. – The eastern end of the Equatorial Atlantic Midocean Canyon at 4° S, 28° W. Insonification from top to bottom of the figure. The thin white line is the trace of the seafloor. Sonograph width 28 km (Belderson and Kenyon, 1980).

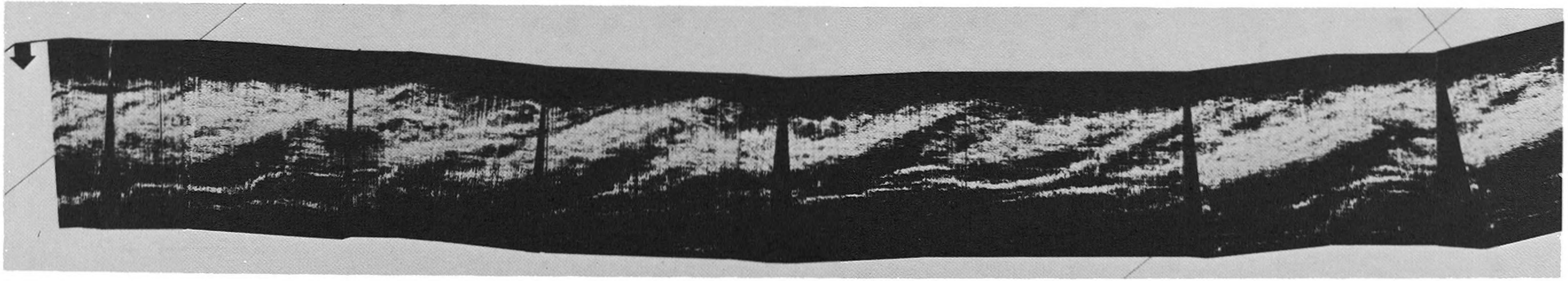


Fig. 15. – A chain of linear volcanic ridges lying en echelon along the axis of the oblique spreading Reykjanes Ridge. The sonograph runs exactly over the Ridge axis and is 13 km wide. To the right of the sonograph, the faults bounding the SE side of the median valley are parallel to the axis. Insonification from the left (Searle and Laughton, 1981).

BELDERSON and KENYON, 1977; KENYON and BELDERSON, 1977; KENYON *et al.*, 1977; STRIDE *et al.*, 1977). These have revealed structural trends, elongated parallel to the major topographic trend, which appear to be characteristic of outer ridges. The outer ridges lie parallel to their orogenic arcs and show outward growth into undeformed ground. The intensity of deformation increases inward across the outer ridge. Figure 11*a* shows examples of simple folding with an amplitude of several hundred meters, a wavelength of 1-2 km, and with a continuity along fold axes up to 20 km; in contrast, Figure 11*b* shows the much more intense deformation where there is thrusting, strike slip, and cross faulting. The association of lengthwise tectonic trends with outer ridges enabled the Calabrian and Cyprus outer ridges to be recognized for the first time.

This work led to a consideration of the outer ridges in front of other island arcs and an appreciation that a considerable thickness of sediment is needed for their Mediterranean-style development (BELDERSON and KENYON, 1977) and to an examination of the role of salt strata in the deformation process (BELDERSON *et al.*, 1978). New data have recently been obtained on the Barbados Outer Ridge where compression of thick sedimentary sequences was suspected.

Sediment deformation in the form of folding has also recently been recognized on the landward side of the Peru and Panama trenches (R.C. SEARLE, personal communication, 1980) in the westward extension of the Pyrenean deformation zone north and northwest of Spain, and as an olistostrome in the Gulf of Cadiz (D.G. ROBERTS, personal communication, 1980).

Mid-plate Tectonic Features

Tectonic forces in the NE Atlantic part of the Eurasian plate have given rise to some substantial morphological features (e.g. King's Trough, Azores-Biscay Rise) on which there are large faults and hence exposures of oceanic crust. One of the earliest GLORIA sonographs in the deep ocean showed Palmer Ridge, a 2,800 m high feature separating Peake and Freen deeps, on which the sedimentary and basaltic horizons sampled by CANN and FUNNELL (1967) could be seen (Fig. 12). In studies of King's Trough in 1977, GLORIA was used not only to map the structural trends that determined the linear nature of King's Trough but also to guide a dredging and rock-coring program on one cliff by mapping the basement outcrops.

The origin of the Azores-Biscay Rise which crosses the southeast end of King's Trough has long been a problem. In an attempt to gain insight into its formation, a survey was made with GLORIA in 1978. Its blocky structure defied any instant interpretation, no outstanding fault patterns emerging, but some large seamounts on it were seen to be volcanic rather than tectonic in nature (R.C. SEARLE, personal communication, 1980).

Similarly, the origin of Walvis Ridge has not yet been convincingly explained. In a cooperative effort with the Centre Océanologique de Bretagne, GLORIA and SEABEAM were used in the RV *Jean Charcot*, and many morphological data were collected (NEEDHAM, 1979) and are currently being interpreted in France.

