DEEP OCEAN FLOOR MAPPING FOR SCIENTIFIC PURPOSES AND THE APPLICATION OF AUTOMATIC CARTOGRAPHY

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Editor's Note. — This article was presented at the Symposium on Oceanic Cartography at the Sixth International Cartographic Conference of the International Cartographic Association held in Ottawa, Canada, in August 1972.

It was written partly in response to an article on the needs for World Bathymetric Charts, by L.N. PASCOE, published in the January 1972 number of the *International Hydrographic Review*, and furthers the discussion on this topic.

The Tables listing deep-ocean bathymetric charts provide a useful catalogue of known material.

ABSTRACT

Oceanographers require good bathymetric charts. Their specific needs and the extent to which they are met by existing chart series are discussed, and suggestions are made for the future. The problems of contouring sparse data in the oceans are illustrated with reference to the bathymetric chart series of the National Institute of Oceanography, part of which has been published with the aid of automatic cartography.

INTRODUCTION

The continually increasing scientific, commercial and military awareness of the oceans and their resources emphasies the need for good bathymetric charts. It is therefore appropriate to review not only the current status of bathymetric charts, but also the extent to which the needs of these groups are presently being fulfilled and what is required in the future. The exact nature of these requirements is not always recognised and it is the aim of this paper to present the viewpoint of the oceanographer, whether a marine geologist or geophysicist, a physical oceanographer or a marine biologist, who is interested in an accurate description of the shape of the sea floor in order to formulate his research programme and to interpret his observations.

For the earth scientist on land examining some new area, his first assessment is visual. He will see the presence of mountains, valleys and plains by viewing from a distance and can then determine the character of the terrain — whether it is rocky, muddy, vegetated, etc. — by closer visual examination. Only when he has mentally digested what he has seen, will he start to plan a more sophisticated programme of surveying, photography, sampling and instrumental measurement.

Under the sea, however, a totally different situation prevails. Sound replaces light, and its greater wavelength does not allow pictures of the topography to be easily obtained. The oceanographer must collect data laboriously and work at its correlation to produce bathymetric charts. Although he has the advantage of a fixed reference level and relative ease of mobility, the mechanisms that operate to shape the deep sea floor are so different from those on land that comparisons cannot be made with topography that can be seen.

THE NEED

The need for good bathymetric charts by oceanographers has been recognised since Prince Albert of Monaco initiated a world series in 1903.

A number of international and national series have been produced since then, some of which are world wide and others are limited to oceans and parts of oceans. The more important series published in the last two decades are listed in Tables I and II. Some of these have been produced by oceanographers for their own requirements, but others have been produced by organisations who have no immediate interest in using their products. As a result, the quality of the charts varies tremendously. Furthermore it is impossible in all but a very few of the series, to judge what the quality is from the chart itself since no indication is given of the coverage of soundings on which the contours are based.

The continuing and increasing need for good bathymetric charts has recently been discussed by many international organisations of earth scientists. The Intergovernmental Oceanographic Commission of UNESCO set up a group of experts on long-term scientific policy and planning (GELTSPAP) who recommended in their report of November 1970 :

"Para. 63. **Geo-science Exercise**

4.1 (*Outline project* 4.1). *Morphological charting of the sea floor.*

"This falls in the category of global activities. It is of great general scientific and practical importance for detection and exploitation of mineral and biological resources, marine engineering and transport, etc. International co-operation is essential for: —

(a) rapid evaluation and editing of existing data;
(b) acquiring new data; using additional methods such as seismic profiling and, if possible, side-scan, magnetic and gravimetric measurements and bottom sampling;
(c) extending surveys and avoiding duplication, ensuring maximum utilisation of ship cruises;
(d) encouraging active participation by both advanced and developing countries;
(e) exchanging new data.

TABLE I

List of World Series of Bathymetric Charts

Series title	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour interval	Author, reference, or chart No.
General Bathymetric Chart of the Oceans	IHB Monaco	1923-1969	24	Mercator and Polar	1/10 000 000	1 000 m	THOULET (1904) I H O Spec. Pub.
The World	U.S. Navy Oceanographic Office	1961	12	Mercator	1/12 000 000	500 fm	H.O. Misc. 15,254
Bottom Contour Charts	U.S.N.O.O.	1951-1971	190 (partial world cover)	Mercator	4″ = 1 deg. long.	100 fm	B 0107 - B 3612
Ocean Charts	National Geological Committee U.S.S.R.	1963-1965	6	Various	1/15 000 000 to 1/25 000 000	500 m and 1 000 m	
World Map	Department Geod. and Cartography ; German Dem. Rep.	1965 onwards	244	Conic Equidistant	1/2 500 000	1 000 m	RADO (1966)
Deutsche Meereskarte	Germany	1968	3	Minimum Error	1/25 000 000	1 000 m	DIETRICH and ULRICH (1968)

We propose that the seventh session of the Commission consider the organisational aspects of implementation taking into account the experience of the IHB as well as that gained in editing the Geological Map of the World".

An International Workshop on Marine Geoscience promoted by the Scientific Committee on Oceanic Research (SCOR) and held in Honolulu in September 1971, considered this proposal, together with the marine aspects of the Geodynamics Project (jointly sponsored by the International Union of Geodesy and Geophysics and the International Union of Geological Sciences) and recommended to SCOR that a working group should be set up. As a result, in February 1972, SCOR established Working Group

TABLE II

List of Ocean Series of Bathymetric Charts

Series title	Area covered	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour Interval	Author, reference, or chart
ATLANTIC								
Atlantic Ocean	Atlantic	Inst. Oceanology U.S.S.R.	1971	6	Equal Area	1/10 000 000	500 m	
Atlantic Ocean	Atlantic	Woods Hole Oc. Inst., U.S.A.	1972	10	Mercator	1/5 000 000	400 m	I.D.O.E. (NSF) 71-72
North Atlantic Bathymetric Chart	North Atlantic	Hydrographic Office, U.S.A.	1950	8	Mercator	1/4 000 000	100 fm	HO 6750
Bathymetric Chart, East U.S.A.	Nova Scotia to Gulf of Mexico	W.H.O.I.	1965-1968	6	Lambert Conformal	1/1 000 000	20 and 200 m	UCHUPI, U.S. Geol. Survey. Misc. Geol. Inves. 1-451
Newfoundland Shelf	43°-50°N	Can. Hyd. Serv. and W.H.O.I.	1970	1	Lambert Conformal	1/1 000 000	20 and 200 m	802
Bathymetric Maps of Eastern Continental Margin, U.S.A.	24°-45°N	American Association of Petroleum Geologists	1970	3	Transverse Mercator	1/1 000 000	1, 5 and 25 fm	
Oceanic Regions adjacent to Canada	Parts of Pacific, Atlantic & Arctic	Can. Hyd. Serv.	1971	1	Lambert Conformal	1/6 750 000	500 m	800-A

TABLE II (contd.)

