# GRAVITY AND MAGNETIC NATURAL RESOURCE MAPS (1972), OFFSHORE EASTERN CANADA

## PHILOSOPHY AND TECHNIQUE IN PREPARATION BY COMPUTER

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## ABSTRACT

The final product of a recent data processing contract issued by the Atlantic Geoscience Centre was a suite of 72 Natural Resource maps published by the Canadian Hydrographic Service representing the most comprehensive published collection of marine gravity and magnetic data on the eastern Canadian continental shelf. Because of the techniques employed, the charts have a style different from that employed on previous charts in the series. The method of preparation of the charts is described together with consideration of the basic limitations of a contour chart used as a source of data. Deficiencies in the data collection and processing and chart preparation techniques are discussed.

## INTRODUCTION

Since 1964, personnel at Bedford Institute of Oceanography have been collecting bathymetry, gravity and magnetic field data on routine, detailed surveys off the east coast of Canada. The first such survey was carried out in 1964 in the Bay of Fundy. This provided a highly detailed survey of a limited area. In 1965, ship breakdown prevented extension of that multi-disciplinary beginning but geophysical personnel were able to return to a cooperative venture with the Canadian Hydrographic Service in their 1966 survey of the Tail of the Bank (the south eastern extremity of the Grand Banks of Newfoundland). This cooperative relationship has continued and expanded each subsequent year and as a result there is extensive hydrographic-geophysical coverage of the southern portion of Atlantic Canada's continental shelf.

The Natural Resource map series published by the Canadian Hydrographic Service was initiated in 1969 as a means of presentation of the bathymetry, gravity and magnetic data at a scale of 1/250 000 so that it might be made available to all potential users. In its effort to maintain support for these multi-disciplinary survey operations as well as fulfilling other commitments, the geophysical personnel were able to check the data collected each year but rarely to compile or interpret it. As a result, by March 1971 the maps for only one 2° × 1° area had been published with the charts for four other areas at the colour proof stage. Gravity data collected in the Gulf of St. Lawrence during the surveys of 1968 and 1969 were compiled by hand in 1971 and published as Natural Resource maps in 1972. Despite the fact that data collection and reduction facilities had improved so that they needed less attention, more geophysical surveys were carried out and the backlog of data awaiting publication increased. Early in 1972 it was recognized that there was little chance of reducing the backlog while trying to compile and publish current surveys. As a result, the decision was made to invite proposals from industry for the production of draft Natural Resource maps from the unpublished data. A set of specifications were drawn up which covered the problems foreseen for contractors and these were subject to discussion at a bidders conference held at Bedford Institute of Oceanography in May 1972. To ensure that contractors were aware of the difficulties they might face in processing this data, and that the contractors could demonstrate their expertise in this field, they were asked to produce a set of trial maps based on data provided to each of them. As a result of these submissions, a contract was finally entered into with Computer Data Processors (C.D.P.) to produce the 72 draft Natural Resource maps within 120 days from 1 September 1972 with the author as the inspector on behalf of the Atlantic Geoscience Centre.

The distribution of data upon which the Natural Resource maps have been based is shown in figure 1. Along all the tracks shown, either bathymetric, gravity or magnetic data (or any combination) had been collected and were available in digital form at the Atlantic Geoscience Centre in January 1972. Track density was considered sufficient to allow for presentation of the geophysical measurements in the form of Natural Resource maps in the areas outlined. After editing, 166 537 magnetic field data points and 121 157 gravity field data points were used in preparation of the maps. This corresponds to an average track spacing of the less than 5 km over the area surveyed. An example of one of the draft maps produced by the contractor is shown at a reduced scale in figure 2. That map has been chosen to illustrate several of the points which are made in this paper. Since most of those remarks refer to the failings of the methods used, the example is of a lower standard than most. Bathymetric contours, landforms and the location of measurements are provided as a subdued background to the contours of geophysical data on the published maps. In their published form the maps are also provided with marginal notes which describe the data collection procedure and provide a statistical analysis of the data and its accuracy. As each of the Natural Resource maps becomes available through the Canadian Hydrographic Service, the

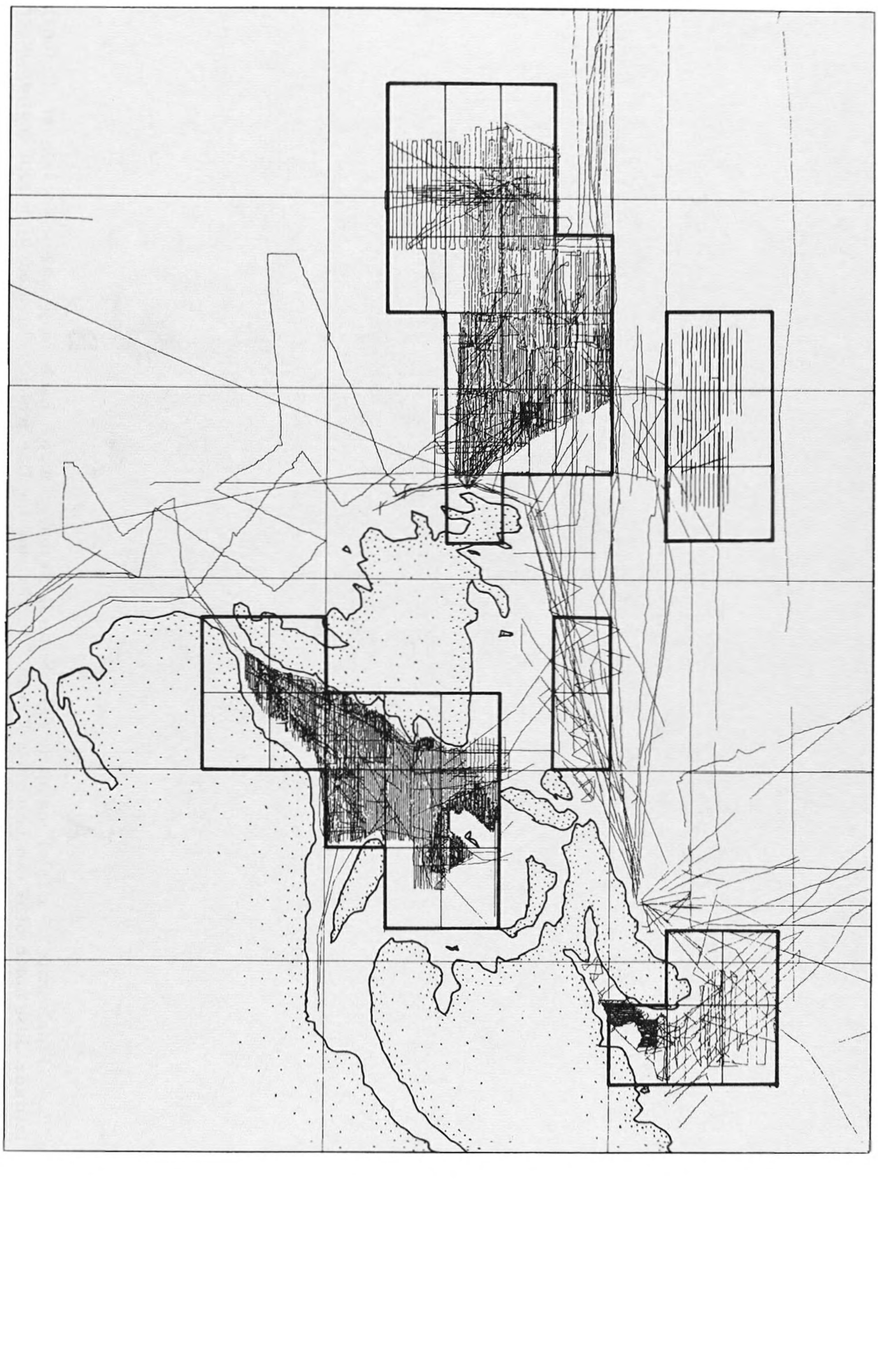


FIG. 1. — Tracks of cruises from Bedford Institute of Oceanography on which geophysical data have been collected.