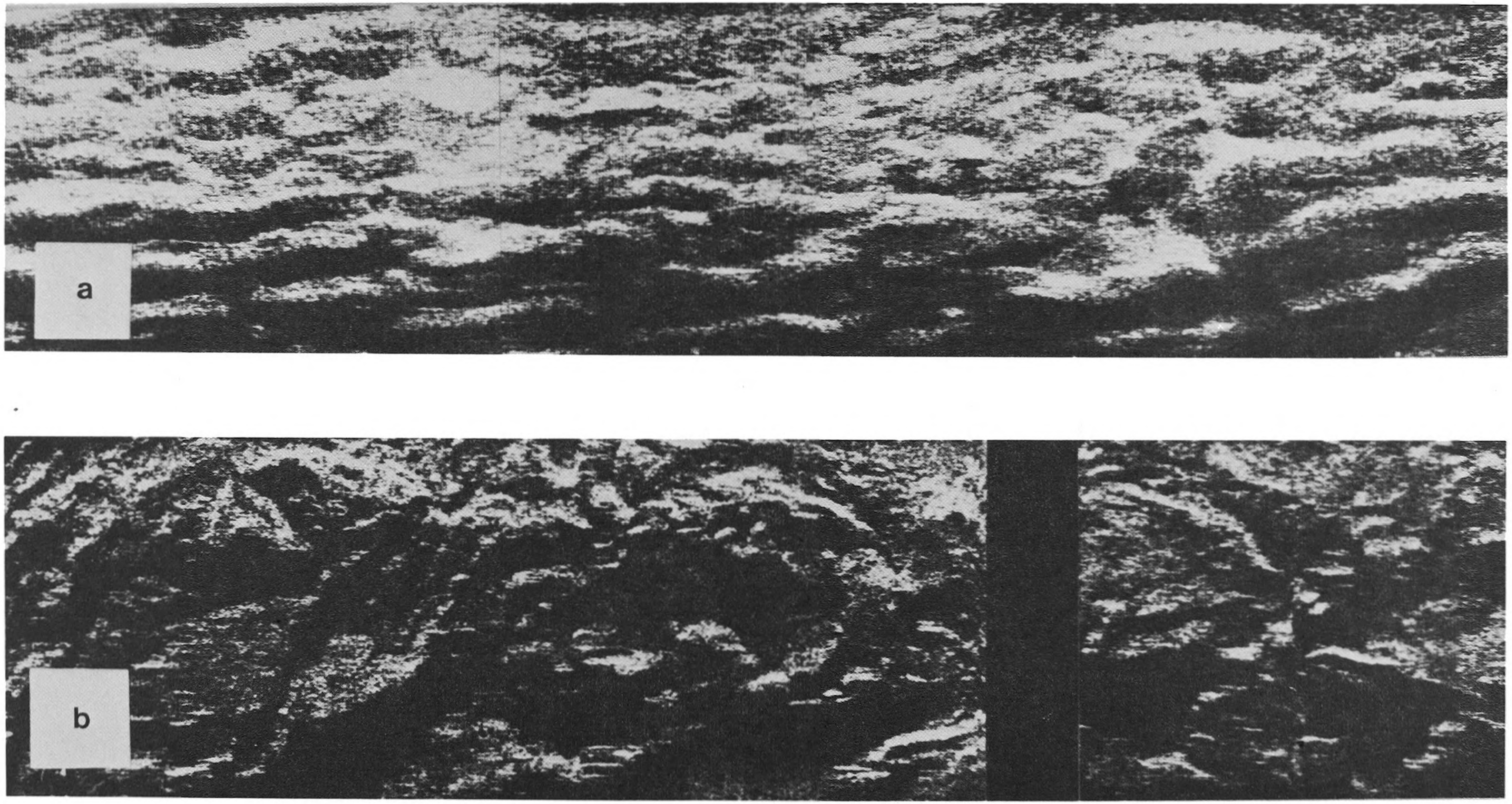


FIG. 11. – Examples of relief arising from compressional tectonics in sedimentary strata on the Hellenic Outer Ridge in the Mediterranean. (*a*) Simple folds with about 300 m amplitude. (*b*) Thrusting, strike slip, and cross faulting. The white square is 2 by 2 km. Insonification is from top to bottom (STRIDE *et al.*, 1977).

