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Rotation of Alaska and the opening of the Canada Basin

By

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ROTATION OF ALASKA AND THE OPENING OF THE CANADA BASIN

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Introduction

The Canada Basin, also known as the Amerasian Basin, is a roughly triangular ocean basin bounded on the south by Alaska and on the east by the Canadian Arctic Islands. The origin of the basin is controversial, but the possibility that Alaska may have rotated away from a position much closer to the Canadian Arctic Islands, thus forming a new ocean basin, was suggested some years ago, apparently first by S.W. Carey (1956). Since then a number of investigators have added support to the idea that the Canada Basin may have formed by rifting or sea floor spreading. Their ideas were based on geological correspondences and, more recently, on paleomagnetic results (see below). This paper introduces a new line of evidence based upon gravity data from the continental shelves of present-day northern Alaska and arctic Canada. When the present continental shelf edges are used as a guide to restore the rifted Canada Basin to its hypothetical pre-rifting configuration, the major features of the gravity field on either side of the presumed line of rifting bear a striking similarity to one another. Within the constraint imposed by the shape of the continental shelf edges, it turns out that there are two different ways of obtaining a satisfactory match of the gravity anomalies across the rift, as will be shown. Unfortunately this ambiguity, which amounts to a shift of about 120 km, cannot now be resolved on the basis of the available data. However an argument in favor of one of the alternatives will be made. This new evidence is circumstantial rather than direct, and it merely expands upon the basic idea of the rotation of Alaska. Nevertheless the implications of the models to be presented are significant in that they indicate, subject to the ambiguity mentioned above, the probable position once occupied by Alaska with respect to Canada, as well as the amount of rotation that may have taken place. Each of the alternative models has its own implications for the geological interpretation of the observed gravity anomalies. When the ambiguity can be resolved, the observed correspondences across the rift zone may prove useful as an aid in the joint interpretation of the Alaskan and Canadian Arctic continental margins.

The detailed analysis of the present study is limited to a portion of the present margins of Canada and Alaska. However the implications for the remainder of the Arctic Ocean basin are considerable. These will be discussed in speculative fashion.

Background

S.W. Carey (1956) put forth the idea of an Arctic sphenochasm as an adjunct to the supposed oroclinal bending of mountain ranges in Alaska. He defined a sphenochasm as "the triangular gap of oceanic crust separating two cratonic blocks with fault margins converging to a point, and interpreted as having originated by the rotation of one of the blocks with respect to the other". The geometrical picture suggested here is similar, although the amount of rotation is greater than he suggested. Tailleur (1969) was perhaps the first to mention geological similarities between northern Alaska and the Canadian Arctic Islands in the context of modern plate tectonics. He noted particularly similarities between Devonian carbonates in the Brooks range and those in the Canadian Arctic, and proposed that sea floor spreading provides a plausible explanation for large-scale thrusting in the Brooks Range. Tailleur speculated further that a plausible reconstruction could be made by "straightening out" the Brooks Range to continue the Cordillera into the middle of the present Arctic Ocean , as well as linearizing certain Devonian to Triassic depositional belts in northern Alaska and Canada, which now show a 45 degree deflection. Rickwood (1970) speculated on the opening of the Canada Basin in early Cretaceous time, and his figure 5, presumably based only on matching of continental shelves, indicates roughly the same geometry as that suggested by this study.

In a review paper Churkin (1973) discussed the development of the Arctic Ocean basin, invoking this general concept. More specifically Tailleur (1973) restated the arguments for a palinspastic fit and extended possible plate action into pre-Mississippian time. More recently, Newman et al. (1977), in a study of paleomagnetic poles determined from late Devonian and Mississippian sediments from the Brooks Range in northern Alaska, found that northern Alaska appears to have rotated counterclockwise by about 70 degrees with respect to the North American plate since Mississippian time. Their results are said to be consistent with crustal shortening determined in the Brooks Range, and with the arcuate trends of mountains in northern Alaska and Yukon Territory. They suggest that the rotation probably began in late Jurassic or earliest Cretaceous time, although it could conceivably have begun as early as the Triassic. Yorath and Norris (1975) analyzed the development of the Canada Basin, concentrating on the development of the Canadian margin. They invoked the concept of a spreading ridge parallel to the Canadian margin as an explanation of the origin of the Beaufort Sea. Although there are differences in detail between their proposed model and those of this paper, it appears that the incompatibilities could be worked out without fundamentally disturbing their conclusions or violating the available data.

Thus the principal contribution of this paper is not to suggest a radically new model, but rather to present another line of evidence for palinspastic fit upon restoration of the rifting.

Development of the Two Models

The impetus for the present study was a recent compilation of marine gravity data obtained along the Beaufort shelf of Alaska over the past several years by the U.S. Geological Survey and the University of Connecticut (Boucher et al., 1977). The coverage of the gravity field over the continental shelf and rise between Pt. Barrow and the Canadian border is now nearly comparable with the extensive coverage of the Canadian Arctic compiled by the Earth Physics Branch, Division of Energy, Mines, and Resources, Canada (Sobczak et al.,1973, and Sobczak and Weber,1970). These data form a consistent, fairly densely sampled representation of the gravity field, with locations of gravity stations determined to an accuracy of 1 km or better in most cases. The resulting detail permits comparison of gravity features on either side of the Canada Basin. Fig. 1 shows the geography of the Arctic Ocean between Canada and Alaska, as well as the 1000 m bathymetric contour and the main features of the free-air gravity field in the vicinity of the continental shelf break.