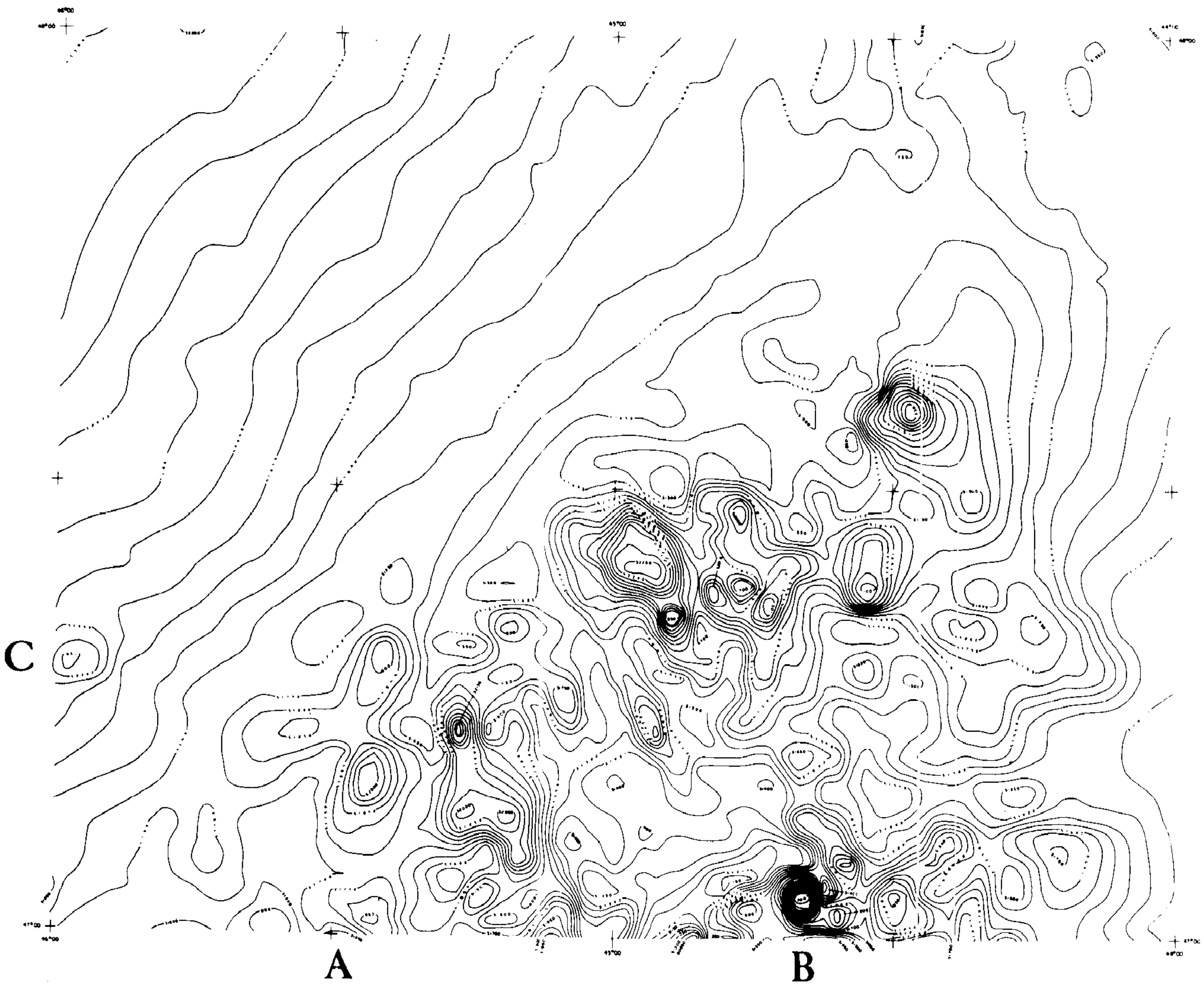



FIG. 2. — Final draft of a total magnetic field Natural Resource map. Each map covers an area of 2° longitude by 1° latitude. Just north of A can be seen a " cusp " in the contour line which is created by a combination of erroneous data and the method of contouring. The feature near B illustrates the effect of extremely close contouring. All contour lines have been retained. The feature at C shows that the contours are machine drawn in a smooth manner except at the point of closure

digital data upon which the map is based will be released by the Atlantic Geoscience Centre.

The experience gained by both the contractor and the inspector led to the establishment of a fixed procedure by which the final charts were produced. That procedure and the reasons for it are explained in this text so that users may fully appreciate the nature of the maps and the extent of their usefulness. Many of the comments, particularly with regard to the philosophy of preparation of contours maps, are personal ones and in no way does the content of the paper necessarily reflect the policy of the Canadian Hydrographic Service, the publication agency for the maps.

## RATIONALE

Examination of the trial maps submitted with tenders led to lengthy debate about the style of portrayal of features on the maps because of the variety of techniques used by the contractors and of the effects of this on contoured versions of the same data and the interpretations which could be placed upon them. The variety was in part due to the degree of noise associated with the data. Some contractors opted for a detailed examination of the error characteristics of the data followed by editing and precise contouring of the remaining data. Others applied a general edit scheme followed by a powerful filter so that only large amplitude or wavelength features of the data remained. In addition to a mathematically treated map, some contractors provided what was an aesthetic map which had been "interpreted" by geophysicists at some stage of production to determine what "erroneous" information could be deleted. One proposal suggested that considerable use would be made of published information to help decide the form of the contours. In view of the basic unreliability of much geophysical data and the speculative nature of the conclusions based upon them, this latter approach using previously published information might well perpetuate previous errors. These maps represent the most detailed published collection of gravity and magnetic field data in the areas mapped. In some cases they represent the most detailed published collection of any type of geophysical or geological data. The interpretation must therefore follow from the data, rather than the representation of the data shall follow from earlier interpretations.

Merit can be found in the contractor's modifying the final map in terms of an "interpretable" field. The latter has merit in that the contour map is based on a geophysical reality : a potential field which has a solution, that particular one decided upon by the contractor. However a user of the published map may have a considerable amount of supplementary information at his disposal and this user may not find the contractor's interpretational map acceptable. With a contour map of the original data and a statement of the error limits, that user might have no difficulty in accommodating his interpretation, whereas the difference between that interpretation and the contractor's interpretation might be beyond the error limits, thereby apparently invalidating the alternative view.

After considerable discussion within the Atlantic Geoscience Centre and in consultation with other interested parties within the Department of Energy, Mines and Resources, it was decided that the most objective approach was desirable. Webster's 3rd New World Dictionary defines *objective* as "dealing with outward things and not with thoughts or feelings, exhibiting actual facts uncoloured by exhibitor's feelings or opinions". Thus, objectivity necessitates starting from facts. The problem then becomes that of trying to decide which data are factual, and because of the errors encountered in the collection of marine potential field data, this problem can be immense.

The geophysical methods used at sea are direct descendants of those used on land and, so far as many interpreters are concerned, the errors are similarly related and of comparable magnitude. This is not so. The most obvious discrepancy is that between the magnitude of errors of gravity measurements at sea and on land. On land the elevation of the gravity station is a source of error. At sea the Eötvös correction (dependent upon the latitude, course and speed of the measuring vessel) is a source of error. However, their relative magnitude, demonstrated by the fact that the errors of marine gravity measurements are generally a factor of at least 10 and maybe 100 times greater than those on land, is not widely appreciated. That an error in east-west ship's speed of 0.2 knot creates an error in gravity measurements off the east coast of Canada of approximately 1 mgal is a basic fact of life and cannot be overcome. The accuracy of marine gravity measurements is therefore limited by the navigational accuracy.

For marine magnetic data the main problem, as on land, is that of the temporal variations of the magnetic field. On land the solution is to use two magnetometers proximate to each other, one stationary to monitor the diurnal variations while the other is used on measurement traverses, that data being corrected for the monitored temporal variations. At sea the same solution is attempted. However, until recently the technology was not available for mooring a monitor magnetometer in the survey area, and the practice was to use a nearby shore based magnetometer. Because of differences in the environment at the two magnetometers (one is completely surrounded by water, a conducting medium, and may well be making measurements over a different geological province from that at the monitor station) the diurnal variations differ in amplitude and phase (see figure 13). The amplitude of a short period magnetic disturbance in the marine survey area may be a factor of two or more greater than that on land, and that factor may, spatially, be quite variable. Correction for magnetic variations at sea is therefore considerably more of a problem than it is on land.

If it can be demonstrated that the data are subject to the errors just mentioned, the data will be corrected or deleted as described in a later section. However, where the presence of errors cannot be thus justified, the Scottish judicial verdict of "not proven" prevails, and the original measurements are retained. These then are the "factual" data which are to be presented in an objective manner.

Repeated observations at a single point of a time invariant parameter may be used to give the distribution in magnitude of the errors in those observations. In the hydrographic-geophysical surveys, multiple observations are not made except at points where the survey lines cross. Because of navigation errors, although the track chart indicates two times at which the vessel was supposed to occupy the same position, it is possible that at those two times the real positions of the vessel were different. Thus there will be a discrepancy between the readings at the supposed track intersection times which will be dependent upon the gradient of the potential field in the vicinity of that intersection. By analyzing the discrepancies in measurements at track intersections we therefore get an indication of the errors inherent in the data from their sources as a result of navigation errors or as observational errors. The distribution of discrepancies thus presented represents the degree of reliability of all the data within the survey area. A histogram of discrepancies tells the user that say 70 % of all magnetic field data are accurate to better than 30 $\gamma$ (fig. 15). The user then has to recognize that at any point in the representation of the survey data there is a 30 % probability that the data value he picks will be in error by 30 $\gamma$. This is true in whatever form the data are presented, although in this case the data were to be presented in the form of contour maps.