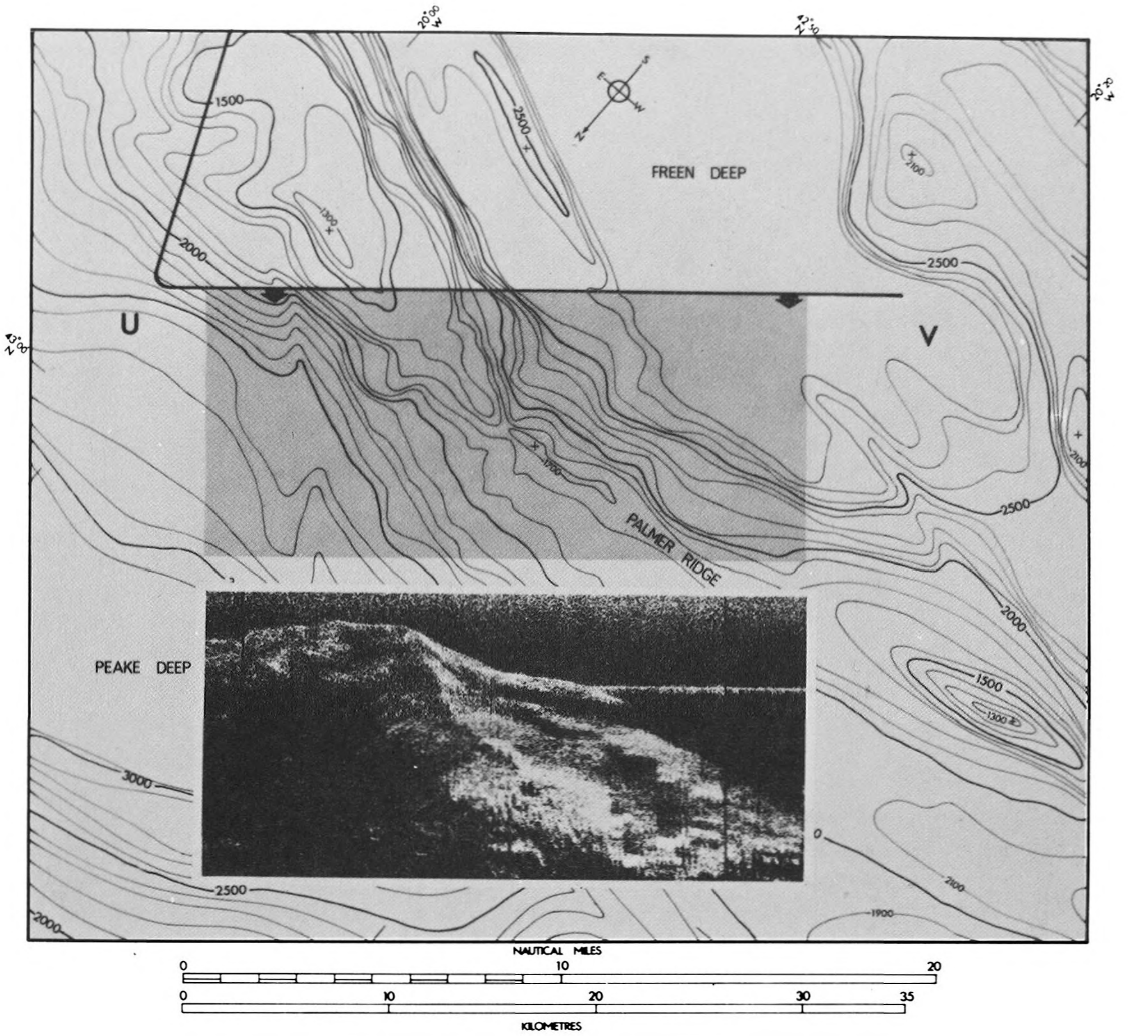


FIG. 12. – Palmer Ridge, separating Peake and Freen deeps in the NE Atlantic. The ridge stands 2,800 m above the floor of the Freen Deep. The shaded area shows that of the sonograph. Depths on the chart are in fathoms.

Volcanoes and Seamounts

Some of the earliest sonographs in the Mediterranean showed the contrasting underwater morphologies of volcanic islands and seamounts, the presence of channels and low sea level benches (BELDERSON *et al.*, 1972, 1974*b*). Since then many of the passage tracks in the Atlantic and Pacific have shown volcanic seamounts, many of which are circular in plan, some with relatively smooth tops, and others with central circular depressions which may be calderas. One of these, on the Walvis Ridge, was also surveyed by SEABEAM on RV *Jean Charcot* and provides an interesting comparison between the systems (Fig. 13). In the eastern Pacific clusters of volcanic seamounts were found, some with smooth tops, some with central depressions, and some with moats (Fig. 14). One is cut by a fault,

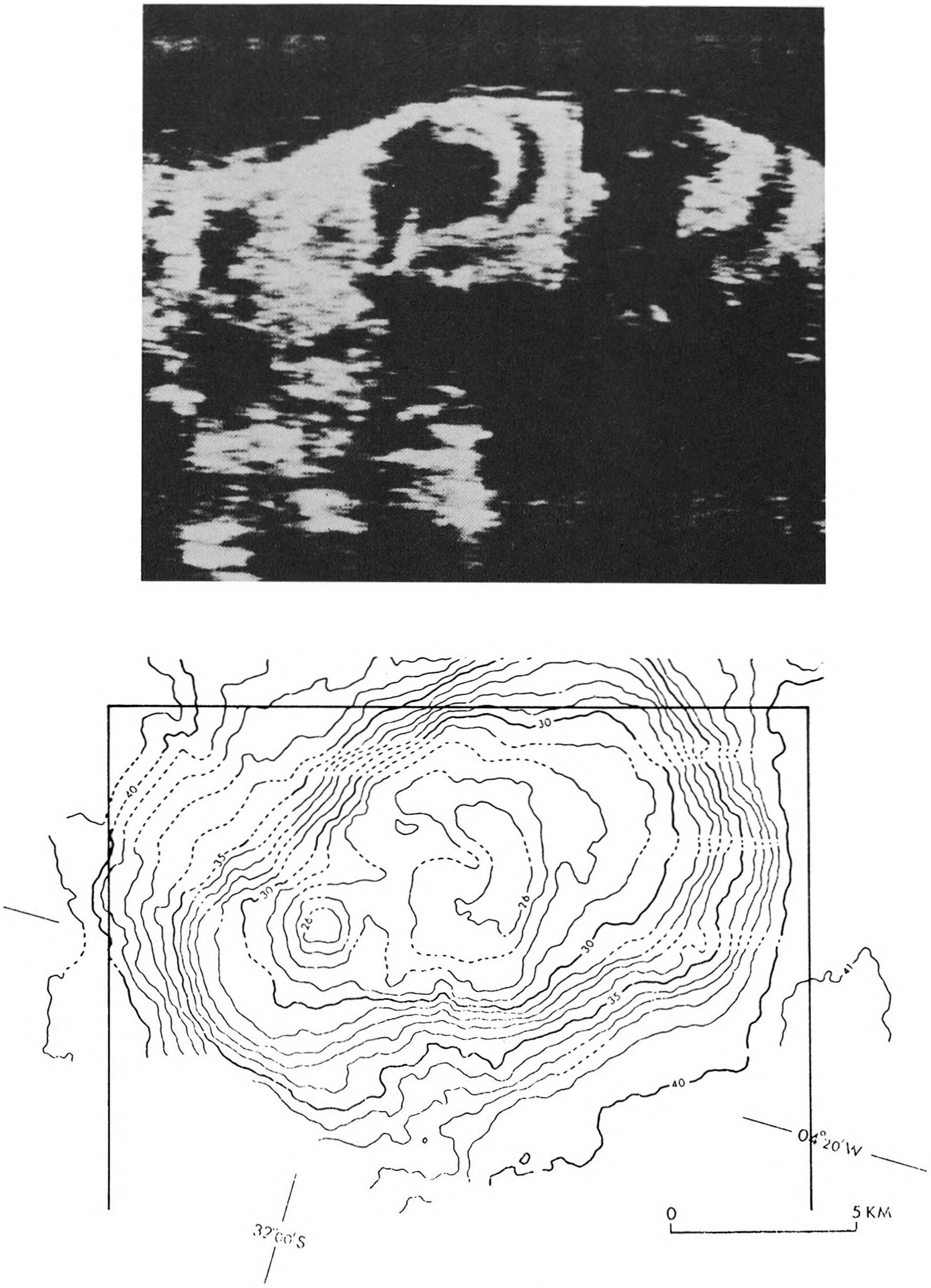


FIG. 13. – A comparison made between the sonograph (insonification from the top) and SEABEAM survey of a volcanic seamount on the northern flank of the Walvis Ridge. The track is along the line across the north side of the seamount, and the area covered by the sonograph is given by the other lines. The dark circular patch at the upper center of the sonograph is interpreted as a sedimented area within a breached crater (NEEDHAM, 1979).

believed from other evidence to have formed at a spreading axis, thus enabling the age of the volcano to be determined.