Series title	Area covered	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour Interval	Author, reference, or chart
Natural Resource Chart	Grand Banks and Adjacent Areas	Canadian Hydrographic Service	1971	Appx. 50	Transverse Mercator	1/250 000	10 – 100 m	Can. Hyd. Serv. Inf. Bull. 21
Abords du Plateau Continental	North East Atlantic 42°-64°N	Inst. Sci. et Tech. des Pêches Maritimes France	1961	18	Mercator	1/300 000	200 m	BERTHOIS (1962)
G.E.B.C.O. Collected Soundings	North Atlantic	D.H.I. Germany	1969	20	Mercator	1/1 000 000	500 m	
N.I.O. Bathymetric Charts	North-East Atlantic	N.I.O., U.K.	Unpublished Revised to 1971	16	Mercator	1/1 000 000	100 fm	
South-East Atlantic and South-West Indian Oceans	Oceans around S. Africa	University of Cape Town, S. Africa	1967	1	Mercator	1/10 000 000	500 m	SIMPSON and FORDER 123 A(1202-67)
PACIFIC								
Pacific Ocean	Pacific	Inst. Oceanology U.S.S.R.	1964	6	Equal Area	1/10 000 000	500 m	

TABLE II (contd.)

Series title	Area covered	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour Interval	Author, reference, or chart
Topography of North Pacific	North Pacific	Scripps Inst. Oc. and Inst. of Marine Resources	1971	1	Mercator	1/10 000 000	200 fm	CHASE, MENARD, MAMMERICKX, IMR Tech Rep Series TR-17
Bathymetry of North Pacific	North Pacific	Scripps Inst. Oc. and Inst. of Marine Resources	1970	10	Mercator	1/6 500 000	200 fm	CHASE, MENARD, MAMMERICKX, IMR Tech Rep Series TR-17
Bathymetric Atlas of the North Western Pacific Ocean	4°S-60°N	U.S.N.O.O. and Scripps Inst. Oc.	1969	41	Mercator	1/2 400 000	20, 100 200 fm	HO Pub 1301 2101-2604
Sea Floor Topography of the Central Eastern Pacific Ocean	35°N-24°S	U.S. Fish and Wildlife Service, Bu. Com. Fish.	1968	24(+2)	Mercator	1/2 000 000	200 fm	CHASE, Circ. 291
Bathymetry of the Aleutian Arc, Alaska	Aleutian Arc, Alaska	U.S. Dept. of Commerce	1966	6	Transverse Mercator	1/400 000	50 fm	NICHOLLS and PARRY (1966)
Bathymetric Chart of the Adjacent Seas of Nippon	North West Pacific	Hydrographic Office, Japan	1966	4	Mercator	1/3 000 000	500 m	6 301, 2, 3, 4.

TABLE II (contd.)

Series title	Area covered	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour Interval	Author, reference, or chart
Ocean Chart Series	South West Pacific	New Zealand Oceanographic Institute	1969	18	Mercator	1/1 000 000	250 m	N.Z. Oceanogr. Inst. Chart Oceanic Ser. 1/1 000 000
INDIAN OCEAN								
I.I.O.E. Atlas of Geology and Geophysics	Indian Ocean	UNESCO	In preparation	14	Mercator	1/5 000 000	500 m	Source material at 1/2 000 000 by NIO (UK), SIO (USA), U. Capetown (SA) and Inst. Oc. (USSR).
N.I.O. Indian Ocean	North West Indian Ocean	N.I.O., U.K.	Unpublished	16	Mercator	1/1 000 000	100 fm	
Indian Ocean South West Zone	South West Indian Ocean	Institute of Global Physics, France	1970	6	Mercator	1/2 000 000	500 m	BERTHOIS, SCHLICH and PATRIAT (1968)
–	Red Sea	N.I.O., U.K.	1970	1	Mercator	1/2 000 000	100 fm	LAUGHTON (1970)
–	Gulf of Aden	N.I.O., U.K.	1970	1	Mercator	1/2 000 000	100 fm	LAUGHTON, WHITMARSH and JONES (1970)

TABLE II (contd.)

Series title	Area covered	Organisation responsible and country	Date of publication	No. of sheets	Projection	Scale	Contour Interval	Author, reference, or chart
ARCTIC								
Arctic Bathymetry	N of 72°N, 90-180°W	Canadian Hydrographic Service	1967	2	Polar Stereographic	1/2 000 000	500 m	896, 897
ANTARCTICA								
Antarctica	–	Amer. Geog. Soc. of New York	1970	1	Stereographic	1/5 000 000	1 000 m	AGS/AMS 13
MEDITERRA-NEAN								
Mediterranean	Med.	Saclant ASW Res. Centre, Italy	1970	9	Mercator	1/750 000	100 fm	ALLAN & MORELLI (1971)
	Western Med.	Musée Oceanogr. Monaco	to 1962	12	Misc.	Misc.	Misc.	BOURCART (1960)
Carte Bath. de la Mer Ligure	Ligurean Sea	Musée Oceanogr. Monaco	1969	16	U.T.M.	1/50 000	5, 10 20 m	ALINAT *et al* (1969)
Carte Bath. de la Mer Ligure	Ligurean Sea	Musée Oceanogr. Monaco	1969	4	U.T.M.	1/100 000	20 m	ALINAT *et al* (1969)

41 on Morphological Mapping of the Ocean Floor under the Chairmanship of Dr J. Ulrich of the Institut für Meereskunde, Kiel, with the following terms of reference:

"To determine a rational scheme for reduction and presentation of sounding data that would constitute a framework in which the international geological mapping of the sea floor could proceed; to present recommendations to the International Cartographic Association meetings in Ottawa in September 1972; to recommend further action to be taken by SCOR".

EXISTING INTERNATIONAL ORGANISATION FOR PRODUCTION OF BATHYMETRIC CHARTS

The above recommendations reflect the current dissatisfaction amongst scientists with the existing international organization for the production of bathymetric charts on a world scale. The Permanent Specialised Centre for the exchange of bathymetric data, designated by the Intergovernmental Oceanographic Commission (Manual on International Oceanographic Data Exchange — UNESCO 1967), is the International Hydrographic Organization, Monaco, who organize GEBCO (General Bathymetric Chart of the Oceans) both as a data centre to compile soundings at 1/1 000 000 and to prepare and publish a series of 1/10 000 000 contoured charts (table I). The organization is outlined in their publication "Regulations for the General Bathymetric Chart of the Oceans, GEBCO 1970". The input to the IHO is through national Hydrographic Offices according to allocated oceanic areas.