The principal justification for attempting the matching of gravity anomalies at just this location is the similarity of the arcuate Beaufort Shelf to the complementarily arcuate portion of the shelf edge off the Canadian Arctic Islands. Fig. 2 shows the relationships across the rift zone of the free-air gravity anomalies and the 1000 m isobath after Alaska has been rotated in such a way as to match both the shelf edge and the gravity anomalies on the Canadian margin, with some gap left for clarity. The intent of texturing the contour intervals in the figures is principally to show that the gravity profiles along either side of the line of separation are quite similar.

Fig. 3 shows the fit of the 1000 m isobaths along the two coastlines after a rotation of 67 degrees about the pole of rotation shown in Fig. 2. The fit is not perfect, but in view of the long history of erosion, subsidence, and deposition since the proposed opening, it seems remarkably good over an arc distance of approximately 750 km. The mean mismatch of the 1000 m isobaths in Fig. 5 is 12 km, and the maximum mismatch is about 30 km. For comparison the mean mismatch is a small fraction of the 90 km mean misfit of the 500 fathom contours between Africa and South America as determined by Bullard et al., (1965).

The location of the actual continental margin in the sense of a line of separation is unknown. The present shelf edges are clearly a poor guide to the original margins, because of post-rifting deposition and subsidence. Previous investigators, including Sobczak and Weber (1973) and Wold, Woodzick and Ostenso

(1970) have placed the beginning of the transition zone in the mantle slightly shoreward of the free-air gravity maximum. Following them I have chosen to overlap slightly the 1000 m isobaths upon closing up the basin, thus superimposing the peaks of the free-air gravity anomalies. The arbitrary overlap introduces an additional uncertainty in the rotation angle and the position of the pole of rotation. Because of the arcuate shape of the continental shelf edges the only close constraint available on the lateral location of the rejoined margins is through the alignment of the gravity anomalies.

The transition from continental to oceanic structure implies a decrease in the depth to the mantle, and, other things being equal, one expects a free-air gravity high along the margin as a result of this transition. Thus the "saddle" in the free-air gravity anomaly, located near 148 W. along the Alaskan coast and its counterpart along the Canadian coast, as well as the unusually large positive peaks on the shelf-edge high (>90 mgal), have particular significance, since they are crucial in defining the fit of gravity anomalies across the rift zone. One may perhaps infer some generic relationship between the gravity saddles on the two sundered margins.

An attempt to refine this picture somewhat led ultimately into the alternative interpretation for the restoration of the rifting that will be discussed later. The train of thought proceeds as follows. Free-air marine gravity anomalies are strongly influenced by water depth, and an attempt was made to improve the resolution of Fig. 3 by introducing a Bouguer correction for water depth. Addition of a Bouguer correction for water depth results in a map in which the shelf-edge gravity high is replaced by a transition across the continental shelf to a plateau over the oceanic areas having regional Bouguer anomalies of 150-200 mgal. The Bouguer anomaly reflects the shoaling of the mantle beneath oceanic areas, since the isostatic effect of the water mass is undone by the Bouguer correction. A more readable map can be produced by subtracting from the Bouguer anomaly map a correction for the configuration of the mantle, in order to 'flatten' the Bouguer anomaly field. Under the assumption that the continental margin along the Beaufort shelf is arcuate, an obvious approach is to compute the effect of a more or less 'normal' continental to oceanic transition in mantle depth, using the arcuate continental shelf edge as a guide to determine the shape, in plan view, of the crust-mantle interface. This is shown schematically in Fig. 4a, which illustrates the shape of the crust-mantle interface and the shape of the body of excess mass for which the gravitational effect was calculated to produce what will be called the 'arc-reduced' anomaly. Fig. 5 is analogous to Fig. 2, except that it shows the juxtaposition of the arc-reduced anomaly maps for the two margins, rather than free-air anomalies. The apparent matching of anomalies across the line of rifting is more satisfying that that of Fig. 2, and Fig. 4 might be taken as best defining the original relative positions of the two margins before the rifting, according to this model.

There are, however, a number of aspects of Fig. 5 that are disturbing , and these are developed along lines leading to the alternative model. First of all, the assumption of a smooth, arcuate mantle interface implies that the source of the major features of the arc-reduced anomaly map is located above the crust-mantle interface. Therefore mass anomalies within the crust are required to explain the variations of gravity anomaly along the line of rifting. Concentrating on the Alaskan side, I refer specifically to the two large gravity highs separated by a saddle, or low, at about 145 W. If these features correspond to complementary features on the opposing margin, the saddle implies the probable presence of a sedimentary basin on both sides of the rift, which must either pre-date the rift, or, or near the time of rifting. Yet the basins must actually be of rather recent origin, according to conventional theory, which dictates that the low density is a sign of youth. This is a possibility, but is is not very satisfying as an explanation. Even more disturbing is the character of the gravitational highs on either side of the saddle, on the arc-reduced anomaly map. According to the model developed thus far, these relative highs indicate the presence of large, relatively dense bodies located within the crustal section. Although there is no direct evidence against this possibility, at least on the Alaskan side, it is highly unexpected, and the character of such dense bodies is a mystery. At this point in the analysis, the alternative model for the restoration of the rifting, entailing a quite different approach to matching the gravity anomalies across the rift zone, was developed.

The basis of the alternative representation lies in a new approach: suppose that the gravity highs on one margin be matched with the gravity lows on the other margin, and vice-versa. The question is, then, is it possible to infer another way of describing the original line of rifting, this time abandoning the notion of a smooth, arcuate rift, in such a way as to satisfy the geometrical constraints, on the one hand, and on the other hand, to produce a plausible model of the gravitational effects of such a revised line of rifting which is consistent with the observed gravity data? The answer is in the affirmative.