During the study of the axial region of midocean ridges in the Atlantic, many circular central depression volcanoes were found, sometimes well-preserved. A typical diameter of the depression in volcanoes on the Reykjanes Ridge is 1-4 km.

FIG. 14. – A cratered and possibly moated volcano 1,500 m high, on the East Pacific Rise (11°27′ S, 84°52′ W). The crater is 2 km across, and its base is 10 km across in 4,000 m water depth. The record is 30 km from top to bottom and insonified from the top (SEARLE *et al.*, 1981).

Volcanic Ridges at Plate Accretion Boundaries

In contrast to the circular volcanoes, the accretion axes of both slow and fast spreading ridges are characterized by linear volcanic ridges. Those on slow ridges were mapped in detail by high-resolution echo-sounding and submersible studies in project FAMOUS between 1971 and 1974. In 1973, GLORIA was used to examine the fine-scale morphology of the median valley and showed that there were several nearly parallel ridges in the valley floor and that the spreading axis often jumped from one position to another (LAUGHTON and RUSBY, 1975). The sonographs were able to show the presence of volcanic cones and possibly individual flow fronts on the scale of 200 m.

On the oblique spreading Reykjanes Ridge, the accretionary volcanic ridges are en echelon (fig. 15) (see page 28) and approximately orthogonal to the spreading direction (LAUGHTON *et al.*, 1979) in contrast to the tectonic fabric which parallels the ridge axis. This phenomenon, which has been seen in a minor degree in the FAMOUS area and in a GLORIA survey on the Mid-Atlantic Ridge at 45° N, enables the midocean ridge morphology to be attributed to two separate mechanisms related to the stresses of plate separation and to lithospheric thickening (SEARLE and LAUGHTON, 1981).

Tectonic Fabric of Midocean Ridges

A sonograph mosaic of 30,000 km^2 of the FAMOUS area revealed a tectonic fabric of linear faults, facing in toward the median valley, superimposed on the major mountainous relief (WHITMARSH and LAUGHTON, 1975, 1976). The success of this surveying technique led to studies of areas near the Kurchatov Fracture Zone (Fig. 16) at 40-1/2° N (SEARLE and LAUGHTON, 1976, 1977), at 45° N (LAUGHTON and SEARLE, 1979; SEARLE *et al.*, 1979), at 52° N, and on the Reykjanes Ridge at 60° N (LAUGHTON *et al.*, 1979; SEARLE and LAUGHTON, 1981). From these surveys, SEARLE and LAUGHTON (1976, 1977) and LAUGHTON and SEARLE (1979) concluded that slow spreading ridges are characterized by inward facing normal faults which are generated very close to the spreading axis and which are responsible for the occurrence of a median valley. The faulting is considered to reflect stresses associated with the tapering edge of the lithospheric wedge.

Subsequent studies of medium and fast spreading ridges in the east Pacific have shown that there also are linear patterns of inward facing faults whose spacings are not significantly different from those in the slow spreading Mid-Atlantic Ridge (R.C. SEARLE, personal communication, 1980).

Transform Faults and Fracture Zones

An early achievement of GLORIA was the identification of the active fault valley east of the Azores separating the Eurasian and African Plates (LAUGHTON *et al.*, 1972). Studies of the extension of this simple strike slip fault to the east showed that it splayed into a region of combined strike slip and compression (LAUGHTON and WHITMARSH, 1974) and to the west into the complex of the Azores spreading center. South of the Azores, the Trident Ridge (WHITMARSH, 1971) is probably an inactive relic of these complex plate movements.

Small, offset transform faults and fracture zones were seen in the FAMOUS area (WHITMARSH and LAUGHTON, 1975, 1976) and examined in detail in the Kurchatov Fracture Zone (Fig. 16) (SEARLE and LAUGHTON, 1976, 1977). Far from being simple linear structures parallel to the spreading direction, they exhibit a complex morphology reflecting oblique tension as well as pure shear (SEARLE, 1979) and may contain short oblique spreading axes, frequently shifting and dislocated by repeated shearing and healing and by vertical movements. By contrast, the large offsets of the Charlie-Gibbs Fracture Zone (Fig. 17) result in extremely linear valleys (SEARLE, 1981).

Where the normal faults parallel with the spreading axes join transform faults, they exhibit a curvature, seen first in the FAMOUS area. If the offset is small, then this curvature (or obliquity) dominates. SEARLE (1979), in a review of side-scan studies of North Atlantic fracture zones, showed that these oblique scarps occur in all fracture zones so far studied and believes that they arise from differential movement in tension gashes formed in the earliest stages of shearing.

Triple Junctions

The pattern of normal inward facing faults associated with both slow and fast spreading ridges has by now become familiar enough for it to be used to identify the location of new and old spreading centers, and to unravel some of the problems associated with triple junctions.

In the Atlantic a survey of the pattern of faulting around the Azores triple junction is enabling the most recent history of spreading to be analyzed (SEARLE, 1981). In the Pacific in 1980 the survey of the Galapagos triple junction (Pacific-Cocos-Nazca plates) suggests that its structure and evolution are considerably more complex than would have been suspected from conventional geophysical surveys (R.C. SEARLE, personal communication, 1981).

Fish Studies

Although not in the geomorphological field of achievements discussed above, GLORIA has proved its capability of long-range detection of fish shoals and, by repeated surveys of a given shoal, of tracking the shoal movements. In a survey on the continental shelf west of Scotland, herring shoals up to 5 km in length were insonified from a range of 10 km and tracked using a rocky outcrop as a reference mark on the bottom (RUSBY *et al.*, 1973; RUSBY, 1977).