An appraisal of the GEBCO series from a hydrographer's point of view has recently been published by Newson (1971). The oceanographer's view is that it does not form a world series of uniform quality, many of the charts are out of date (some have not been revised since 1923), there is not an aggressive policy of compiling all available soundings, it does not incorporate the results of modern surveys, it fails to make use of modern interpretation of sea floor morphology, and the charts do not indicate in any way the reliability of the contours shown.

THE NATURE OF THE SOUNDING DATA IN THE DEEP OCEAN

Until the 1930's deep ocean soundings were made by the wire and weight method, which was subject to errors caused by non-vertical wires and the failure to identify bottom contact. Early echo-sounding was crude and the timing often inaccurate; even today there are echo-sounders where the basic timing mechanism is governor-controlled requiring stopwatch calibration. Such soundings can easily have errors of 100 metres or more unless great care is taken. Precision echo-sounders using a tuning-fork or crystal-controlled time base became common by the early 1960's allowing an accuracy of about 5 metres to be achieved (CREASE, LAUGHTON and SWALLOW, 1964), and the existence of abyssal plains to be recognized. Other errors in soundings, however, arise from a misinterpretation of the phase of an echo-sounder (errors of say 1 000 m), from confusion between the bottom and deep scattering layer echoes (often responsible for non-existent "shoals") and from confusion in knowing the velocity of sound in sea water used when converting from a time measurement to a depth measurement (errors up to 200 m).

The other aspect of the quality of the data is the accuracy of position. Although a navigational accuracy of better than 3 n.m. is required by GEBCO before soundings are submitted to data centres, there are many soundings which are demonstrably 20 n.m. or more in error. Today, many ships are equipped with accurate navigational aids (satellite, Loran, etc.) although there are still many which totally rely on intermittent celestial observations.

Up to 1950 there were so few oceanic soundings that the Hydrographic Department was still able to publish lists of oceanic soundings, but this method was clearly impractical for continuous echo-sounding. As part of the compilation for the 3rd edition of GEBCO, soundings were transferred to a series of 1/1 million Mercator plotting sheets and the responsibility shared between various member nations of the IHB. This system is still in use for compilation of the 4th edition, now being prepared sheet by sheet. Collaboration between national Hydrographic Departments has led to the extremely useful compilations of ocean soundings at the 1/1 million scale which form the basis of many oceanic bathymetric charts.

Although high standards of quality control of the data are laid down by GEBCO, nevertheless many of the compilation sheets contain soundings which incorporate errors of the type discussed above and it is important to identify these when interpreting the soundings in terms of contours. Because of the mixed quality on these sheets, new high quality data are often not submitted by those who collect them and never appear on the collected sounding sheets. Other data are often not submitted because of a lack of interest in international data exchange. In a recent updating of contour charts in the North Atlantic about 30% additional data were obtained direct from organizations known to have obtained soundings which had not been found on the collected sounding sheets of the Hydrographic Department responsible. Ultimately the completeness of the collected sounding sheets will depend on the goodwill of oceanographers to submit their data.

The density of sounding data at the 1/1 million scale varies from near saturation (i.e. when there is inadequate space to write any more soundings, or when the track spacing approaches the positional accuracy) to extremely sparse when there are no data at all for several hundred miles. Only 20 sheets out of a total of 575 have a sounding density of greater than 50% as defined by the U.K. Hydrographic Department (Hydrographer, 1971). The production of a world series of contoured charts from this data therefore requires considerable interpretation and interpolation that can only be properly based on a knowledge of sea floor morphology and the geological processes operating, and a detailed indication of the sounding control used is necessary to show where interpolation has been made.

In addition to the random track data on the GEBCO compilation sheets, large areas of ocean floor have been surveyed systematically for military purposes using precision echo-sounders and accurate navigation. Very few of these surveys are presently available to oceanographers in the form of raw data, but contoured charts at a reduced scale are sometimes published (e.g. Hydrographic Dept., U.K., Chart C6101) and doubtless more will become available in the future. Any world series of bathymetric charts must include the results of these surveys and accept them in a contoured form since they represent by far the most accurate and consistent data on the sea floor yet available. They must replace all other random track data in the area.

THE REQUIREMENTS OF OCEANOGRAPHERS

In this context, the term "oceanographers" is considered to include all scientists who are concerned with describing and understanding the ocean, and the processes that operate in it and below it. The needs of oceanographers are therefore extremely varied depending on the particular aspect which they are studying. In some cases an overall view of the world's oceans is needed to compare different areas or to evaluate world-wide distributions of some parameter. In other cases, the greatest detail possible is required for a very limited area, where a small feature is being studied. However there are certain common characteristics which oceanographers desire on bathymetric charts, which are worth discussing separately.

(1) The closest approximation to the truth that can be made from available data and existing knowledge about the sea floor is required. As more and more data become available, so the real shape of the sea bottom will be progressively revealed, and the need, therefore, is for charts which are as up-to-date as possible and which include all the latest data.

(2) Recognizing that any contoured chart contains a greater or less degree of interpretation, the oceanographer requires to know the basis and hence reliability of the contours, without having to turn to the original compilation sheets. Methods of indicating the sounding control to meet this need will be discussed later.

(3) To meet the widely varying demands of oceanographers, charts need to be at varying scales and with varying contour intervals. For a world series, a scale of 1/10 000 000 provides a useful wall chart that can be viewed as a whole. For expedition planning and passage work, a scale of 1/1 000 000 is very commonly used and found to be convenient. For special studies, scales of 1/250 000 or 1/100 000 allow full advantage to be taken of currently available methods of accurate navigation in the ocean.

(4) Various projections are required to meet various needs, such as preservation of equal area, preservation of angular relationships, ease of correlation with charts containing other data, and special problems such

as oblique Mercator projections about the poles of rotation of lithospheric plates.

(5) For some oceanographic purposes, e.g. the effect of topography on eddies and wave-like motions in the water mass, the bathymetry needs to be filtered so that irregularities with wavelengths shorter than some chosen value are removed. Although there are some computer programmes that will do this on sparse data, intelligent manual contouring can also be used.

(6) Ease of visualisation of the three-dimensional relief which is presented in two-dimensional form. Conventional contour charts are not always the most effective way to communicate the sea bed morphology, and physiographic diagrams (HEEZEN, THARP and EWING, 1959) (see table III) and other methods have been successfully used.