The approach taken was to align the gravity anomalies in the vicinity of the continental shelf edges 'out-of-phase', that is by aligning the positive anomalies on one side with negative anomalies on the other side in a visually satisfying way. After a satisfying alignment was determined, using the arc-reduced anomalies , the next step was to introduce a cut, signifying the original marginal rift, that would allow the two margins to fit together like adjoining pieces of a jigsaw puzzle. In the absence of a clear indication of how this should be done, the segments of the margin were constructed in the form of spreading ridges radial to the supposed pole of the rifting, connected by transform faults at right angles. Since the arc-reduced anomaly was based on the notion of a smoothly arcuate rift zone, the difference between that model of the mantle and the ridge-transform-ridge model can be computed directly as a perturbation of the arcuate model. The model for the Alaskan side, derived from such a jagged continental margin by translating slices of the arcuate model perpendicularly to the coastline to match the assumed new shape of the margin, is shown in Fig. 4b. It consists of a series of blocks of positive and negative mass; the model for the Canadian margin is the same, except with the signs reversed. The results of the calculation are shown in Fig. 6, alongside the observed arc-reduced anomalies for the Alaskan and Canadian margins. Certain features of the model, including the general locations of the major features, their magnitudes, and various features of the gradient along the rift zone are so near to that observed, that the general appropriateness of the model is evident. It is clear from the figure that the marginal rift was not chosen exactly right, and an improved version could be generated, but this has not yet been done. The general numerical agreement is striking. The most encouraging feature of this model is that the sedimentary basins and high-density masses, implied by the first model, have disappeared, along with the awkwardness of explaining their presence. The palinspastic fit based on this model, shown in Fig. 7, results in a northward shift of the restored position of Alaska by about 120 km, a rotation pole at 70.11 N,128.16 W., and a rotation angle of 73 degrees. The shelf edge fit is just as good as that shown in Fig. 3. Lest Fig. 7 be misinterpreted as being indicative of crustal structure on the outer shelf, let us backtrack briefly. The point of Fig. 6 was to show how well the gravity field can be described on the basis of some crude assumptions about the shape of the crust-mantle interface. Although the first-order effect of the continental-oceanic mantle transition has been removed from the gravity map of Fig. 7, the second order features relatable to the perturbation model still dominate the reduced gravity field. Assuming that the second model for the palinspastic fit is appropriate, it would be necessary to describe the shape of the mantle interface more exactly than was done in Fig. 4b, and then subtract the perturbation field from the anomaly field of Fig. 7 in order to separate mantle effects from crustal effects. The message is that inferences about crustal structure from gravity anomalies in this area (or anywhere) must be made with great caution until there is good seismic control available. The most direct way to resolve the ambiguity springing from the two alternative suggestions for restoring northern Alaska to its pre-rifting configuration is by means of seismic data, which may be expected to show the presence or absence of the crustal features implied by the first model.

Other Areas

Up to now I have confined attention to a segment of the Alaskan margin where the gravity data are adequate, and the corresponding segment of the Canadian margin. I shall consider briefly areas closer to and more distal from the pole of rotation.

It seems apparent that the rift zone did not converge to the indicated pole of rotation, as can be seen from the geology of the Mackenzie Basin area recently summarized by Young, et al.(1976). This is not surprising in view of the substantial post-rifting thrusting and transcurrent faulting that have occurred in the area. The physical apex of the rift zone is probably located to the southeast of the geometrical pole of rotation. It should be emphasized again that the conclusions of this study apply only to the northern margin of Alaska; the area to the south, including the Brooks Range, has been severely deformed.

I am not now in a position to do more than speculate about the remainder of the Arctic Ocean basin beyond the many discussions in the literature. Nevertheless it would not be proper to avoid the subject entirely, because the rifting of the Canada Basin has important consequences to remaining parts of the Arctic Ocean. If indeed the Canada Basin was formed by rifting and rotation of Alaska, it is important to find the extent of the area swept out by the rotation of Alaska. Although I have been able to treat the Alaskan continental margin only as far west as about 155 W., beyond which the restored coastline fails to match the Canadian coastline, this is probably not the extent of the continental margin that was actually rifted away from Canada. The Lomonosov Ridge is regarded (see for example Churkin, 1973) as the edge of the former continental margin of Eurasia which was rifted away by the currently active Gakkel Ridge. Without claiming any more than speculative insight, I mention that the Lomonosov Ridge, and thus by implication the former Eurasian margin is a good candidate for the locus of the great transform fault that bounded the opening of the entire Arctic Basin. It shows the proper direction of curvature and the proper symmetry to be an arc struck about the pole of rotation proposed in this paper. This interpretation is rather specifically implied in Churkin's 1973 review paper, and it is interesting that the geometry of the rotational separation of Alaska and Canada implied by this study is supportive.

These speculations are included here only as halting steps toward extending the concept of the rifted Canada Basin beyond the limited area where the picture is clearer.

Conclusion

The conclusions of this study conflict with the schematic model of Herron et al.(1974) for the Paleozoic and Mesozoic history of the Canada Basin. Their model requires, among other things, that the Kolymski Massif, now part of Siberia, slid into the Canada Basin in the early Paleozoic in order to form the Parry Islands fold belt. Kolymski supposedly then slid back out again in the Jurassic. The presence of Alaska adjacent to Arctic Canada obviates the necessity to slide the Kolymski Massif into the Canada basin and then out again, since Alaska assumes the role of the land mass needed to form the Parry Islands fold belt by collision against the Canadian land mass, as suggested by Tailleur (1973). Sobczak (1975) interpreted the elliptical gravity highs along the continental shelf edge of the Canadian margin as being largely due to the presence of wedges of uncompensated Tertiary and Quaternary sediment. Although his argument is difficult to accept, it is perhaps not incompatible with the smooth-arc model of this paper, which requires some buried mass excesses to explain these features. My second model, however, which invokes a jagged line of rifting, satisfactorily explains the gravity highs along the shelf edge without the need for such a seemingly contrived argument.