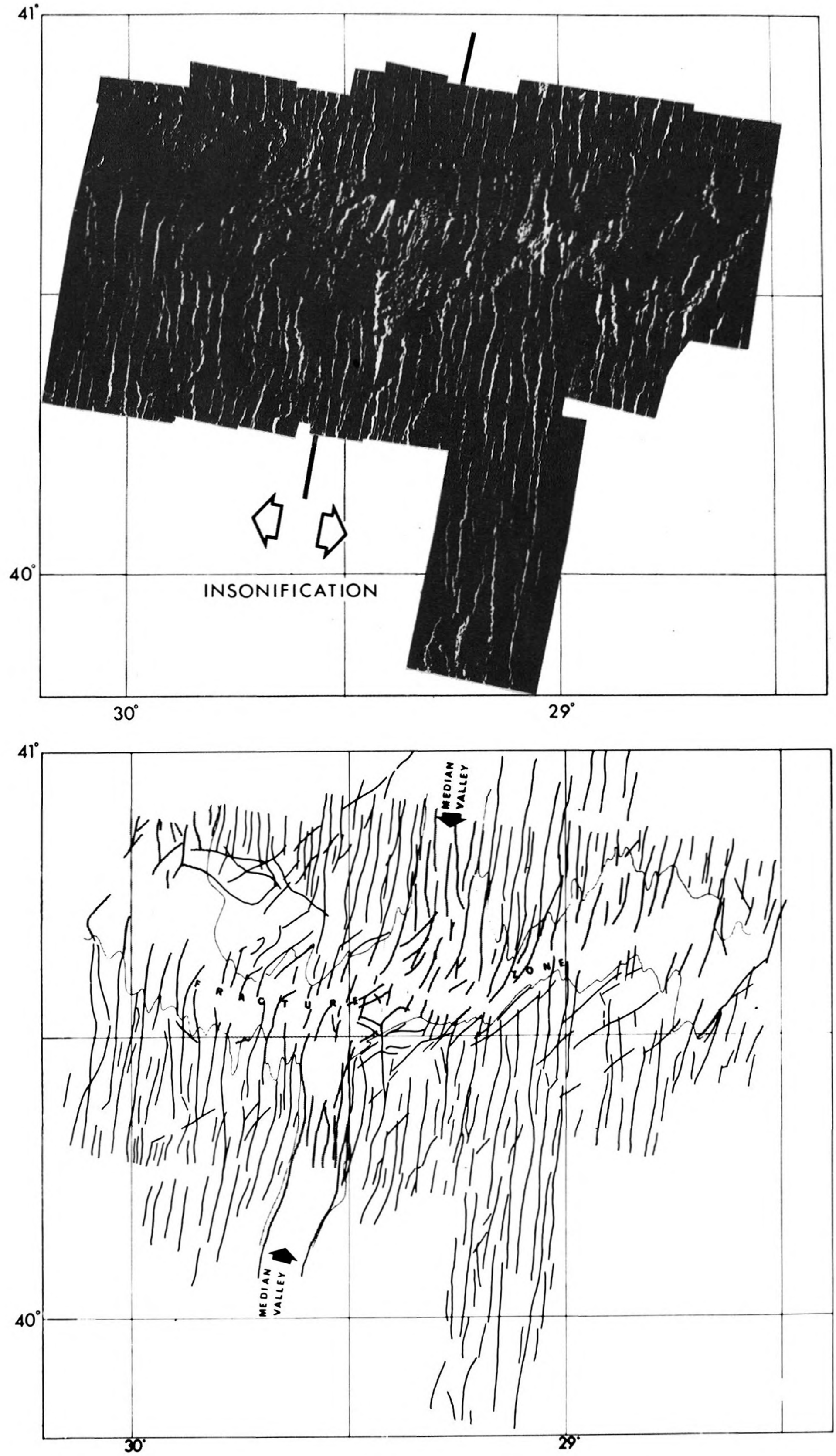


FIG. 16. – A sonograph mosaic of the Mid-Atlantic Ridge in the vicinity of the Kurchatov Fracture Zone and the interpreted pattern of inward facing normal faults (SEARLE and LAUGHTON, 1977).