Two important consequences of using the contoured form are that the three dimensional aspects of the data are quantized, and that whatever the path of the contour between data lines, there is no definitive information along that path. Consider the change in the contoured parameter on one of the lines along which that parameter was continuously measured. The change in parameter may only be determined from one contour to another, and the profile may be defined by discrete samples along the line where the contour intersects it. Representation of the data in the form of contours has therefore reduced the definition (fidelity) of the data. The reliable *data* content of the contoured form is therefore the set of values at those locations where the contours intersect the data lines. This is why many geophysical companies reduce geophysical contour maps to digital data, by digitizing only those points. The contoured form is used to express the three dimensional aspects of the data. If only a two dimensional representation is required, the profile data with its high resolution is used. The shortest wavelength component which can be defined for the entire three dimensional surface which the contours hope to represent is one which has a half wavelength equal to the greatest distance between the points at which the contours intersect the data lines. Where samples are made of features with a wavelength less than twice the sampling interval, those samples may be interpreted as samples of a feature with a longer wavelength (fig. 3). This effect is referred to as "aliasing". So, to define a three dimensional surface accurately, the shortest wavelength component of that surface of interest must be determined and that surface must be sampled in three dimensions at an interval less than half that wavelength. Conversely where a surface has been sampled, only features which have a wavelength greater than twice the

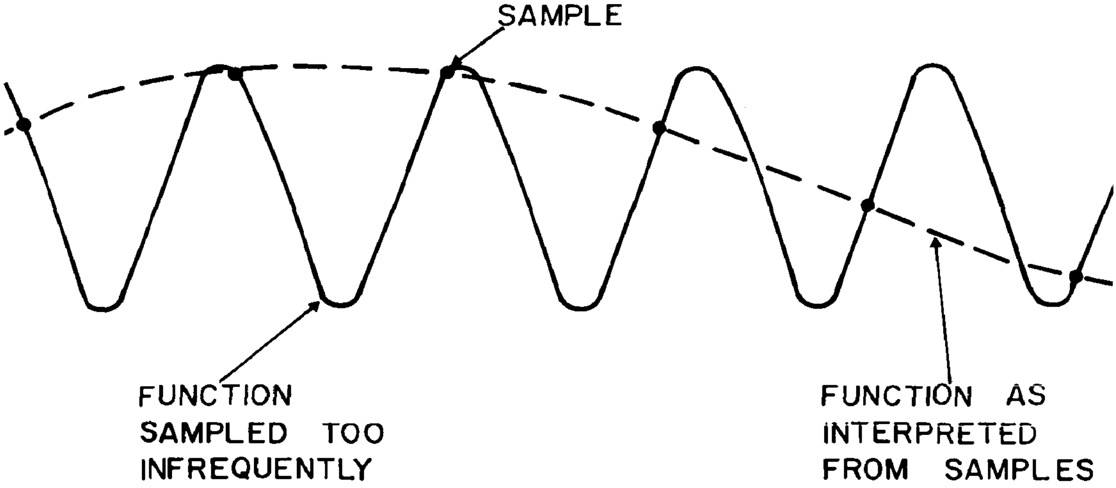
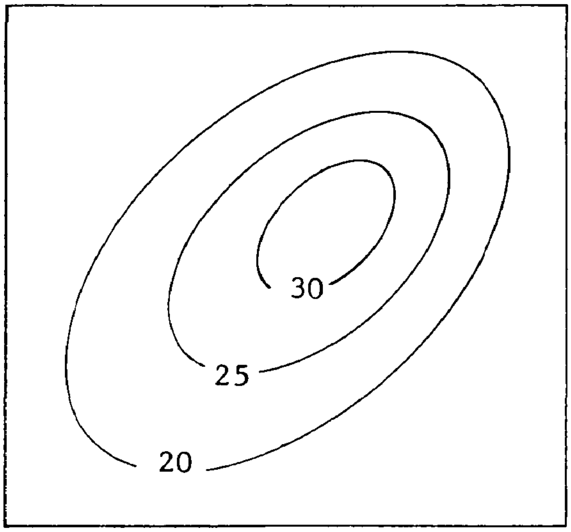



FIG. 3

maximum sampling interval (usually equivalent to twice the line spacing) can be defined.

Consider again the errors implicit in the contours and the data from which they were derived. The contours quantize the change in field which was measured. If a range of N contours of different values defines a feature, its maximum amplitude is $(N + 1)\beta$ and its minimum is $(N - 1)\beta$ where $\beta$ is the contour interval (fig. 4). If the uncertainty in range is defined as being $\frac{\text{Deviation from mean range}}{\text{Mean range}}$, the uncertainty becomes 1/N. If more definition of a feature is required, $\beta$ (the contour interval) should be reduced to increase N (the number of contours) and hence the certainty in the form of the field. However $\beta$ is limited by the accuracy of measurement. In the worst case, the amplitude of any anomaly depicted on a contour map is unknown by twice the contour interval. At the same time the amplitude is unknown by up to twice the maximum error at any observation point. No advantage is therefore gained in contouring at less than the probable error. Hence, users of contour maps must recognize that in three dimensions : 1) the amplitude of any anomaly cannot be defined to better than two contour intervals, 2) the amplitude of any anomaly cannot be defined to better than two probable errors, and 3) no anomaly having a wavelength of less than twice the line spacing can be defined. The use of contour maps as a source of data is therefore limited. Contour maps are quite adequate for interpretation of any three dimensional geophysical pattern with a wavelength greater than twice that of the line spacing. As the user examines progressively smaller features, the accuracy of their representation and interpretation diminishes. For features with an extent equivalent to the line spacing, the profile data is most useful. However, these small scale features can be interpreted only in the context of regional variations which the contour map most effectively shows.




| | | | | | |
|---|---|---|---|---|---|
| Highest | possible | value for | top | of anomaly | 35 |
| Lowest | " | " | " | " | 30 |
| Highest | " | " | bottom | " | 20 |
| Lowest | " | " | bottom | " | 15 |

| | |
|---|---|
| Greatest possible amplitude | 20 |
| Smallest possible amplitude | 10 |
| or amplitude | 15 ± 5 |
| Uncertainty in amplitude | 1/3 |
| or in general | 1/ Number of contours |

FIG. 4. — The uncertainty in amplitude of an anomaly displayed on a contour map is the reciprocal of the number of contour levels used to portray it.

With the general limitations of a contour map in mind some of the relative merits of human or computer contouring can be examined. A trivial observation is that whatever the computer can do, so can the human. The human programs it to perform a task according to a series of principles decided upon by the human. Any decision which the computer has to make is dealt with according to the possibilities and corresponding decisions given to it by the human. The distinction between the two is the speed and accuracy with which the computer can perform that task. Now a contour is "a line at all points of which a certain quantity, otherwise variable, has the same value " (Webster's 3rd New World Dictionary). As seen earlier, the value of a variable between sample points cannot be defined accurately. So as a first approximation points with the same value on adjacent profiles might be joined with a straight line. This is really what the human tends to do, followed by a scan of adjacent points and a mental weighting of those adjacent points to see where a higher order line might go to "best fit" those adjacent points. What shall constitute a "best fit" is something about which the human when contouring does not need to be specific. If he is not specific, he is not consistent.

Because of the quantity of new data being used and because of the speculative nature of previous interpretations of geological structures in the areas covered by the charts, consistency and greatest objectivity in dealing with the data were considered to be of utmost importance. It was therefore decided to use a computer contouring method for at least the initial presentation of the data. The examination of all tenders submitted using a variety of contouring methods suggested that basically there was little difference between the processes used by any of the contouring methods. The human interplay with those methods in terms of data editing and corrections was however quite variable and the tender submissions reflected the appreciation of the contractors for the data they were using and their treatment of it. C.D.P. used a computer package which produced a result acceptable in terms of the potential of contours maps, and had an appreciation for the data they were using.

The rationale outlined in this section has evolved during the author's monitoring of the contract. It has developed as a consequence of seeing how the field is presented in terms of contours after the data are collected, processed and related to other potential field data on adjacent lines and of trying to recognize what the consequences were of each step. Weaknesses can be recognized in the entire process from the contouring method right back to the initial collection of data, and a later section is devoted to outlining some of those problems. C.D.P. have, however, within the bounds of their basic technique been most cooperative in acceding to changing requirements and the fact that the contract has resulted in the production of detailed maps of the magnetic and gravity fields for approximately 50 000 sq km of the continental shelf of south eastern Canada attests to its success.

## CONTOURING SYSTEM USED IN CHART PRODUCTION

In order to appreciate fully the published maps and their content, the method of contouring must be understood. The computer contouring package used is that developed by C.D.P. and the following is a brief description of their proprietary system.

Assume that the data have already been edited where necessary to remove erroneous values. Details of the editing procedure will be outlined later since the implications are not clear until the contouring method has been described. The contours are drawn on the basis of a square grid of data points. Since the basic data are initially in the form of point values along profiles the irregularly spaced data have to be transformed into the regular grid. The grid spacing obviously has a bearing on the order of surface presented, and for all the maps a grid size of 2000 m by 2000 m was used, represented by 0.8 cm at the 1/250 000 map scale. This grid interval is just larger than the smallest regular line spacing and extends over approximately three data recordings (the data input were recorded at 2 min intervals of time at a ship's speed of up to 20 km/hr). This interval was selected after several contour maps were produced, and is a best compromise to ensure representation of the short wavelength (1 or 2 sample) anomalies as well as the long wavelength variations. Having established the grid, where a grid box is occupied by more than one observation the data are averaged both in amplitude and X, Y coordinates. This provides a single value in each grid box in which data had been collected (fig. 5(a)).