The matching of coastlines and gravity features was suggested by the gravity map of the Canada Basin. Application of scissors to the map verified the initial appearance of correspondence between the two opposing coastlines and subsequent work consisted primarily in refinements and choice of representation. Unfortunately the conclusion of this study is ambiguous in that two distinct ways of restoring northern Alaska to a position adjacent to arctic Canada have been demonstrated, and both have their merits. I have given some arguments favoring my second alternative, in which the major gravity features are matched 'out-of-phase' across the rift, but the ultimate decision must be made on the basis of seismic data. Whichever of the proposed models is ultimately deemed most appropriate, the gravity data seem to support the notion that northern Alaska was once adjacent to the Canadian Arctic, and their original relative positions may be fixed rather precisely, once the ambiguity has been resolved. It is to be hoped that the inferred constraints on the pre-rifting geometry of part of the coastlines of the Canada Basin will provide a useful addition to broader interpretations of the origin of the Arctic Basin.

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Figure Captions

Fig. 1. Area of study, shown in polar stereographic projection. Heavy line off coast is the 1000 m isobath. The position of the 1000 m isobath along the north coast of Alaska was taken from the Map of the Arctic Region (American Geographical Society, 1975). The position of the 1000 m isobath along the Canadian Arctic Islands was taken from bathymetry observations accompanying the dense network of gravity observations there. Contour lines near 1000 m isobath are 0, 30, 60, and 90 mgal contours of free-air gravity. Data east of 141 W. are from the Canadian National Gravity file. The rotation pole at 69.08 N., 130.88 W. was used in the restoration of the pre-rifting configuration on the basis of free-air gravity anomalies in Fig. 2.

Fig. 2. Nearly complete closure of the Canada Basin by rotation about the pole at 69.08 N., 130.88 W., to demonstrate correspondence of free-air gravity anomalies shoreward of the 1000 m isobath. Corresponding 30 mgal contour intervals identified by texturing are offset 30 mgal for the data along the Canadian Arctic coast, compared with the data along the Alaskan coast. This difference reflects both a regional offset and the different data reduction schemes used.

Fig. 3. The fit of 1000 m isobaths after a clockwise rotation of Alaska by 67 degrees about the pole of rotation shown in Fig. 3. The degree of overlap of the 1000 m isobaths is arbitrary, representing an estimate of the positions of the original continental margins.

Fig. 4 a. Schematic representation of the continental-oceanic transition in mantle depth used to 'flatten' the Bouguer anomaly field for purposes of the 'arc-reduced' anomaly shown in figures 5,6, and 7. The crust-mantle interface shallows to seaward from 25 to 15 km depth over a distance of 50 km. The shape in plan view is determined by the shape of the arcuate continental shelf edge. The model for the Alaskan margin is shown. The curvature is reversed for the Canadian margin. b. The model used to compute the model anomalies of Fig. 6 as a perturbation of the smooth-arc mantle model. Blocks of positive and negative mass are indicated by plus and minus signs. The Alaskan margin model is shown; for the Canadian margin the signs of the blocks are reversed.

Fig. 5. Similar to Fig. 3, except that 'arc-reduced' gravity anomalies, developed by subtracting from the Bouguer anomaly a field component calculated for a plausible continent-ocean transition in crustal thickness

are used. See text and Fig. 4a. A small gap is left to delineate the two data fields. "Pole A" is the pole of rotation used to construct this figure. "Pole B" is the pole of rotation that was used to construct Fig. 2.

Fig. 6. Comparison of 'arc-reduced' gravity anomaly for the Alaskan and Canadian margins with the anomalies calculated for the perturbation model of Fig. 4b. Contour interval is 10 mgal. Heavy lines show the line of rifting used to construct the model. Regions above 0 mgal and below -60 mgal are patterned as indicated. The general numerical agreement shows that the jagged margin of the second model of this paper satisfactorily accounts for the major features of the observed gravity field without requiring large anomalous masses in the crust. On the basis of this picture, the marginal cut should be modified somewhat to make a more realistic model, as shown in Fig. 7.

Fig. 7. Similar to Fig.'s 2 and 5, except that the Alaskan and Canadian margins are rejoined with gravity anomalies 'out-of-phase' according to the second model of this paper, the jagged rift model. Contour interval is 10 mgal. The line of rifting has been modified from that shown in Fig. 6, taking into account some of the more obvious shortcomings of the model of Fig. 4b.