TABLE III

Physiographic Diagrams of the Oceans

Series Title	Organisation responsible and country	Date of Publication	Scale	References
Physiographic Diagram of North Atlantic	Geological Society of America	1968 (2nd edn)	1/4 000 000 (approx)	HEEZEN, THARP & EWING (1959)
Physiographic Diagram of South Atlantic	Geological Society of America	1962	1/10 000 000 (approx)	HEEZEN & THARP (1961)
Physiographic Diagram of Indian Ocean	Geological Society of America	1964	1/10 000 000 (approx)	HEEZEN & THARP (1965)
Atlantic Ocean Floor	National Geographic Society	1968	1/30 000 000	Nat. Geog. Mag. *133* (4) 794 (1968)
Pacific Ocean Floor	National Geographic Society	1969	1/36 500 000	Nat. Geog. Mag. *136* (4) 496 (1969)
Indian Ocean Floor	National Geographic Society	1967	1/23 000 000	Nat. Geog. Mag. *132* (4) 594 (1967)
Arctic Ocean Floor	National Geographic Society	1971	1/10 000 000	Nat. Geog. Mag. *140* (4) 518 (1971)
Mediterranean	Heezen & Tharp	1970	1/42 000 000	Fig. 1 in RYAN, STANLEY, HERSEY, FAHLQUIST & ALLAN (1970)
North West Pacific	Institute of Oceanology, Moscow, U.S.S.R.	1966	1/4 800 000	MAROVA (1967)
North East Pacific	Scripps Institution of Oceanography	1964	1/5 000 000	MENARD (1964)

(7) Ease of conversion from one scale, one projection, or one set of units to another will enable oceanographers to use the data most effectively for comparison with other parameters.

By contrast, the navigator requires different characteristics. Emphasis must be laid on features that are either hazards to navigation, such as shoals and reefs, or aids to navigation, such as the 200 m line. More detail and higher positional accuracy is required in continental shelf areas, especially in shipping lanes, but less may be necessary in deep ocean areas. A doubtful shoal area must be retained until it is completely disproved (which is often very difficult and time-consuming) in case it is a hazard, and the minimum possible depths must be shown, rather than a statistically calculated most probable value for the top of a shoal. The design of the charts must be such that positions and tracks can be easily plotted (usually Mercator projection) and easily seen, and readily transferred from chart to chart.

CONTOURING COLLECTED OCEANIC SOUNDING SHEETS

Realistic contouring of widely spaced random sounding data can only be made with experience of the types of sea floor topography that are found in different physiographic regions. Many small areas of the oceans representative of such regions as abyssal plains, submarine canyons, mid-

FIG. 1. — Bathymetry on the mid-Atlantic Ridge showing survey by Bedford Institute, Canada, in box (AUMENTO, LONCAREVIC and ROSS, 1971) and adjacent areas contoured from random tracks (dashed lines). (From N.I.O. working sheet—area 41. Depths in corrected fathoms, contour interval 100 fathoms.)

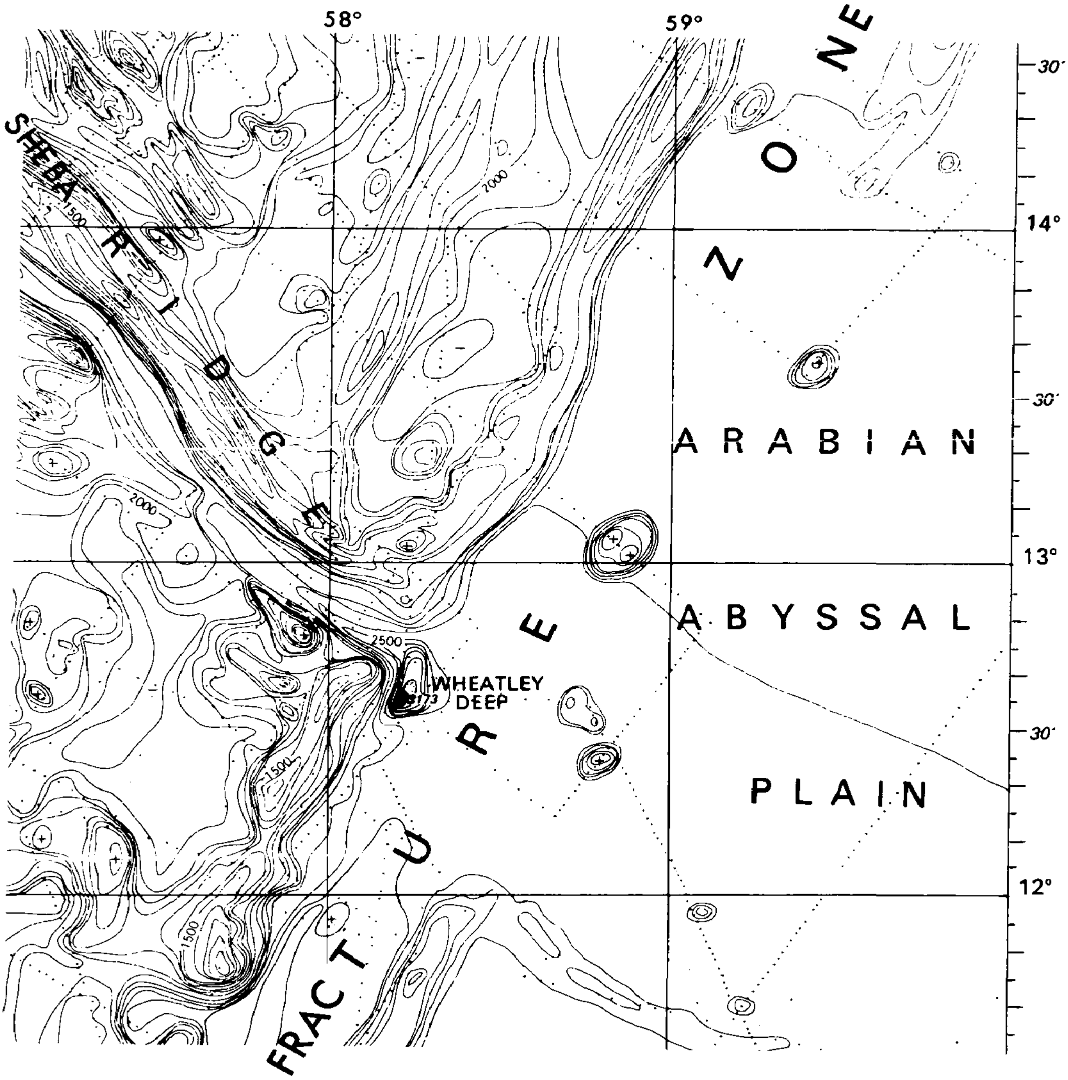

FIG. 2. — Part of the Gulf of Aden bathymetric chart (LAUGHTON, WHITMARSH and JONES, 1970) showing the junction between the Sheba Ridge and the Owen Fracture Zone. The linework was scribed by the automatic cartography process of the Experimental Cartography Unit, U.K. (BICKMORE, 1969). Each sounding used in the compilation is shown by a dot. (Depths in corrected fathoms, contour interval 100 fathoms.)

ocean ridges, fracture zones and so on have been surveyed in sufficient detail to determine the texture of the topography — i.e. the scale of roughness or smoothness, the degree of slope continuity of such features as canyons, the trends of ridges and valleys, and their likely ratio of length to breadth. In similar physiographic regions where only widely separated single profiles are available, soundings can be contoured using the likely topographic texture as a guide. In fig. 1, a very detailed survey by the Bedford Institute, Canada (AUMENTO, LONCAREVIC and ROSS, 1971), within the box, shows the median valley and elongated mountains of the mid-Atlantic Ridge. This texture has been used to contour the neighbouring parts of the Ridge where random tracks are more widely spaced.