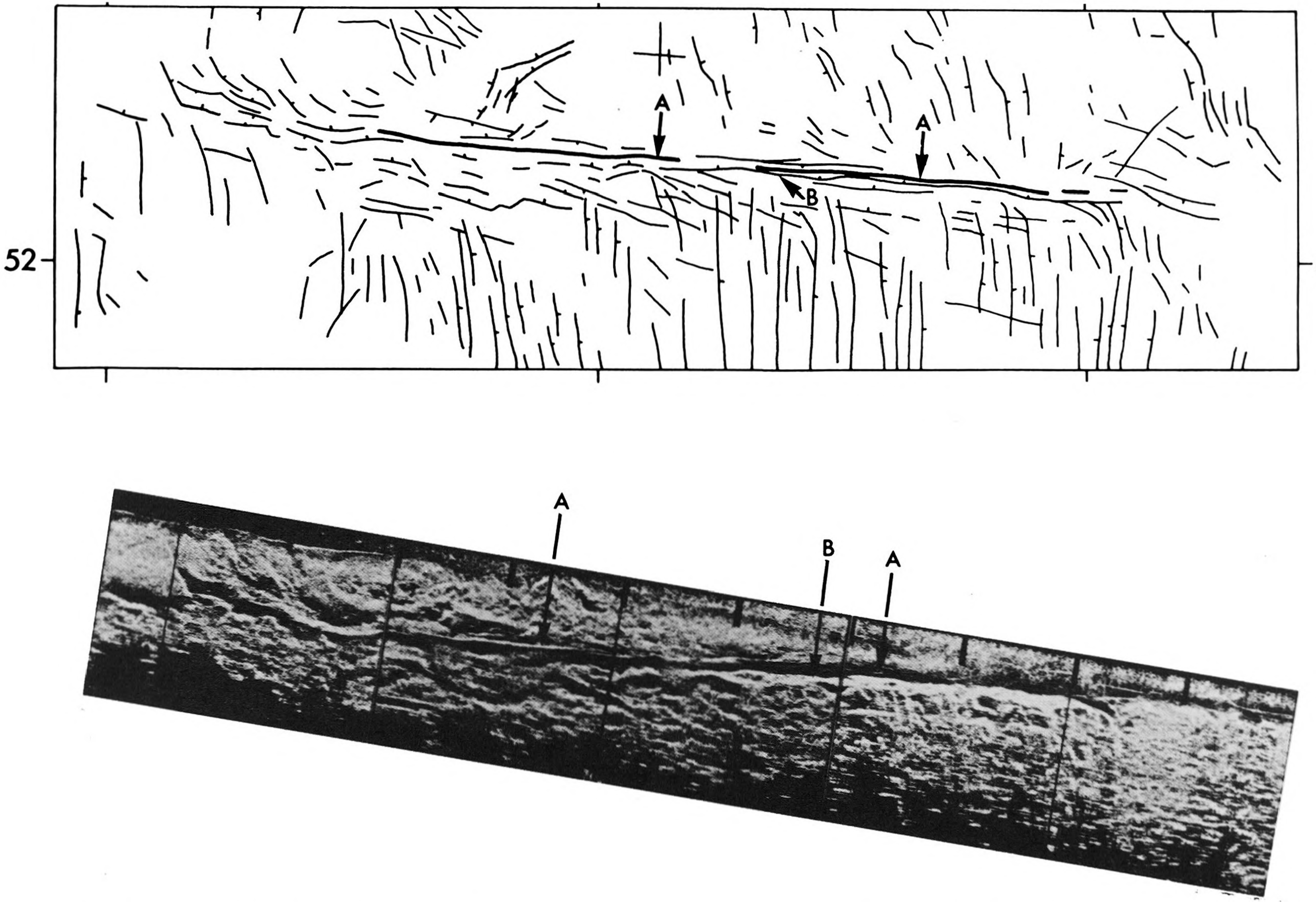


FIG. 17. – A sonograph of the active transform fault (insonified from the north) on the southern part of the Charlie-Gibbs Fracture Zone and tectonic interpretations (SEARLE, 1981). The fine line (A) in the sonograph is believed to be the fault itself, whereas the stronger reflection (B) is the valley wall.

REPRESENTATION OF GLORIA DATA ON AN OCEAN WIDE BASIS

Because of the large swaths of seafloor that can be insonified by GLORIA Mk II (1,100 km^2/h) the resulting sonographs cover a significant area of ocean scale charts. It is therefore instructive to mount reduced sonographs or mosaics of sonographs directly onto bathymetric charts in order to relate the real acoustic pictures to the bathymetry which has often been derived from very inadequate data. Valuable though this is on the wall in the laboratory, it is difficult to reproduce in a publication more than a few selected areas to represent different terrains. A montage of sonographs on a bathymetric chart of a part of the Mid-Atlantic Ridge in the vicinity of the Azores is shown in Fig. 18 and another on the Charlie-Gibbs Fracture Zone and Reykjanes Ridge in Fig. 19. It is clear that although vertical echo sounding emphasizes changes in absolute depth with only rather poor horizontal resolution, GLORIA, with low incident angles, highlights targets of high slope and hence high back scattering coefficient. Although echo sounding data has no azimuthal directionality, the sonographs are a function of the direction of sound propagation and hence may emphasize features of a certain trend and miss others.

For more systematic reference to all GLORIA sonographs it will be necessary to reproduce them in annotated form with reference to track charts at a suitable scale. Many of the sonographs cannot usefully be interpreted in isolation from other geological and geophysical data and this presentation may prove of most value to other scientific and applications groups studying particular areas of the ocean bed. The data are available for use outside the Institute of Oceanographic Sciences and those interested should contact the institute.

CURRENT DEVELOPMENT OF GLORIA

Throughout the decade of GLORIA development, the emphasis has been on optimizing the underwater acoustic design of the system and developing the hardware and ease of handling. Advantage was taken of existing signal-processing techniques based on analogue methods and tape systems. These have led, however, to limitations in adequately exploiting the dynamic range of the system and in the flexibility of subsequent image processing.

Current research is looking at methods of digital recording and the use of image enhancement techniques. Preliminary work in collaboration with the Jet Propulsion Laboratory, Pasadena, has proved very encouraging. Slant range distortion has been removed assuming a fixed depth along track, thus merging the port and starboard images and providing across-track continuity of linear targets. A special mosaicking program enabled overlapping areas to be merged with an almost imperceptible join. Both these techniques are illustrated in Fig. 20, which consists of two adjacent two-sided sonographs.