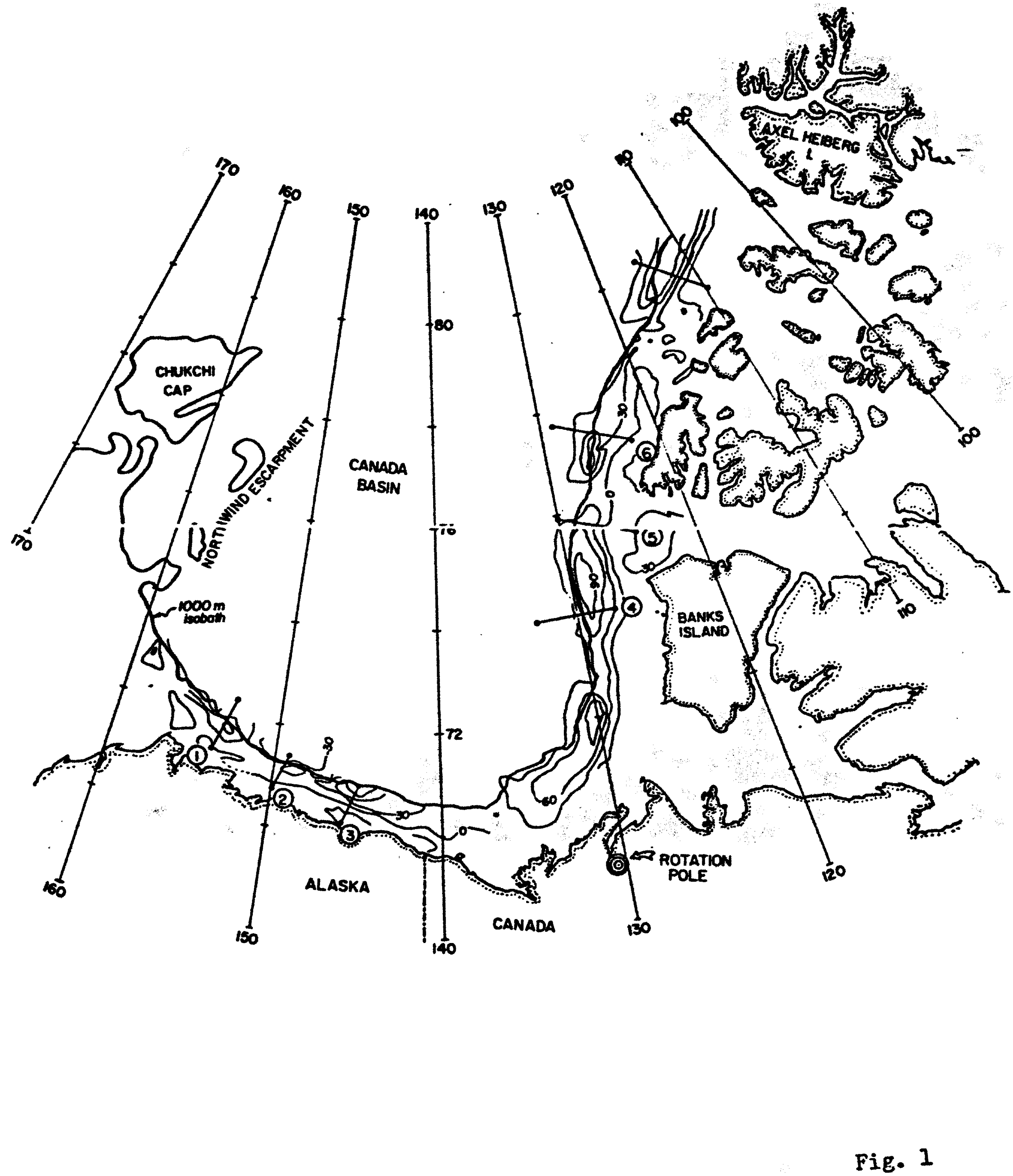
AXEL HEIBERG I.
CHUKCHI CAP
NORTHWIND ESCARPMENT
CANADA BASIN
1000 m isobath
BANKS ISLAND
ROTATION POLE
ALASKA
CANADA
170
160
150
140
130
120
110
100
80
76
72

Fig. 1

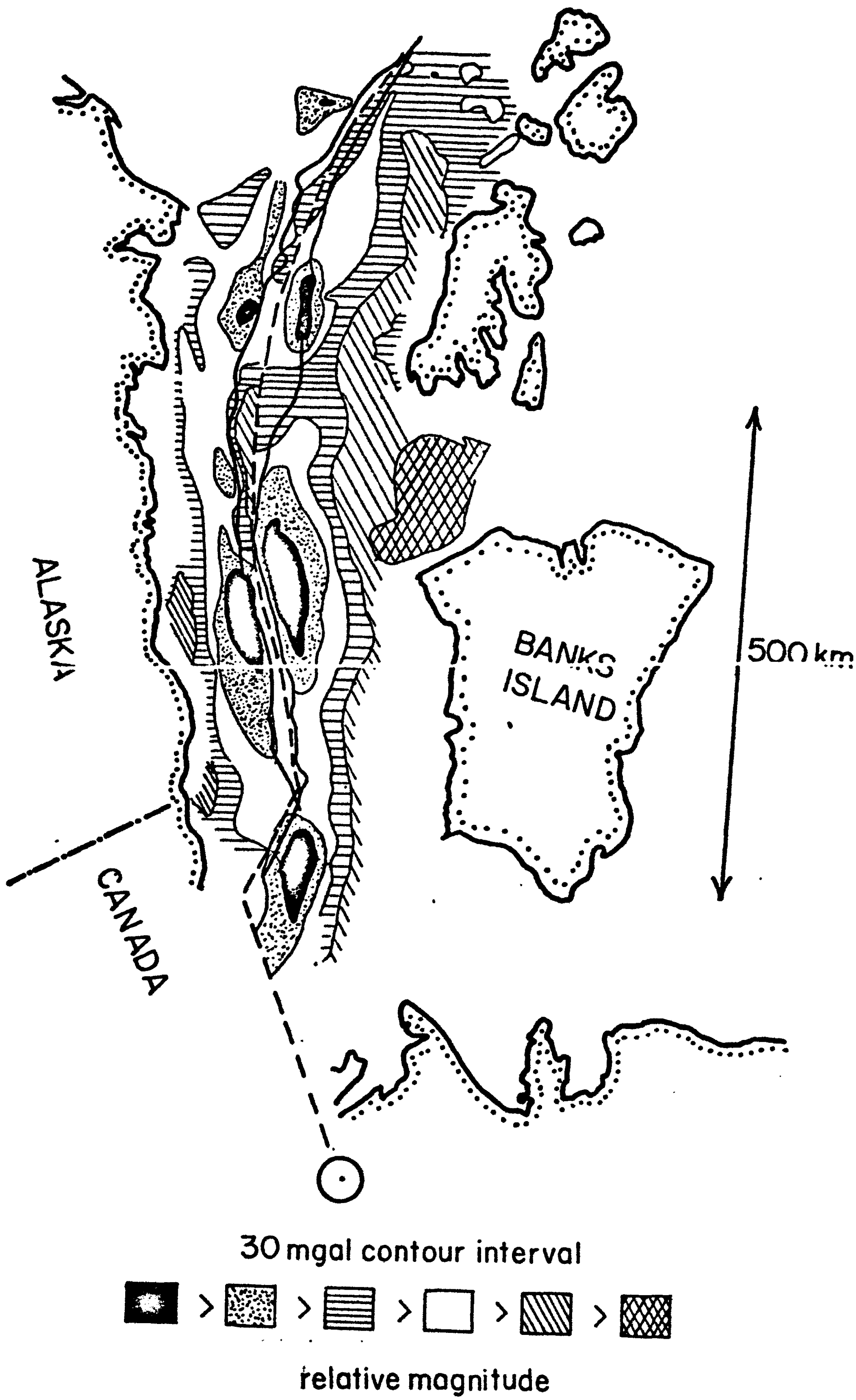
ALASKA
CANADA
BANKS ISLAND
500 km
30 mgal contour interval
relative magnitude