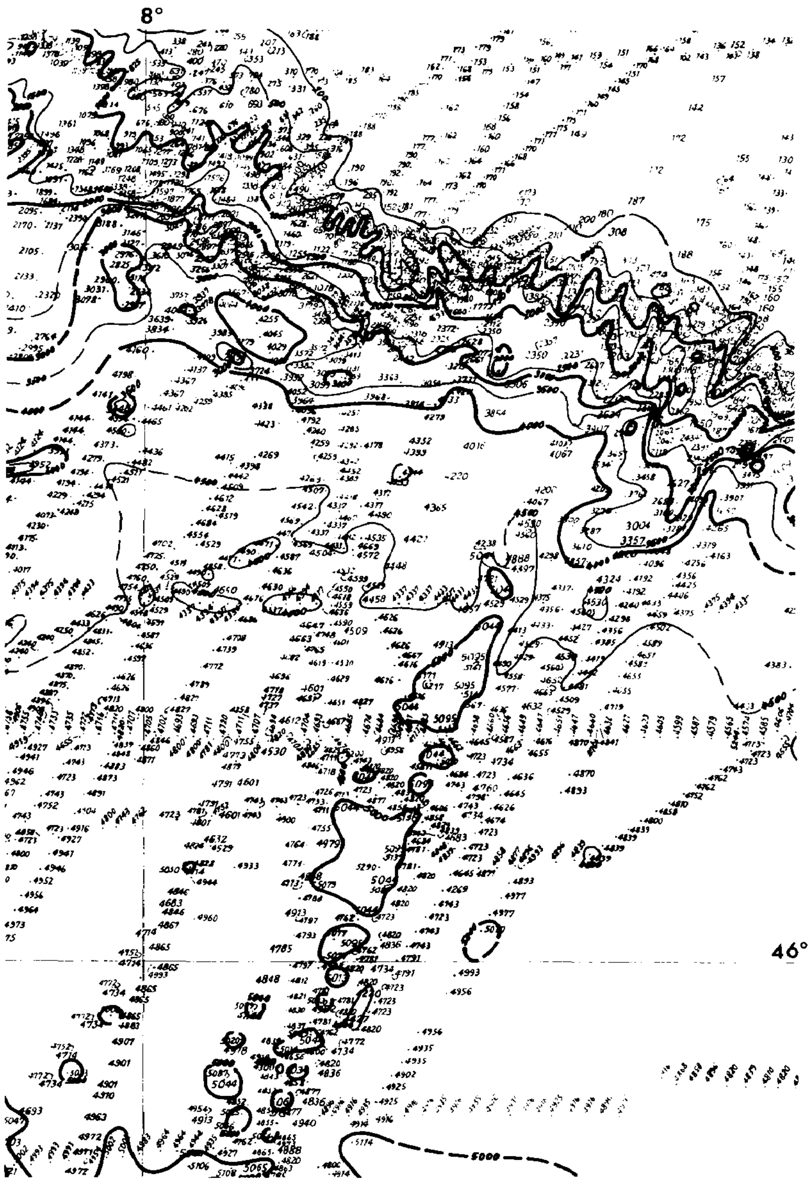

Fig. 3. — Part of GEBCO collected sounding sheet (43) for the Bay of Biscay published by the Deutsches Hydrographisches Institut, 1964. (Depths in corrected metres, contour interval 500 m.)

An understanding of the geological processes moulding the topography can assist in contouring. For instance, abyssal plains result from turbidity currents which are gravity controlled. A continuous gradient of flat sea bed seen either side of a seamount in a single profile indicates that the plain is continuous around the seamount, whereas lack of continuity probably indicates two isolated basins. Similarly deep sea channels are known to have a continuous downhill gradient, so that if two crossings of a channel can be recognized, they must be joined in such a way as to give