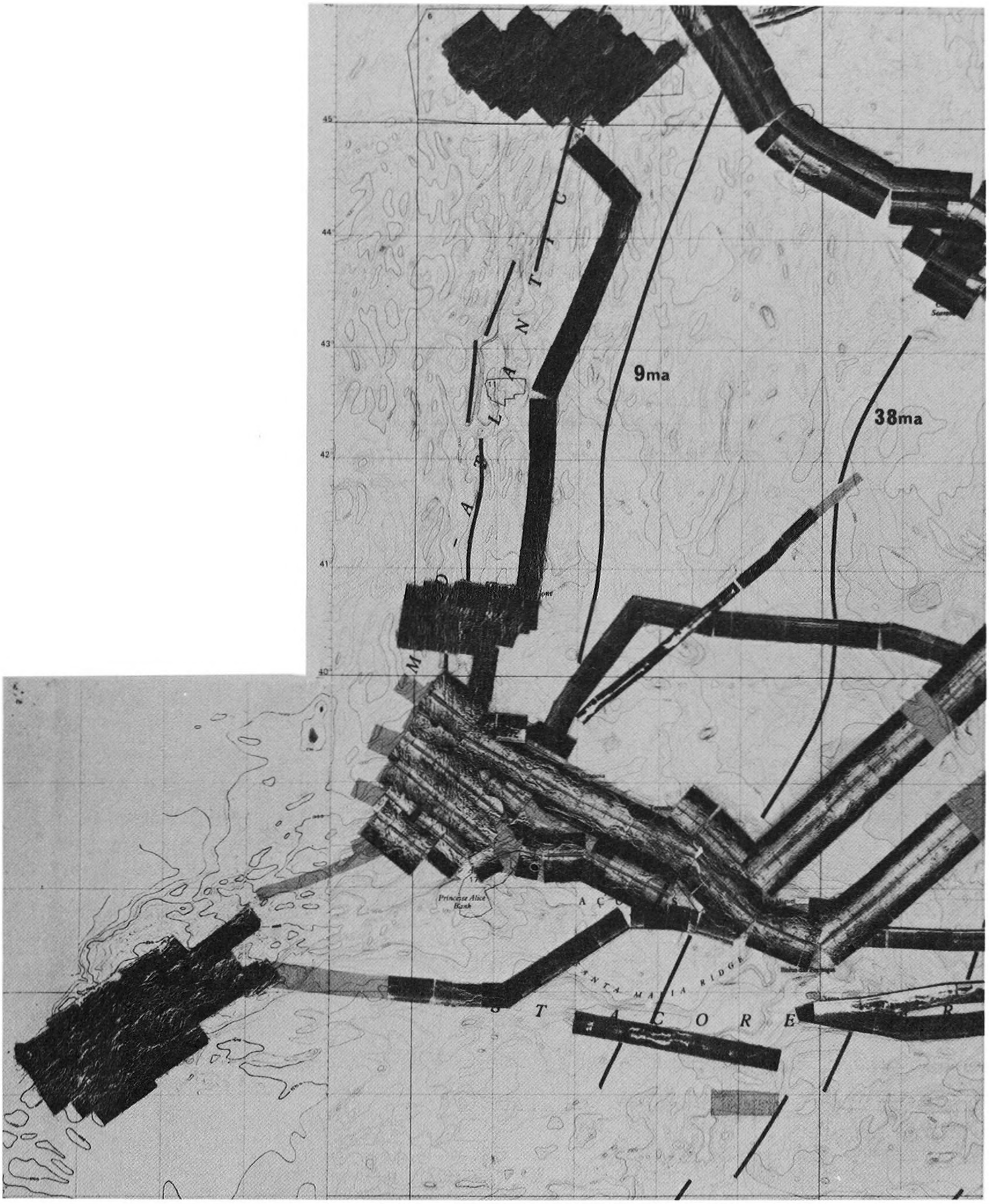


FIG. 18. – Sonographs mounted on part of the bathymetric chart Mid-Atlantic Ridge to South West Europe (LAUGHTON *et al.*, 1975), showing special studies of the Mid-Atlantic Ridge axis at 45° N, the Kurchatov Fracture Zone, the Azores triple junction, and the FAMOUS area, and of the Azores platform. The islands of the Azores in the survey area are black. Heavy black lines give the 0,9, and 38 Ma isochrons.

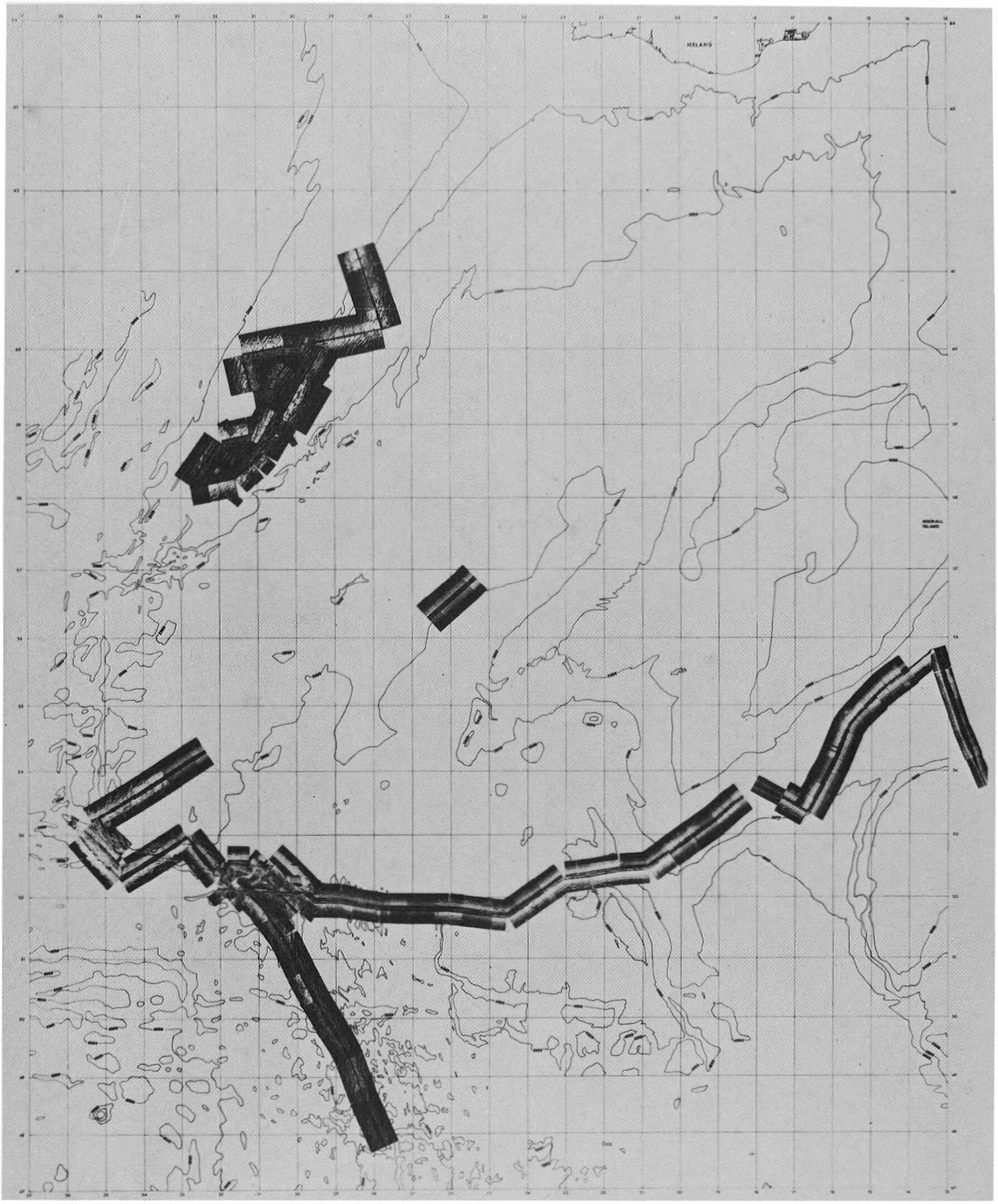


FIG. 19. – Sonographs mounted on a bathymetric base on the Reykjanes Ridge, the Charlie-Gibbs Fracture Zone, the Mid-Atlantic Ridge axis, and in Rockall Trough. Contours are at 1 000 m intervals.