Fig. 2

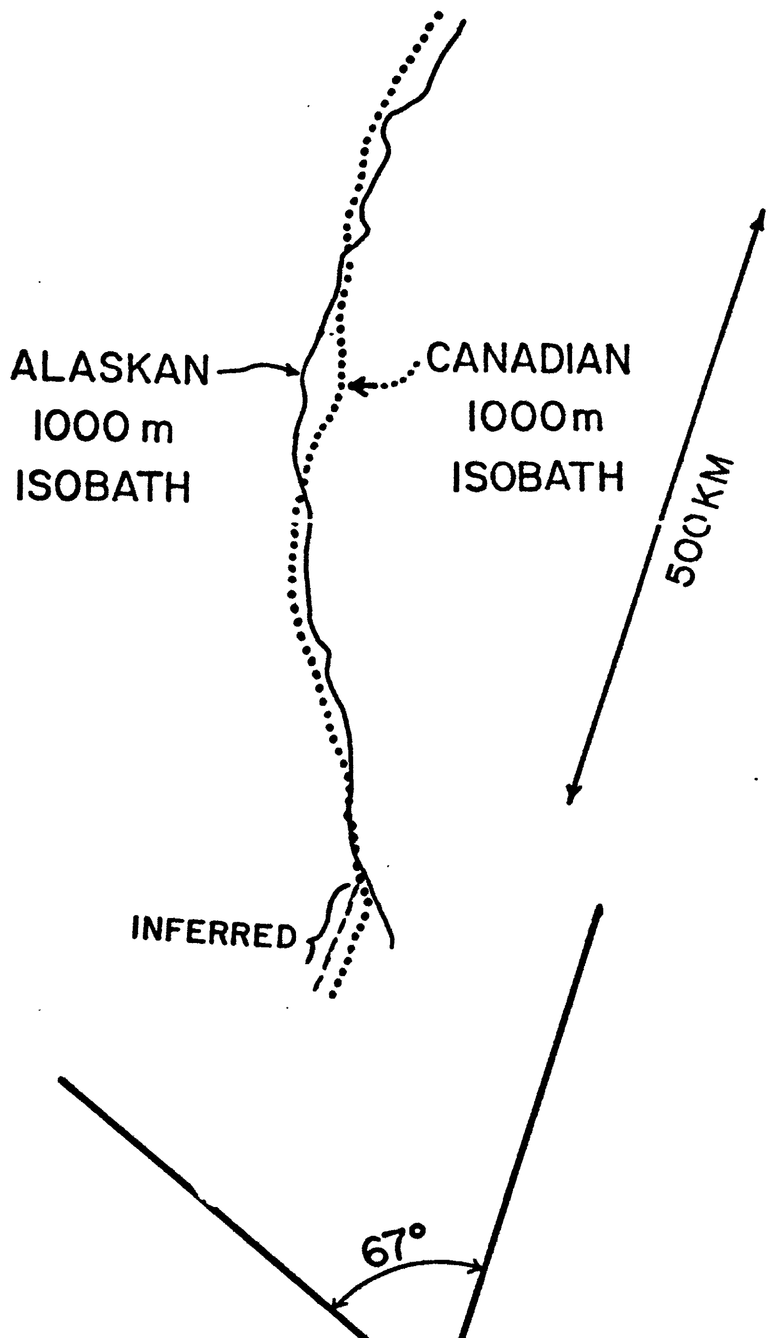
ALASKAN
1000 m
ISOBATH
CANADIAN
1000m
ISOBATH
500 KM
INFERRED
67°