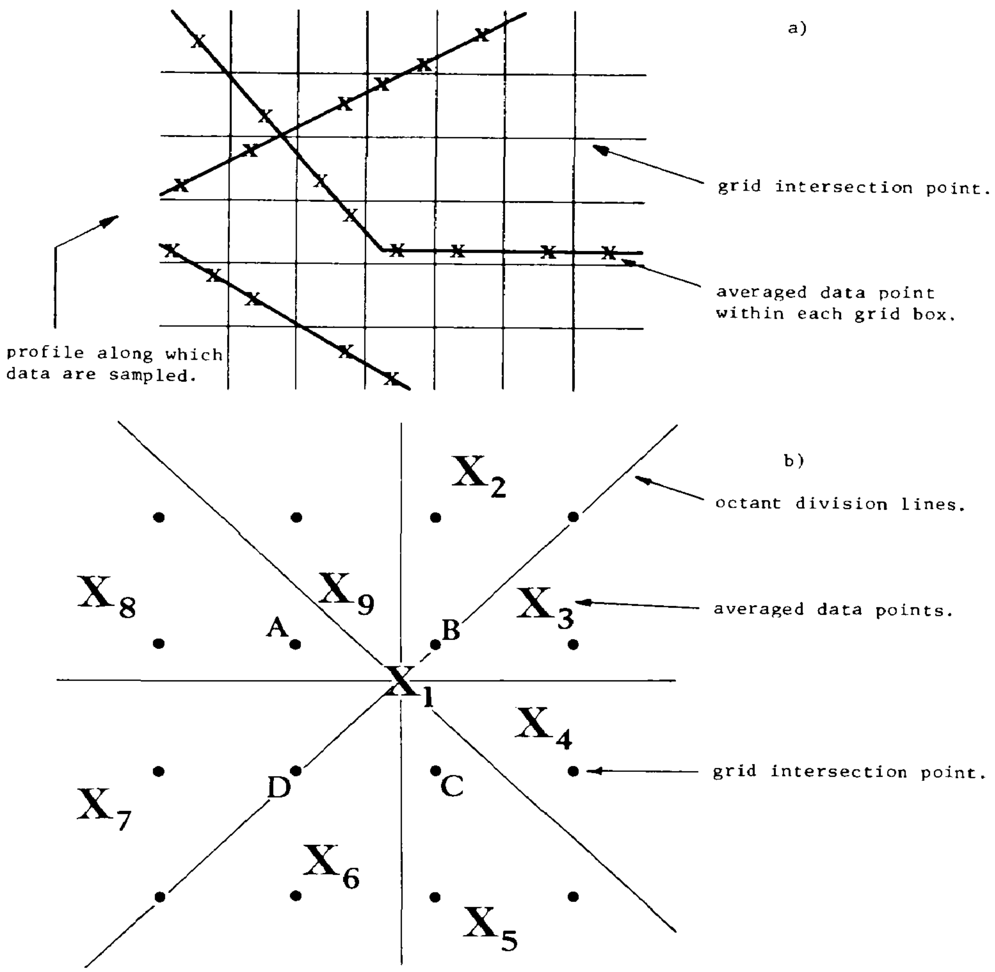
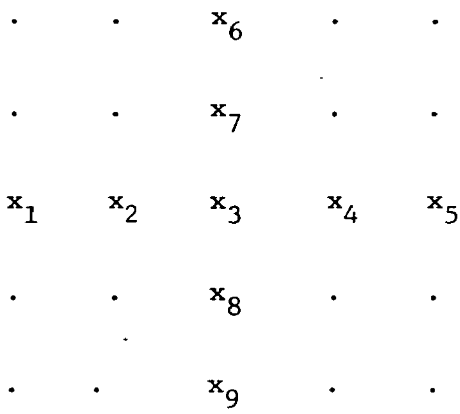



FIG. 5. — Illustration of the gridding technique employed in the contouring package.

The points marked with X indicate the average position of the points falling within the grid box. These single values then have to be transformed to values at the grid intersection points. In the single grid box ABCD of figure 5(b)), grid values are to be established at the four corners A, B, C and D. An octant pattern is established passing through the averaged data point $X_1$ within the grid box. Each of the octants surrounding $X_1$ is searched for the nearest point to $X_1$ within that octant. For the procedure to continue, at least six data points must be found, each point in a separate octant within a radius of 20 grid units but in general all 8 octants yield a value. These are labelled $X_2$ through $X_9$. A plane surface is then fitted through $X_1$ which is the least squares fit to the points $X_2$ through $X_9$, these points being weighted as a function of the inverse distance squared. At points A, B, C and D the values $X_{A1}$, $X_{B1}$, $X_{C1}$ and $X_{D1}$ are determined as points on this best fitting plane. Where the data are sufficiently dense that all 8 grid boxes surrounding grid ABCD have data within them, it can be seen that there will be, for example, four calculations of the value of the parameter at A : the value $X_{A1}$ determined above and three others from the other grid boxes of which A is a corner. The four values of the parameter at A are then averaged to provide a single value, $X_A$. If the data are less dense there may be 1, 2 or 3 determinations of $X_A$, $X_B$, $X_C$ and $X_D$, e.g. $X_D$ has only two estimations in this example. In all these cases, an average value is established at the grid intersection point. Having carried out this procedure for each of the grid boxes within which there are data, there will still be some undetermined grid values. These are calculated as part of a secondary routine. At this stage the original averaged data points $X_{1\ldots N}$ are not considered, and only the previously established grid values $X_{A,B\ldots}$ are used. The secondary routine works in just the same way as the primary routine by taking the grid values surrounding a vacancy, fitting a surface to those grid values and determining the value at the vacant location. This routine is repeated until the grid box is complete. Where the edge of the data is reached, the 6 octant occupancy requirement will not be fulfilled and no interpolation will be carried out. The limit of the grid pattern thus filled is the limit of the contouring.




Filter with weights 0.05, 0.1, 1.0, 0.1, 0.05 is applied along both axes

$$X_3 = \frac{X_3 + 0.1\,(X_2 + X_4) + 0.05\,(X_1 + X_5)}{1.3} \quad \text{on horizontal axis}$$

$$X_3 = \frac{X_3 + 0.1\,(X_7 + X_8) + 0.05\,(X_6 + X_9)}{1.3} \quad \text{on vertical axis}$$

In conjunction

$$X_3 = \frac{X_3 + 0.05\,(X_2 + X_4 + X_7 + X_8) + 0.025\,(X_1 + X_5 + X_6 + X_9)}{1.3}$$

FIG. 6. — Weighting function applied to the gridded data prior to contouring.

Before contouring, a light filter is applied to the gridded values to reduce noise introduced during the grid interpolation process. A 5-weight function is applied along each axis of the grid to give a smoothed value at each grid point. The weighting function and its application to the grid lattice is shown in figure 6.

The contouring of the grid is carried out using a hyperbolic asymptote contouring routine proprietary to C.D.P. In each grid box the entry and exit points of each contour are established and a portion of a rectangular hyperbola is drawn between them to conform to the grid values. Each contour is traced through its entire length at one pass to conserve plotting machine time, and as each grid box is passed through, a flag is set to note whether all entry and exit points have been satisfied.

One situation leads to an " unnatural " representation of the potential field data on the charts. The potential field of which the data are samples must be a continuous surface, and hence contours of it must also be continuous. Since the data has errors within it, and because the contour package only fits part of a rectangular hyperbola to the data at the boundaries of each grid box, C.D.P.'s contour package may create a contour like that portrayed in figure 7 (or above the letter A in figure 2). It should be remembered that the data errors which are responsible for such cusps are present throughout the data, even where the contours produced are more aesthetic. To delete the features would have meant either manual " correction " (which would have destroyed the consistency of the production method) or would have necessitated one of several modifications to the contour package. Since the cusps do not introduce further limitations on the use of the maps than were expressed in the previous section, they have not been deleted. In some ways the cusps are beneficial in that they serve as a warning to the user of the underlying limitations of the product they are using !

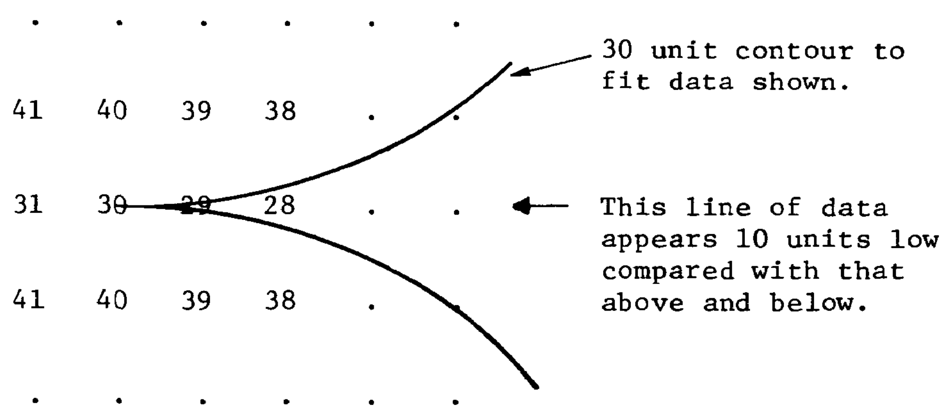



FIG. 7. — Cusp-shaped contour produced as a result of errors in data and the hyperbolic asymptote technique used in contouring package.