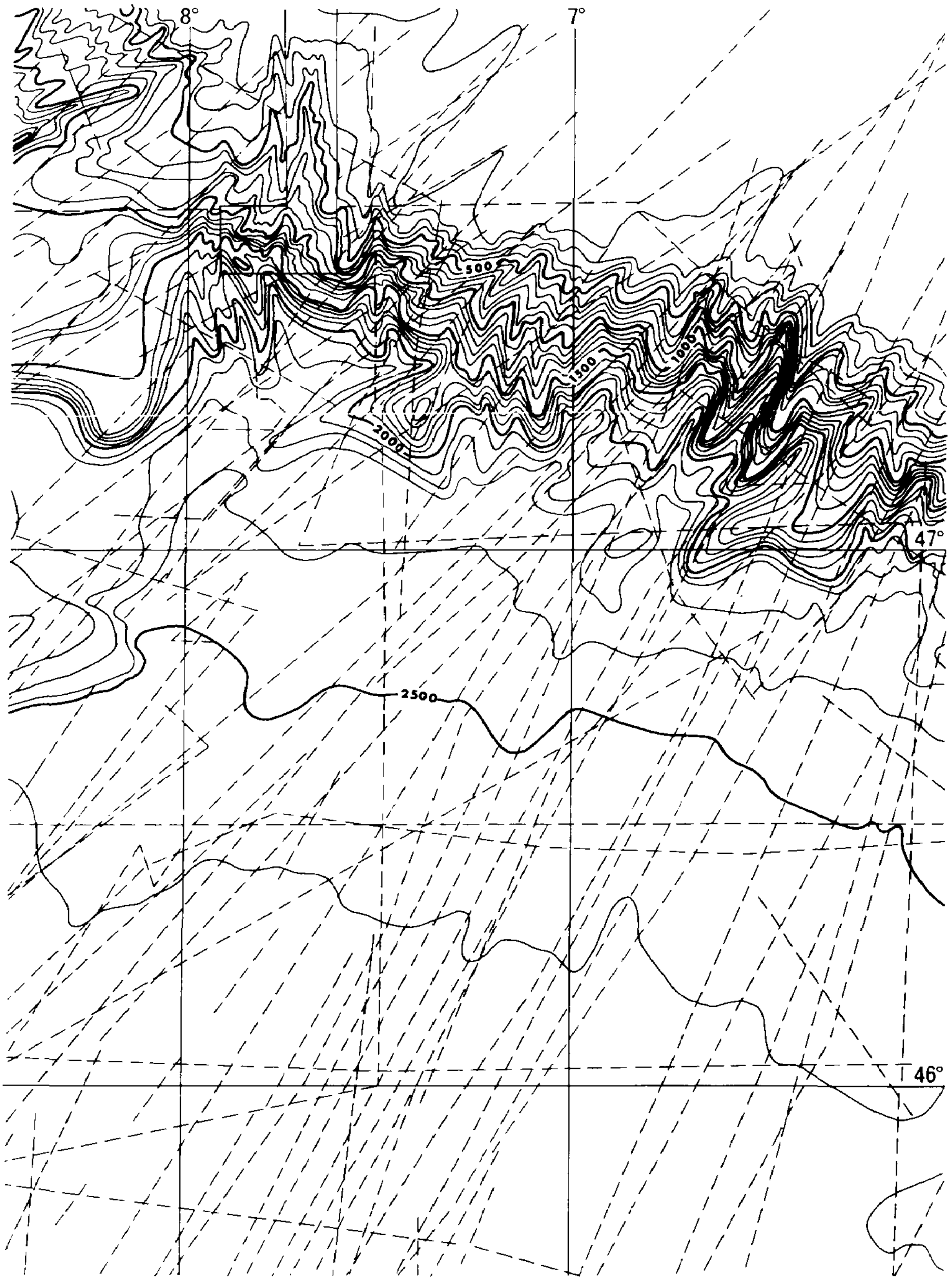

FIG. 4. — Part of N.I.O. contoured working sheet (43) in the Bay of Biscay covering same area as fig. 3. Erroneous data has been corrected or removed. Tracks are shown as dashed lines. (Depths in corrected fathoms, contour interval 100 fathoms.)

such a gradient. Again, the association of a linear valley with earthquake epicentres and parallel magnetic anomalies at a mid-ocean ridge axis, and the crossing trends of fracture zones, enables these linear features to be contoured realistically (fig. 2).

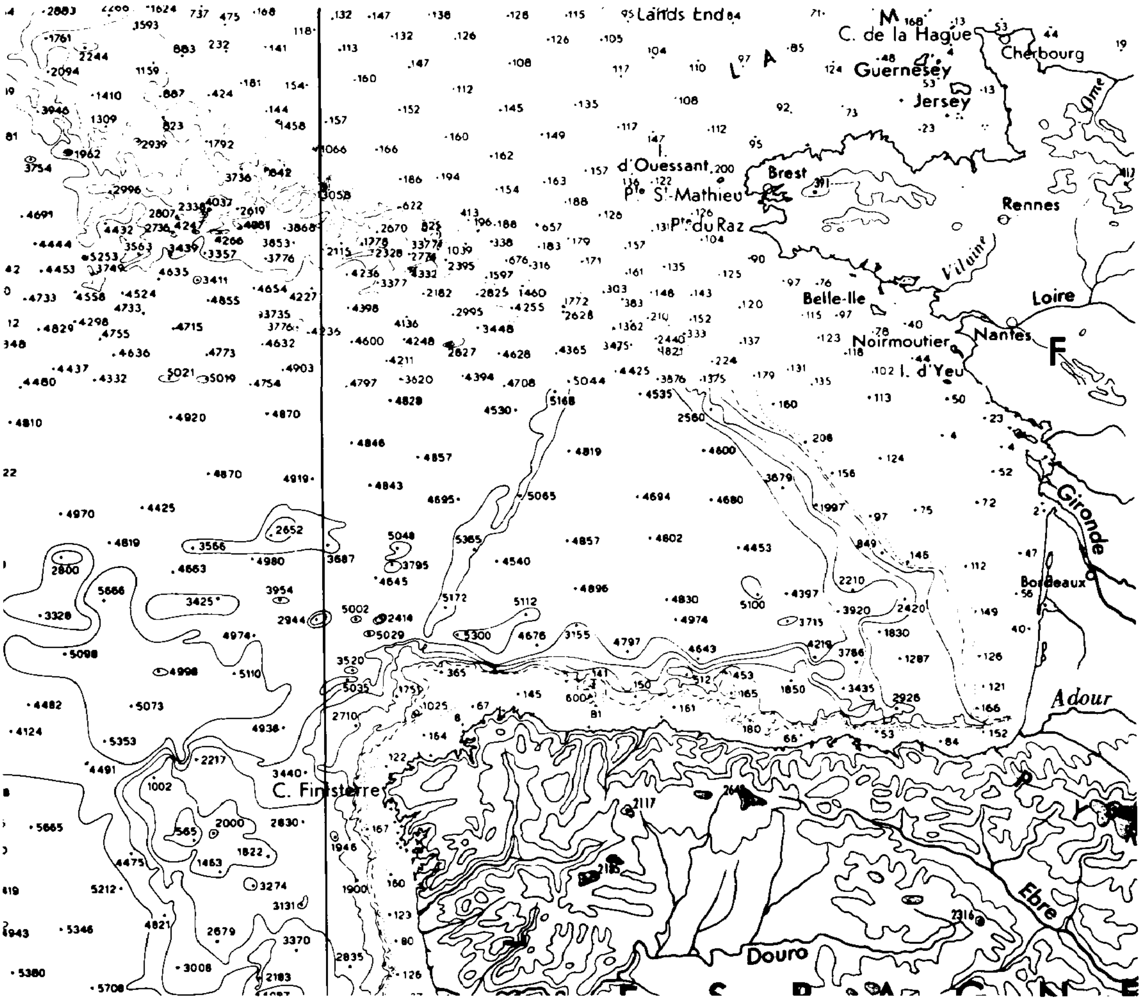

FIG. 5. — Parts of GEBCO sheets AI (4th edition, 1958) and BI (4th edition, 1966) showing spurious trench crossing the Bay of Biscay. (Depths in corrected metres, contour interval 500 metres.)

Frequently it is necessary to identify and reject, or mentally to correct, sounding lines that are in error in depth or position. Checks can be made at crossovers in smooth areas with soundings known to be more reliable or which are mutually consistent. If a line of soundings results in a series of kinks displacing each contour it crosses consistently in the same direction, then its position is probably wrong. Similarly kinks in features known to be usually linear arise from position errors. If all such erroneous soundings are rigorously contoured the resultant contour chart is very much more complex than the sea floor it is supposed to represent. For instance, the mechanism whereby abyssal plains were formed was well known in the 1950's and the Biscay abyssal plain was described in 1959 (HEEZEN, THARP and EWING, 1959). Erroneous soundings on the 1964 and earlier GEBCO compilation sheets for this area were contoured to give a spurious trench (compare figs. 3 and 4) which has persisted in GEBCO sheet AI 4th edition (fig. 5) and other world series.