Fig. 3

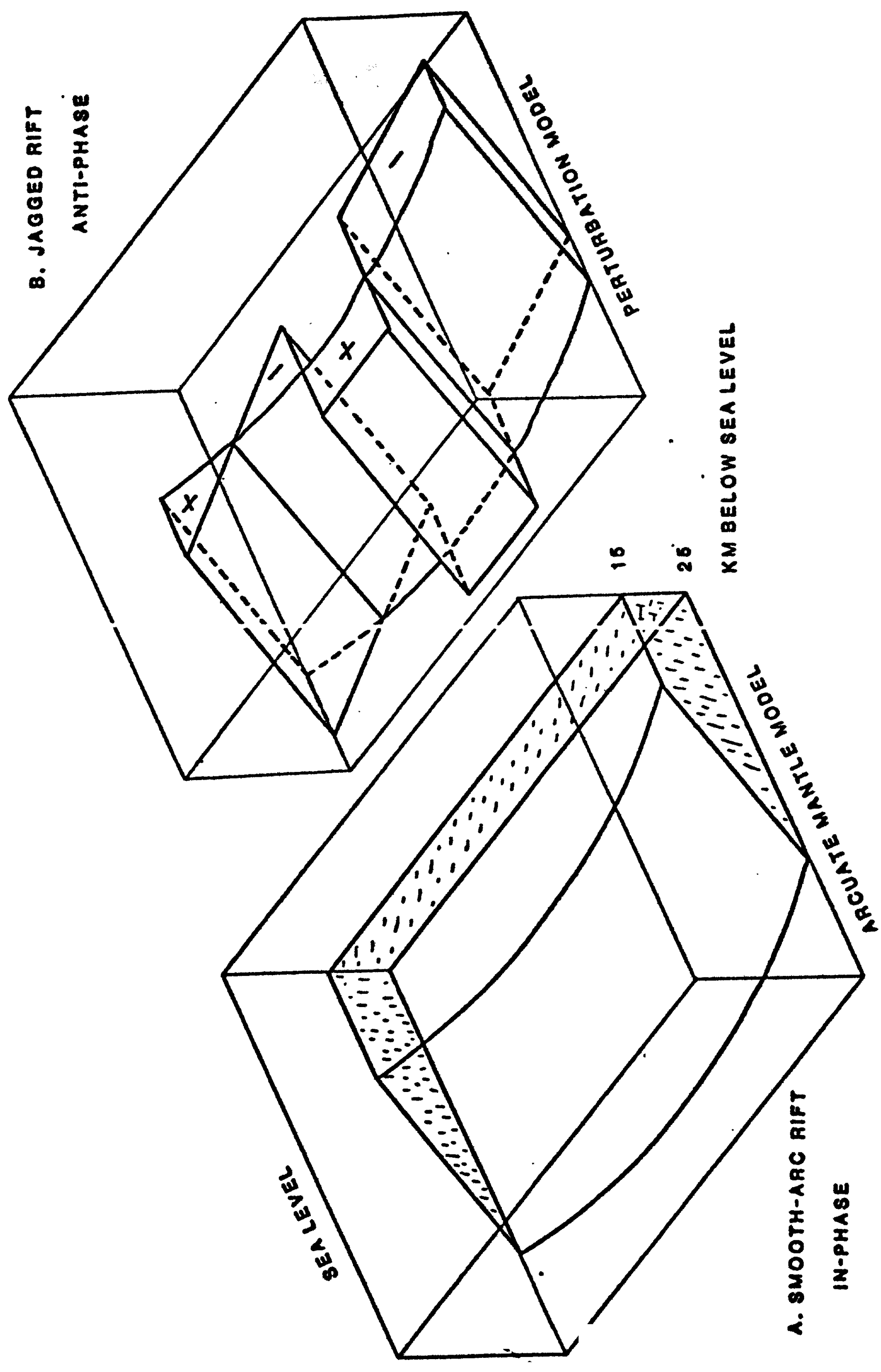
B. JAGGED RIFT
ANTI-PHASE
PERTURBATION MODEL
KM BELOW SEA LEVEL
15
25
SEA LEVEL
A. SMOOTH-ARC RIFT
IN-PHASE
ARCUATE MANTLE MODEL

Fig. 4

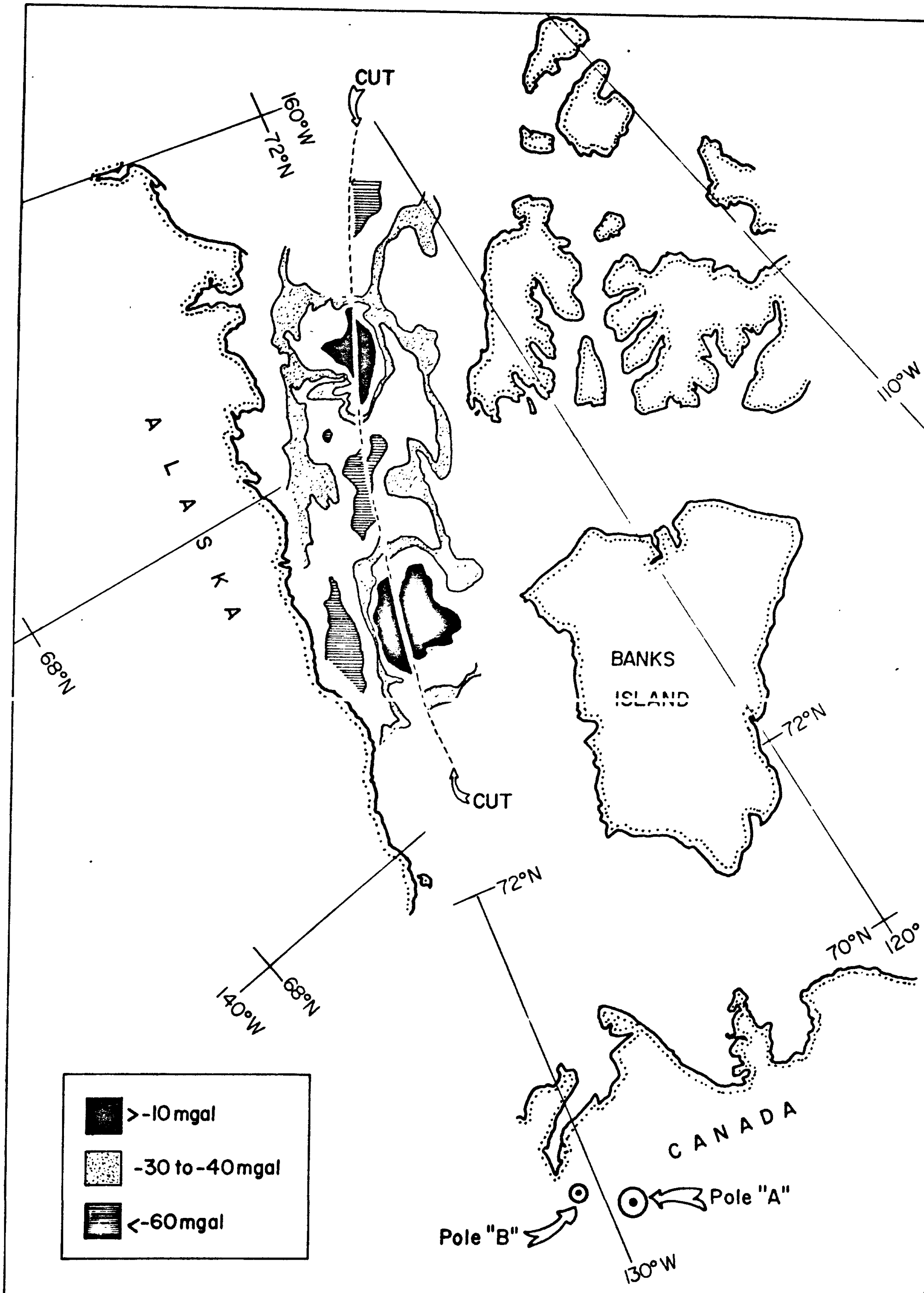
CUT
160°W
72°N
110°W
ALASKA
68°N
BANKS
ISLAND
72°N
CUT
72°N
70°N
120°
140°W
68°N
CANADA
>-10 mgal
-30 to -40 mgal
<-60 mgal
Pole "A"
Pole "B"
130°W