For any grid box, the hyperbolic contour is drawn as a series of straight line segments. The scheme followed ensures that these segments

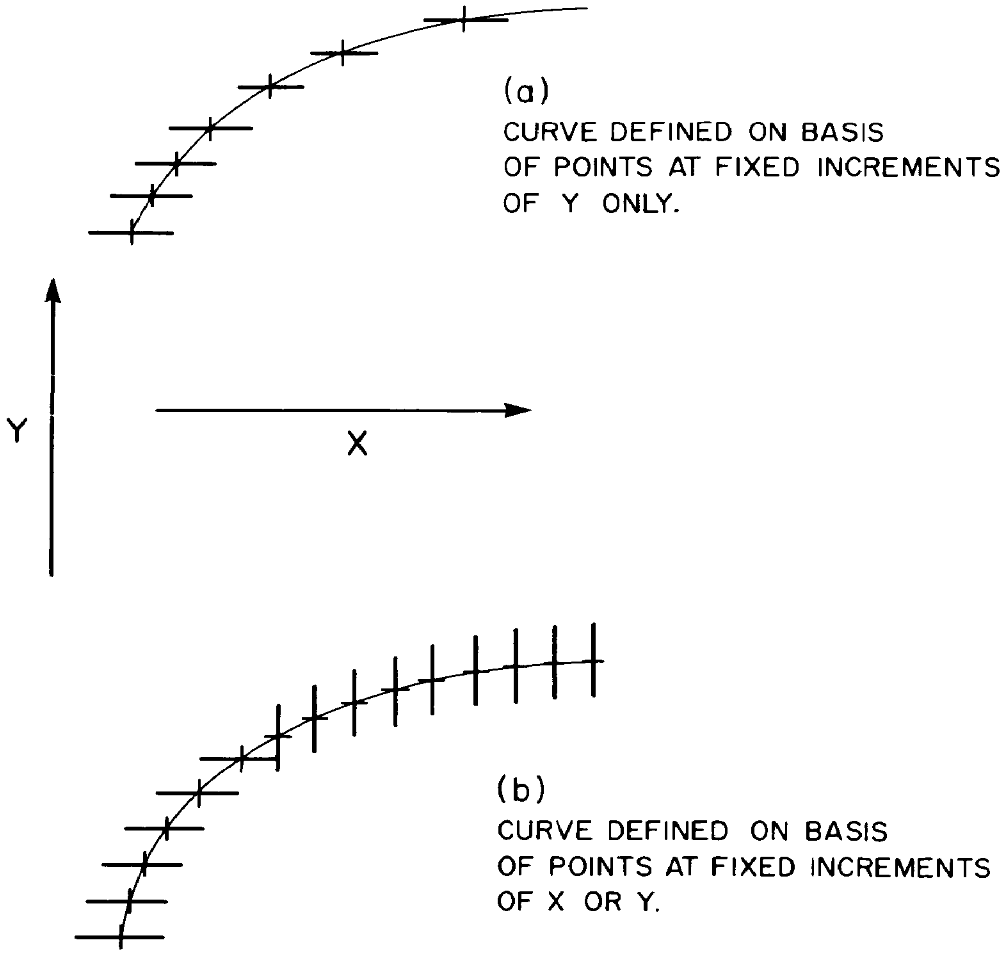



FIG. 8. — Definition of curve by means of a series of straight line segments according to two methods. Method (b) was used by C.D.P.

are as short as possible. If a new X coordinate is calculated for fixed increments of Y within the grid box, a curve might be defined as shown in figure 8 (a), where the X increment becomes far greater than the Y increment. In the C.D.P. scheme, when the X increment becomes greater than the Y increment, new Y coordinates are calculated for fixed increments of X (fig. 8 (b)) to minimize the length of the straight line segments. The fixed increment used is 0.3 cm. that of the longest line segment is of the order of 0.4 cm. In this way the contours are drawn in a remarkably smooth manner while reducing the machine time from that required to follow the curve faithfully at smaller increments. The success of this method may be judged from the machine drawn contours on the final charts such as that reproduced as figure 2. Note that because of its analog driven motion, the scribing pen tends to reduce any angularities in the lines drawn except at the point of closure of a contour (e.g. feature C in figure 2).

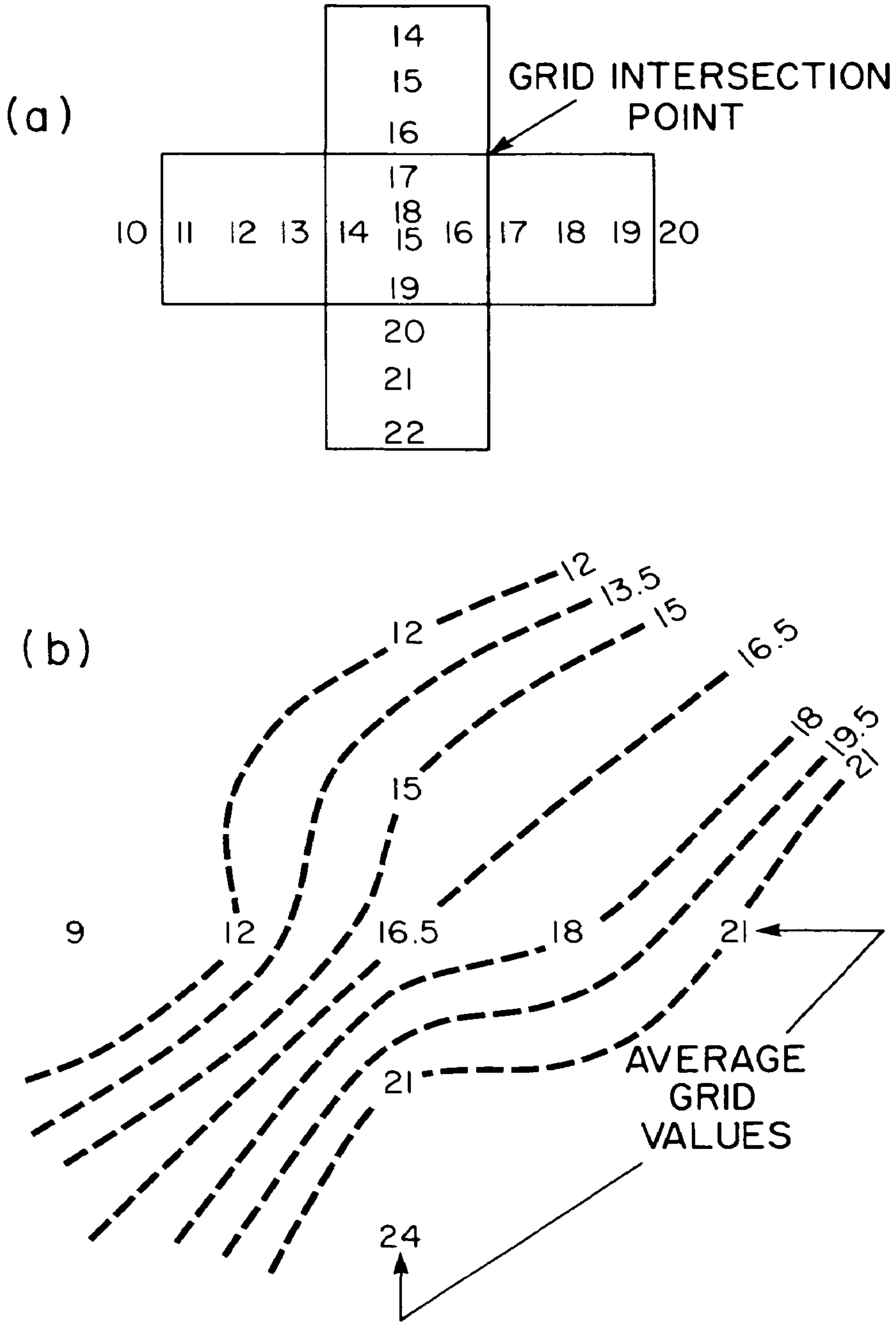



FIG. 9. — Where data conflict at line intersections, the gridding process averages out the discrepancy at the intersection, and the contours distend and contract to accommodate the conflict.