It is impracticable, therefore, to be completely objective in contouring. In places where the sounding lines are close in relation to the size of the features being contoured, there is usually little difficulty in choosing how to relate highs and lows on adjacent lines. In a condition of saturation survey with no inaccurate data, this contouring could be done automatically by computer, or by an inexperienced cartographer. However this situation seldom arises in the deep ocean at present. In many areas, such as the N. Atlantic, parts of the N. Pacific, N.W. Indian Ocean, reasonable interpretations of the topography have been made by judicious interpolation and comparison with detailed surveys.

However, there are many areas where it is extraordinarily difficult to relate one profile to another because they are too far apart. Various conventions have been used on contour charts to indicate something of the roughness of the topography along a single profile while not relating it to another. Since there are statistically more isolated highs than lows in the ocean (the result of sedimentation filling the depressions), one convention is to draw closed circular contours around the peaks on the profile, resulting in strings of isolated contours. If the highs are believed to be ridges parallel, say, to a mid-ocean ridge, they may be drawn out into ellipses with the correct strike.

THE N.I.O. BATHYMETRIC CHART SERIES

These principles of contouring have been applied at the National Institute of Oceanography in studies of the deep ocean floor. For approximately fifteen years N.I.O. has maintained a set of bathymetric charts based on the 1/1 000 000 scale collected sounding sheets and contoured at that scale at 100 fathom intervals. These have been primarily for internal use but have been made available to other oceanographers in U.K. and abroad. The charts, which cover two areas of geological and geophysical interest to the Institute, the N.E. Atlantic and the N.W. Indian Ocean, are frequently revised according to areas of current activity and the availability of new data.

On these charts, the local reliability is indicated by incorporating as dashed lines all tracks used in the compilation (fig. 4). For the contribution of the bathymetry of the N.W. Indian Ocean to the IIOE Atlas of Geology and Geophysics of the Indian Ocean, currently being prepared in Moscow by UNESCO, a more precise sounding control system was used where every sounding is indicated by a single dot. In this way, scattered single soundings and the density of plotted soundings along a track can be shown. This system was successfully used (fig. 2) in published charts of the Gulf of Aden (LAUGHTON, *et al.*, 1970) and the Red Sea (LAUGHTON, 1970) and has been standard practice at the Scripps Institution of Oceanography (e.g. FISHER, ENGEL and HILDE, 1968).

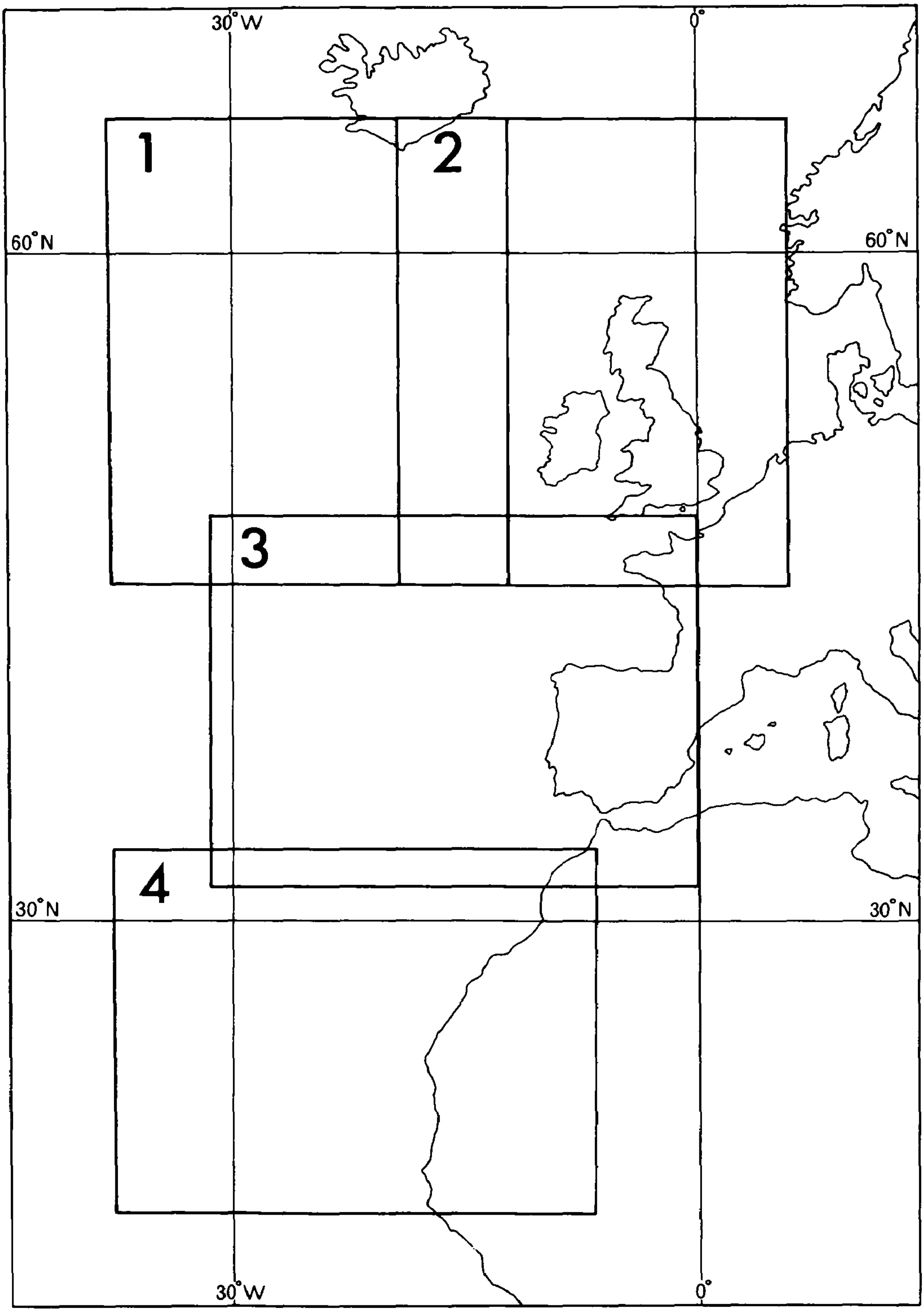

FIG. 6. — Limits of areas of contoured charts to be published by the National Institute of Oceanography, U.K., at a scale of 1/2 400 000 at 41° N.