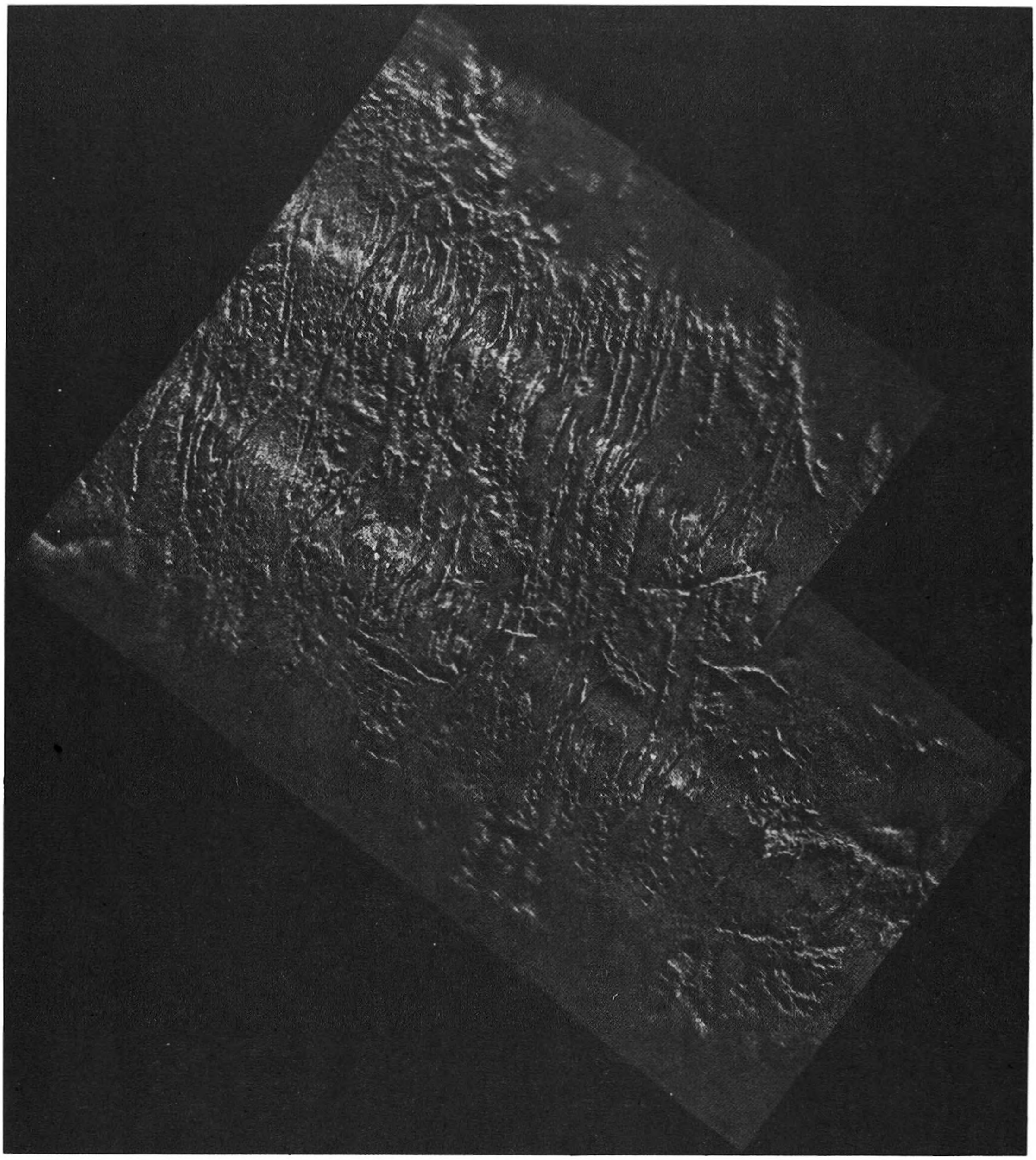


FIG. 20. – Two parallel two-sided sonographs on the crest of the Mid-Atlantic Ridge showing linear tectonic fabric. The tracks run from upper left to lower right along the two lighter strips in the figure. The sonographs have been digitized, corrected for slant range errors, and merged by the Jet Propulsion Laboratory, Pasadena (published by kind permission of JPL).

The scope for further image processing will be increased when the signals are recorded digitally. Future possibilities include shaded relief, stereo imaging, and the accurate representation of absolute signal strengths.

CONCLUSIONS

The faith shown in a deep sea side-scan sonar system in 1965 by the director at that time, Sir George DEACON, F.R.S., has been amply justified by the achievements of this technique. It has provided a unique way of studying ocean floor morphology and has revealed many new features. As a survey tool, it is complementary to other techniques, and its use has been recommended in relation to site surveys for IPOD drill sites, for studying potential disposal areas for radioactive waste, and for examining slope stability for the exploitation of hydrocarbons on the continental margin. As the broader aspects of seafloor geology become better known, high-resolution methods become increasingly important, and GLORIA should continue to be one of these.

Acknowledgements

The development and operation of GLORIA Mks I and II have been the responsibility of a large team within IOS, and its success is a tribute to them; but special mention should be made of J.S.M. RUSBY who pioneered Mk I, M.L. SOMERS who developed Mk II and J. REVIE who has long been a cornerstone of the team and now is manager of the operations group.

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