## CONSEQUENCES OF APPLYING CONTOURING SYSTEM TO RAW GEOPHYSICAL DATA

When data disagree at intersecting lines, there is considerable disruption to the contours. The simple fact that two lines do not agree, or that two different values fall at the same point does not halt the

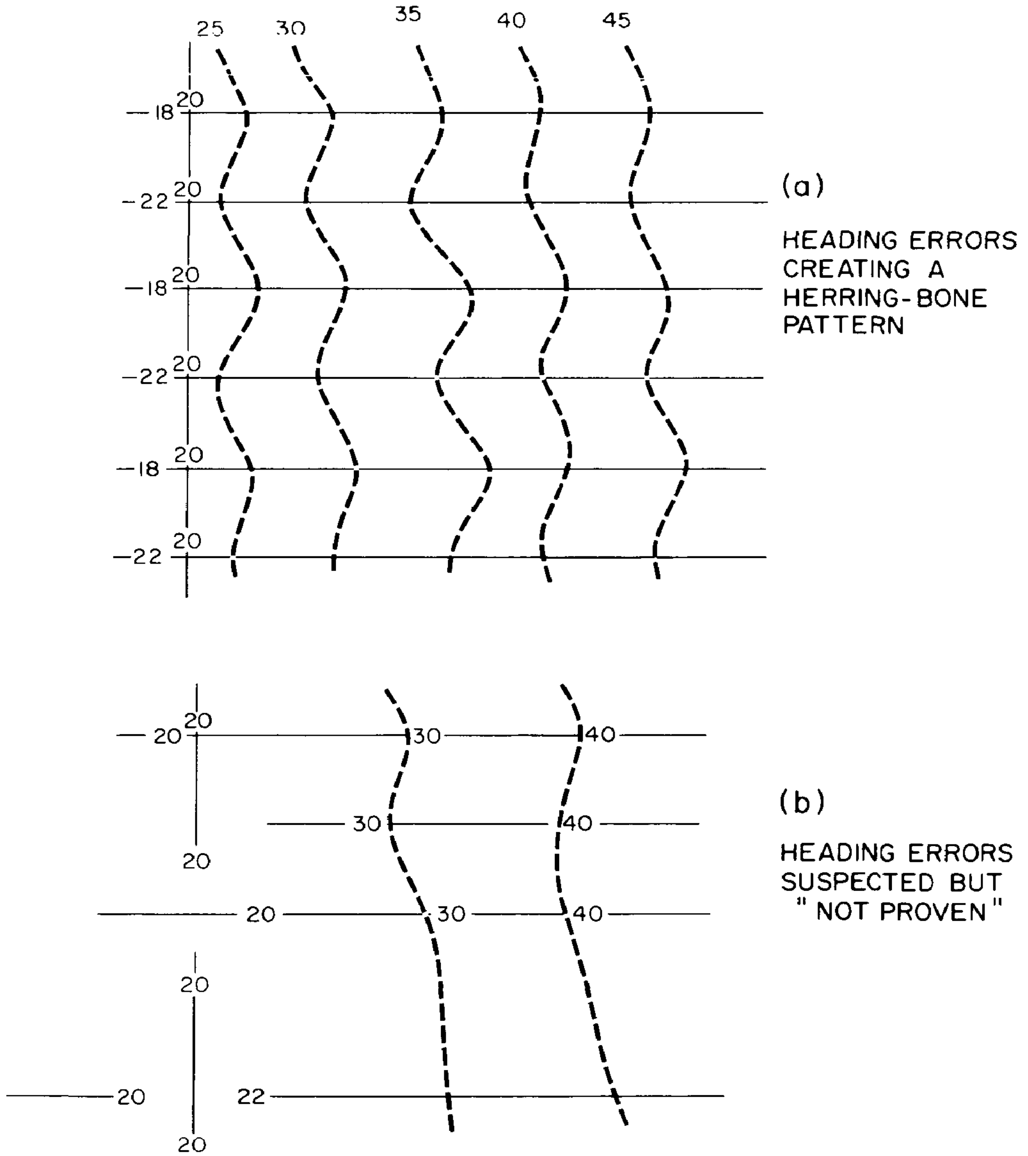



FIG. 10. — Discrepancies at track intersection points substantiate the presence of heading errors in case (a), where such substantiation is not present in case (b).

program because the gridding routine averages out those inconsistencies first (fig. 9). However, the averaging only affects the intersection itself and away from it the contours have to distend and contract to accommodate the inconsistent data. What was indicated as a steady gradient on both lines in figure 9 (a) is not portrayed as such by the contours of figure 9 (b). It is therefore necessary to attempt to remove such inconsistencies or to reduce them to a negligible level.

A well known feature in marine geophysical mapping is the herringbone pattern. This is due to a cyclic variation in errors of measurement (heading correction in magnetics, cross-coupling errors in gravity, etc.). In some cases, such as depicted in figure 10 (a) the presence of these errors can easily be seen. Each line is crossed by a single cross line and the resulting intersection discrepancies are cyclic. Each of the lines can be referenced to the intersection line, the measurement errors may be estimated and corrected, and the herringbone pattern is removed. However in many cases, such as in figure 10 (b), there are lines which exhibit this pattern where there is no justification for an adjustment according to the tie line. In such cases, no correction has been made (" case not proven "). There are many areas in the Grand Banks survey area where this situation prevails.

A generally useful feature of the gridding routine which can prove troublesome with poor data is its extrapolation of data to predict field variations between lines. If two data lines are close together, but exhibit a different data level, a steep gradient exists between them. This gradient is projected from the lines and may result in the creation of fictitious anomalies adjacent to the data lines or in anomalies with erroneous gradients or amplitudes (fig. 11). If the lines are so close together that both lines occupy the same row of grid boxes, the gridding routine averages the data and the extrapolation problem is removed, but the problem of error in datum still remains. Because there are situations in which the extrapolation shown in figure 11 can be real, validity of the data must be ensured. This is done by examining cross lines to establish

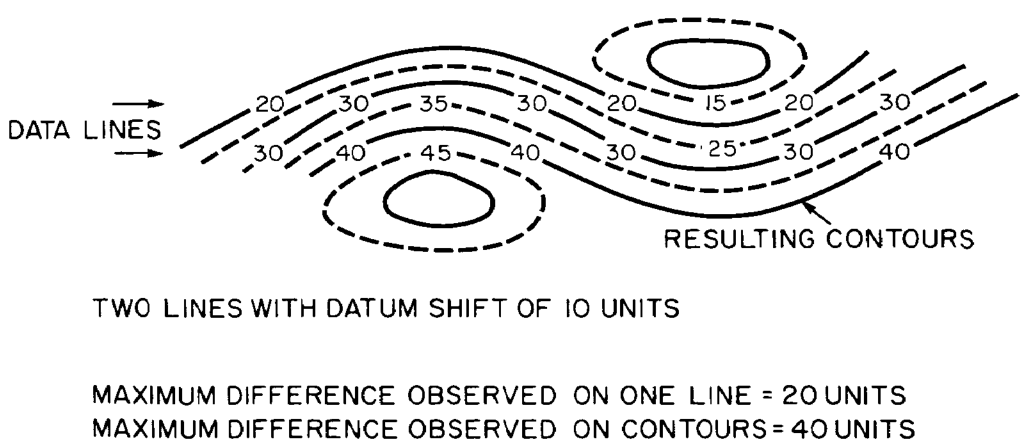



Fig. 11. — Gradients between lines are projected beyond the lines. If measurement errors introduce a datum shift between adjacent lines, erroneous gradients and amplitudes are introduced.

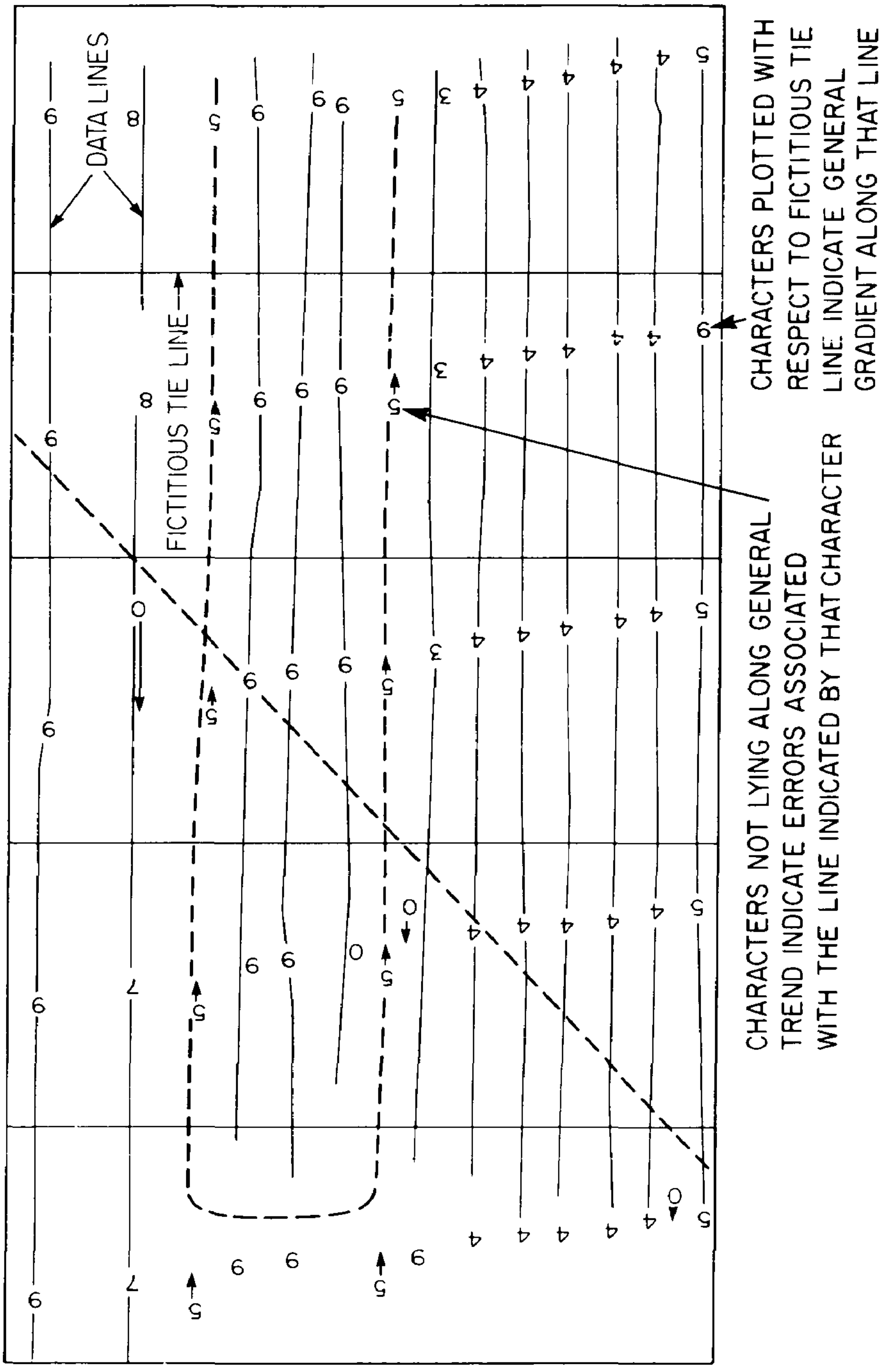



FIG. 12. — Fictitious tie lines may be used to isolate erroneous data lines.