The N.I.O. bathymetric charts of the N.E. Atlantic are now being prepared for publication using automatic cartography at a scale of 1/2 400 000 at 41° N in a series of 4 sheets from approximately 12°- 64° N, and 0°- 35° W (fig. 6). The contour interval will be 100 fathoms (corrected) and soundings will be shown by the dot method.

THE ROLE OF AUTOMATIC CARTOGRAPHY

N.I.O. has cooperated with the Experimental Cartography Unit of the Royal College of Art in the development of automatic methods for handling ocean contour charts (BICKMORE, 1968, 1969, ROBERTS and EVANS, 1969). The N.I.O. contribution to the IIOE Atlas of the Geology and Geophysics of the Indian Ocean, and later the bathymetric chart of the Gulf of Aden at 1/2 000 000 (fig. 2) were draughted under computer control. All contouring was done manually at 1/1 000 000 on the original worksheets; automatic contouring was not possible due to the low density and variable quality of the data. The contours were labelled and digitised at 1/1 000 000, and stored in data bank form in the computer. Linework was scribed and layer masks cut on a high precision flat bed plotter, using the stored data. At this time, all lettering and dot sounding control was prepared manually, although the system now allows this to be done automatically. This production of a conventional layer coloured chart took advantage of the fair drawing and scale changing capability of automatic cartography.

Alternative outputs are possible once the contour data is in digital form. An anaglyph chart of the Gulf of Aden was easily produced from the data bank (ADAMS, 1969, LAUGHTON, *et al.*, 1970), and experiments were made with projection changes, generalizations, oblique viewing and hill shading.

Although many advances in the programming and handling of such data have been made in the last few years, the initial digitisation procedure from work sheet copy has still to be done manually. Considerable time saving may be made by the use of "groovy" digitising where the work sheet lines are deep etched by a photo-mechanical process to form grooves which can be followed at greater speed.

PROBLEMS OF INCORPORATING NEW TYPES OF MORPHOLOGICAL DATA

The development of new instruments and techniques for studying sea floor morphology raises problems of how these data can be incorporated satisfactorily in bathymetric charts. The vast majority of soundings used to prepare charts have been obtained with relatively broad beam (± 15°)

echo-sounders, and the depth quoted is the minimum slant range within the beam angle, so that erroneous values of slope and shapes of targets are obtained (KRAUSE, 1962). Narrow beam echo-sounders are now occasionally used which give shapes more nearly correct (KRAUSE and KANAEV, 1970). For higher resolution of the topography, near bottom echo-sounders are necessary thus avoiding the long water path and consequent geometrical problems (SPIESS and MUDIE, 1970). Scanning narrow beam sounders operating in a near-vertical mode allow a contoured strip of ocean floor either side of the ship's track to be generated continuously (GLENN, 1970).

By contrast, side-scan sonars do not give quantitative depth data, but delineate the shapes of features in plan view as much as radar does. Long range side-scan sonar (RUSBY, 1970) can now operate in ocean depths giving sonograph strips 22 km wide, so that they can be built up into a mosaic. These can best be used in conjunction with bathymetric surveys to aid contouring.

IDEAS FOR FUTURE PROGRESS IN PREPARING BATHYMETRIC CHARTS FOR SCIENTIFIC PURPOSES

Many of the shortcomings and problems of the existing organisation for preparing charts of the deep ocean floor for scientific purposes have been discussed and examples cited of oceanographers' attempts to fill their needs. The work of the SCOR Working Party 41 will be to review how improvements might be made.

A proposal has been made (PASCOE, 1972) that the needs of oceanographers could be met by the publication of the bathymetric contours that have already been drawn from 1/1 000 000 collected sounding sheets during the course of preparation of the 1/3 500 000 International Series of Navigational Charts. We do not believe that the bathymetric charts proposed will meet the needs of oceanographers since they have not been shown to be based on the principles discussed in the previous sections, or to incorporate the best contour charts available. For instance, the illustration of an area at 43°N, 20°W, fails to take into account the work of those oceanographers most concerned with this particular area who had already published in 1969 (MATTHEWS *et al*, 1969) a much more detailed bathymetric chart based on considerably more data.

The quality of any chart ultimately depends on the quality and quantity of the input data. The rate of acquisition of new high quality data is higher now than ever before, and it is essential that all of this is used in any data compilation prior to contouring. The responsible national Hydrographic Departments must be active in seeking out new data acquired in their areas of responsibility and sufficient funds must be found to enable a continual updating of the collected sounding sheets and the progressive removal of older less reliable data. Too often the maintenance of the GEBCO sheets has had a low priority in relation to the other commitments. High quality surveys of ocean areas at present classified should be made available as soon as possible after the military requirements for classification have finished, or before this if possible in some acceptable edited form.

The preparation of contoured charts from sounding compilations should be made by experienced geomorphologists who have an understanding of the sea floor processes and who have studied detailed surveys. All local surveys which have been made in the area whether by surveyors or scientists should be incorporated into the final product even at the risk of producing an unevenness in style. For the scientist, accuracy is more important than elegance. Some progress is being made in this direction with GEBCO Sheet A IV presently being revised, which will include contours prepared for the IIOE Atlas of the Indian Ocean. The sounding control must be indicated, preferably on the chart itself in dot form. Insets showing density of coverage at a very much smaller scale do not allow the contour reliability to be assessed. We can see no advantage in a scattering of selected numerical soundings on a contour chart unless they indicate the maximum depths of basins or minimum depths of peaks (cf. fig. 5).

The physical processes of chart preparation and production introduce considerable delays in updating contour charts, and inhibit the frequent correction of areas where more recent surveys have added new data. The storage of contour data on printing plates or on the printed sheet could ultimately be superseded by storage in digital form in a data bank. Sounding positions can also be stored for subsequent dot output. Computers and automatic graphical methods are now sufficiently advanced to store all the information contained on a contoured bathymetric chart and to reproduce it on demand to cartographic standards in whatever way the user requires. With the data stored in this way, corrections can be introduced into the bank, replacing blocks of data with new data, and integrating them into the whole.

A data bank allows great flexibility of output. Different limits, scales and projections can be demanded, contours omitted or generalised for small scale charts, and conversions made between units. But beyond this, questions can be asked of the data bank itself. Hypsographic curves, volumes of water between different levels, sill depths to basins and many other parameters can be calculated from the stored data.

Much of the software and hardware has already been developed for this type of operation. To put it into effect would, however, require considerable capital expenditure (although small compared with the expeditionary funds now being spent) and the establishment of a team of computer-oriented specialists. But above all it would require the enthusiastic cooperation of oceanographers and surveyors throughout the world and their active participation in supplying the basic sounding data.

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