the gradient between the two adjacent lines and to determine which line is more consistent with the cross lines. Another check on difference in datum is provided if those two lines eventually converge. Having established the true (or more consistent) datum, corrections are applied to the incorrect data prior to final contouring.

Although the configuration of contours tends to indicate where the errors exist, the magnitude of the errors is more difficult to ascertain. Profiles created transverse to the lines along which data are collected can be extremely useful, especially in areas where the general gradients are small. In figure 12 the data lines are crossing a field which increases gently from bottom to top. The character of the field is examined by a series of profiles created at fixed intervals across the survey area along what have been called fictitious tie lines. Where a fictitious tie line intersects with a data line, the value of the variable as measured on the data line is plotted to scale as the distance of a single character from the fictitious tie line. The character chosen is a digit indicating the line for which the data value is plotted. The characters plotted in figure 12 generally lie along a straight line indicating the regional trend of the field measured. However, there is a consistent departure from that trend by the characters 5 and 0, and the extent of that departure is indicated at each point by an arrow. The lengths of the arrows then indicate the extent to which the dashed lines are in error. As the complexity of the field increases so does the limit to which one can reduce the errors, because a general trend cannot be established. At this stage there is no other possibility than to examine the line intersections individually to assess the errors.

## CORRECTING OBSERVED DATA

Establishing the presence of errors is far easier than justifying their correction. For the magnetic data, temporal variations are effectively the only source of error other than the effect of navigation errors in their presentation. The phase and amplitude of the applicable corrections relative to the monitored corrections is not a simple function of the location of the point of measurement with respect to the location of the monitor station. Where $\alpha$ (the amplitude factor) varies much from unity and $\Phi$ (the phase) is appreciable, direct application of the monitored correction cannot adequately compensate for the temporal variations. As a first step, however, the monitored corrections are applied directly. Where $\alpha$ is less than unity, some restoration towards the original measurements is then necessary. Figure 13 shows the case where $\alpha$ is greater than unity. In either case, the additional correction necessary can be approximated to a ramp function. Where there are large discrepancies between measurements of the magnetic field, appreciable diurnal or magnetization variations have usually been monitored. Where it can reliably be established that this is the situation, an additional ramp correction has been applied. A demonstration of the effectiveness of this

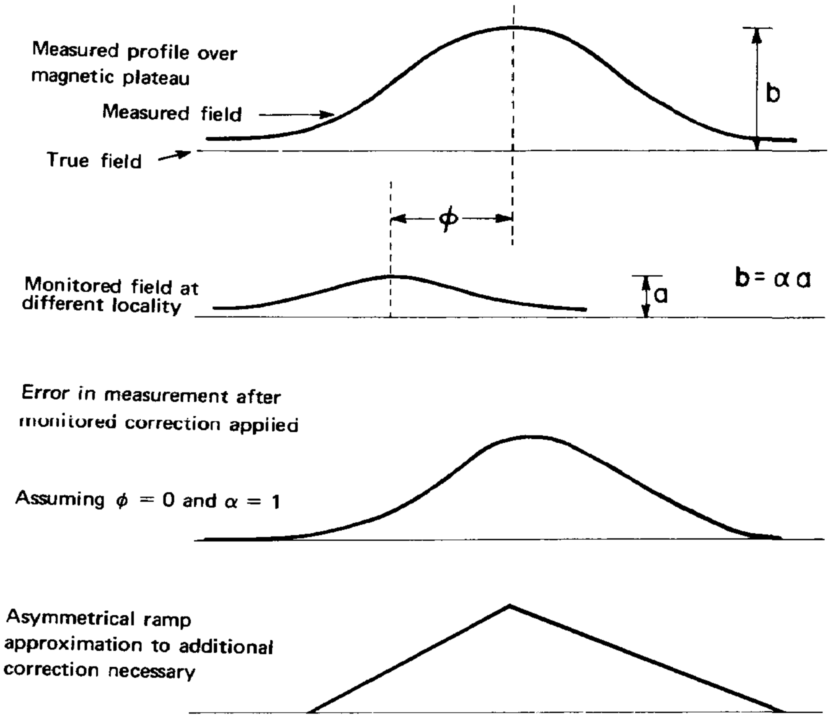


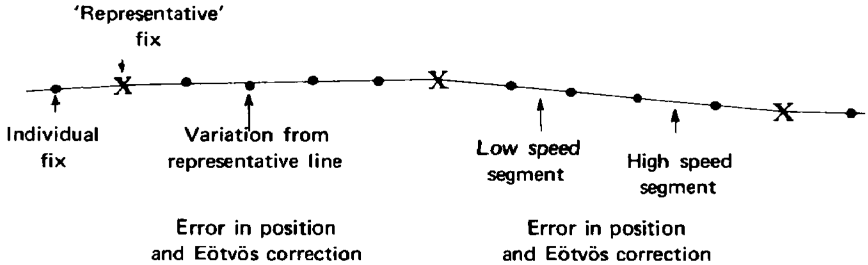

FIG. 13. — $\alpha$ is the amplitude factor and $\Phi$ the phase between monitored magnetic field diurnal variations and those experienced on survey. If the monitored variations are applied assuming $\Phi = 0$ and $\alpha = 1$, an additional correction in the form of an asymmetrical ramp is necessary to correct the survey data.

approach was given when C.D.P. once suggested a ramp correction where no digital diurnal corrections were available to them. A check of the analog monitor records proved that a magnetic storm had been in progress and that the phase of C.D.P.'s suggested ramp agreed well with the monitored correction. Where no monitor records are available however no " correction " is applied, because the field variations may well be real (" case not proven ").

One difficulty has been created with this presentation of magnetic total field data by trying to ensure that adjacent surveys within each of the five general areas covered (fig. 1) have continuity of contours. Since the surveys have been carried out over a number of years the secular variation of the magnetic field creates a problem. However, since the secular variation predicted by the International Geomagnetic Reference Field (IGRF) in the map areas varies only from $-4\gamma$ on Georges Bank to $+25\gamma$ in the Strait of Belle Isle, the error introduced by this approach is relatively small. Even with these naturally favourable conditions we have tried to reduce the errors further by effectively reducing the total field data to the year of the most recent or most complete survey within the area. Such corrections are generally small and constant over extended periods of time.

Corrections to the gravity measurements are generally justified on the basis of drift in the gravimeter, or as a result of navigation (both position errors and Eötvös corrections). During the surveys, connections with land gravity bases were accomplished, on average, every three weeks. These base connections determine the drift of the instrument from mechanical and electrical sources. The values of drift are given on each of the maps. It has been assumed that this drift is distributed linearly throughout the previous phase of the survey and a correction has been applied accordingly. Drift of the instrument in the laboratory seems different from that exhibited under dynamic conditions at sea and the linear approximation may well be in error. This presents the possibility of long period variations in the gravity measurements causing discrepancies at track intersections. It is dangerous to use this explanation as a justification for the errors found since there is little to base it on, but occasionally discrepancies have necessitated bulk corrections, and it is assumed that this is the reason.

More often the discrepancies are attributable to errors in the Eötvös correction applied. Although on the hydrographic-geophysical surveys a fix is generally obtained every few minutes, this navigation data has not been used in its entirety during reduction of the geophysical data. The practice has been to break the continuous track into variable length,




Speed, Course and Eötvös between representative fixes

| Time | Lat. | Long. | Speed knots | Course | Eötvös Correction |
|---|---|---|---|---|---|
| 2030 | 43 44.9 | −63 32.4 | 10.8 | 184.1 | −3.7 |
| 2200 | 43 28.8 | −63 34.0 | | | |

Speed, Course and Eötvös between individual fixes bounded by representative fixes

| Time | Lat. | Long. | Speed knots | Course | Eötvös Correction |
|---|---|---|---|---|---|
| 2105 | 43 38.7 | −63 33.0 | 10.7 | 184.2 | −3.8 |
| 2110 | 43 37.8 | −63 33.1 | | | |
| 2110 | 43 37.8 | −63 33.1 | 10.9 | 183.2 | −2.8 |
| 2115 | 43 36.9 | −63 33.1 | | | |
| 2115 | 43 36.9 | −63 33.1 | 11.1 | 185.4 | −5.2 |
| 2120 | 43 36.0 | −63 33.2 | | | |
| 2120 | 43 36.0 | −63 33.2 | 10.6 | 184.7 | −4.3 |
| 2125 | 43 35.1 | −63 33.3 | | | |
| 2125 | 43 35.1 | −63 33.3 | 10.7 | 184.2 | −3.8 |
| 2130 | 43 34.2 | −63 33.4 | | | |

FIG. 14. — Constant course and speed are assumed between the representative fixes used in data reduction and this leads to errors in both position and Eötvös correction. The gravity data are subject to errors of one or two mgal even where the representative fixes are carefully chosen.

straight line segments between " representative fixes " along the track (fig. 14). Positions are interpolated between these fixes assuming a constant course and speed, i.e. constant Eötvös correction. The representative fixes are checked for changes in the course, speed and Eötvös correction between successive line segments to ensure that any changes adequately represent real manœuvres of the ship. As indicated in figure 14 this approach leads to instantaneous jumps in the Eötvös correction between line segments, errors in position of the data, and probably most important, to short term Eötvös errors along the line segments. Work in progress on this topic indicates that errors of a few milligals are possible.

On one cruise, *Hudson* 17-014 in the Gulf of Maine, an additional fault severely limits the usefulness of the gravity data. A compensation mass within the gravimeter apparently became dislodged. Each time it moved the output of the gravimeter exhibited a sudden change or tare. These tares have been partially traced by examination of the analog records as well as by examination of the discrepancies between data at track intersections throughout the cruise. Where the tares are of limited duration or low amplitude they cannot be isolated or removed. This results in increased errors and the consequent peculiarities in contouring wherever these gravity data have been used.

One final source of errors in the gravity data is cross coupling. These errors are generally small but occasionally, in high sea states, reach 5 to 10 mgal on the Institute's vessels. Since corrections are not presently available for these errors, the data subject to them have been deleted. Their presence is generally noted by a high variance within the data. A short period component of cross-coupling errors produces this, and a test of variance within the data will disclose the erroneous data.

These then are the general reasons for errors within the data, and justification within the bounds of them has been necessary for the data to be corrected or deleted. The remaining data were those which were considered " factual " for contouring by the computer. That is not to say that the contour maps accurately represent real variations in the field. Unrecognized or unverified errors in the data limit this accuracy and the probable error has been used in determining what the contour interval should be. Each of the published Natural Resource maps carries a histogram of the errors in the data used in its compilation as given by an analysis of the discrepancies at line intersections on that map. The errors vary from sheet to sheet depending upon the accuracy of navigation, the gradients of the field, and the accuracy of measurement. As a general indicator of accuracy, the combined histograms from all sheets are shown in figure 15. Of the 2472 line intersections at which magnetic field values were compared, the root mean discrepancy was 28$\gamma$. For the gravity field, the root mean square discrepancy was 3.3 mgal. Following from the considerations mentioned earlier, contour intervals of 50$\gamma$ and 5 mgal are concordant with those levels of error. Within the limits of the error distribution specified for each chart and according to the constraints of any additional information he may have, the user may then proceed with an interpretation of the data displayed by the chart.

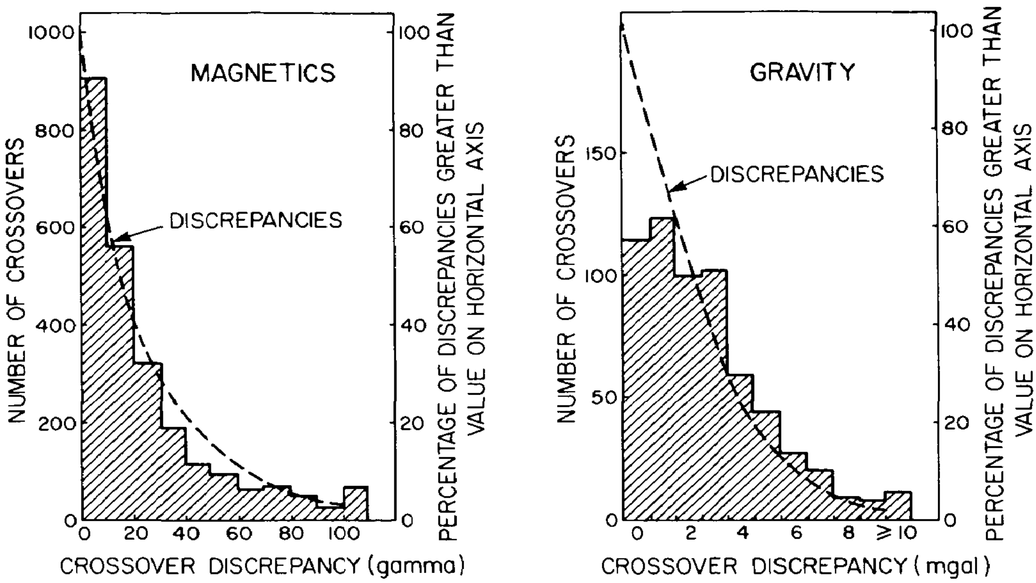



FIG. 15. — Histograms of the data discrepancies at track intersections throughout the entire mapped area. The dashed line portrays the same analysis in terms of the percentage of discrepancies greater than the value on the horizontal axis.

## EPILOGUE

During the life of the contract the necessity to recognize the effects of each of the processing stages has demonstrated the existence of one or two weak links in that chain of operations.

Magnetic field data is probably the easiest geophysical data to collect. The technology has developed to the stage where the sensor is relatively easy to handle and sturdy, and the control unit is compact and relatively free of maintenance. However the accuracy of the processed magnetic field data leaves something to be desired. The problem of correction for temporal variations of the magnetic field is a major one if the accuracy of marine magnetic surveys is to be increased. The development of moored magnetometers to provide the monitor data for the survey area is proceeding. A parallel development of establishing the transfer function between the diurnal variations in a survey area and those recorded at a nearby land monitor station by repeated measurements over the same survey line may also solve those problems. The success of these methods will determine the limit to the accuracy achieved. While there are errors associated with the data, the AGC processing system is also at fault in increasing those errors. The system used so far has involved the examination of successive 6-second samples of the data to see if the gradient is anomalous thereby indicating erroneous (noisy) data. A difference between successive readings of up to 80$\gamma$ is accepted, the equivalent of 2400$\gamma$ per km at normal survey speeds. Unfortunately the real field gradients can be so high, for example in the Bay of Fundy and Gulf ot St. Lawrence, that it is possible for a noisy reading to indicate a lower local gradient than a real reading. The criterion for examining the data to try to sort out the noise from the signal will have to be replaced with a more effective method. Those 6-second readings which pass this test of acceptability are then simply averaged to produce one minute samples of which every other one was used in the contract. As a result of this sampling method, some aliasing has been introduced and this too should be investigated to examine its effect upon the data presented.

An investigation of the gravity data processing system has been completed and will be published elsewhere. The most important result of that investigation was to demonstrate that the processing carried out to correct for the attenuation and phase shift of the powerful filters used in the measuring system was very effective. The main problem remaining is to improve the accuracy of the Eötvös corrections. As was mentioned earlier, on the hydrographic-geophysical surveys navigation data is sampled at a far higher frequency than that used in the data processing system. Use of all the navigation data with an approximate smoothing operator would probably result in the reduction of the total error as determined from a track intersection analysis by a factor of 2. Work on this problem is fundamental to increasing the accuracy of marine gravity data.

One aspect of navigation may become more important as the hydrographic-geophysical surveys progress northwards. Where there is an interruption in the acquisition of continuous positional data, so that only isolated navigation fixes are available, considerable help can be given by the other data being collected continously. Ship's heading and ship's log data have been collected on a one minute sample basis for some time but so far no use has been made of it. This data might well be of considerable use in providing a dead reckoning track between isolated fixes. At present, when comparing geophysical data at track intersections a strong opinion may be formed that the errors are due to poor navigation. Even without higher data accuracy the survey might be " improved " by minimizing such discrepancies by adjusting track positions. This latter technique can be a dangerous one, and considerable care will have to be taken in assessing the relative weights of navigation information provided by the various input parameters. In conjunction with this investigation there should be some consideration of the type of survey pattern which might optimize the error recognition and recovery process.

Finally the method of contouring requires considerable attention. No one aspect of this may be discussed in isolation. The relative merits of human and machine contouring cannot be discussed in isolation from the relative performance of machine contouring packages as applied to a wide variety of circumstances. Nor can those topics be discussed without consideration of the uses to which the resulting contour map will be put. Some effort should be made by the Canadian government agencies responsible for the preparation of the Natural Resource series of maps to examine this overall topic and assess the implications for the program.

## ACKNOWLEDGEMENTS

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Texts from which the reader may pursue this topic are :

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Computer Contouring : CRAIN, I.K., 1970. Computer Interpolation and Contouring of Two-Dimensional Data : A Review. *Geoexploration*, V. 8, pp. 71-86.