Fig. 5

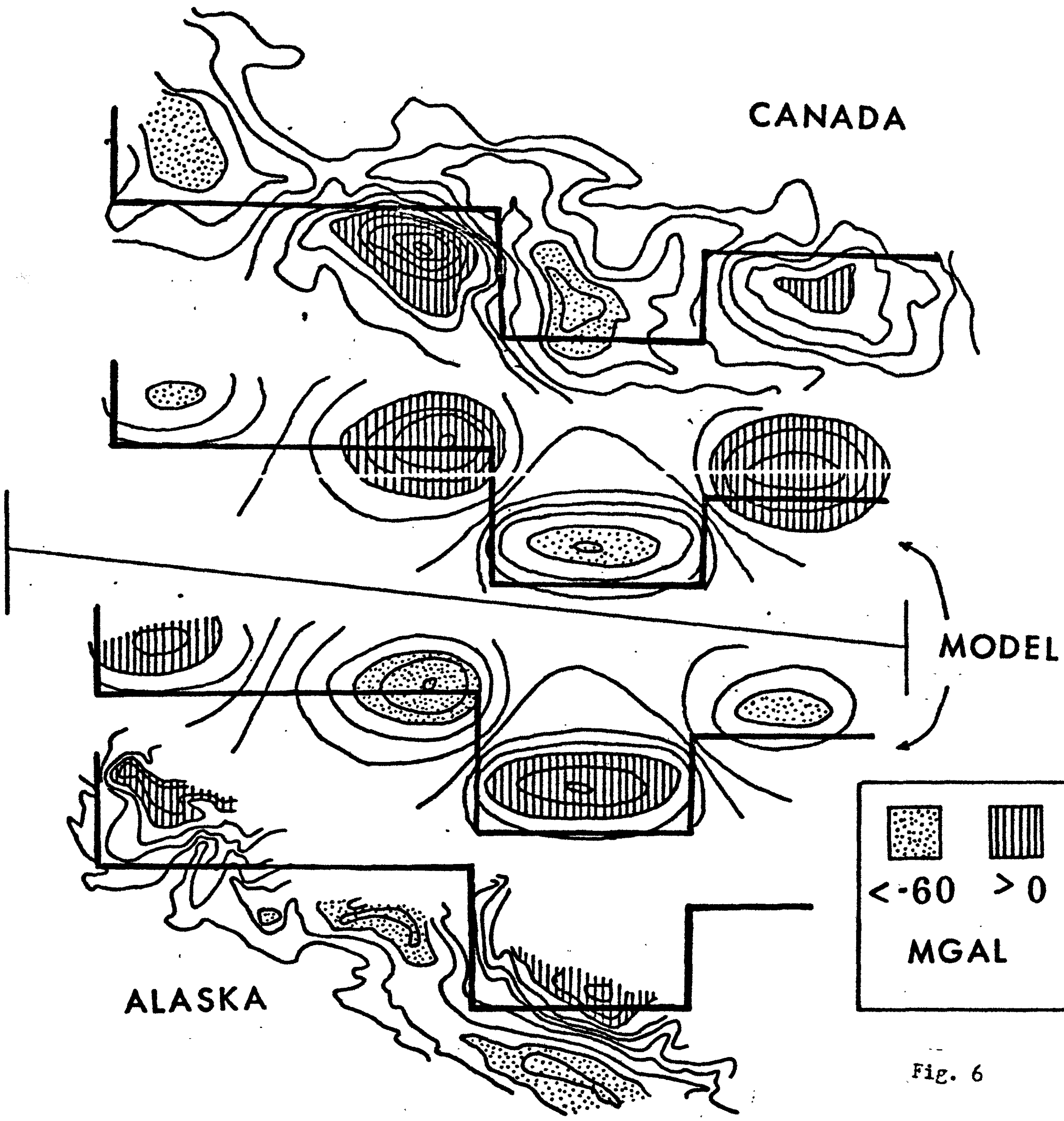

Fig. 6

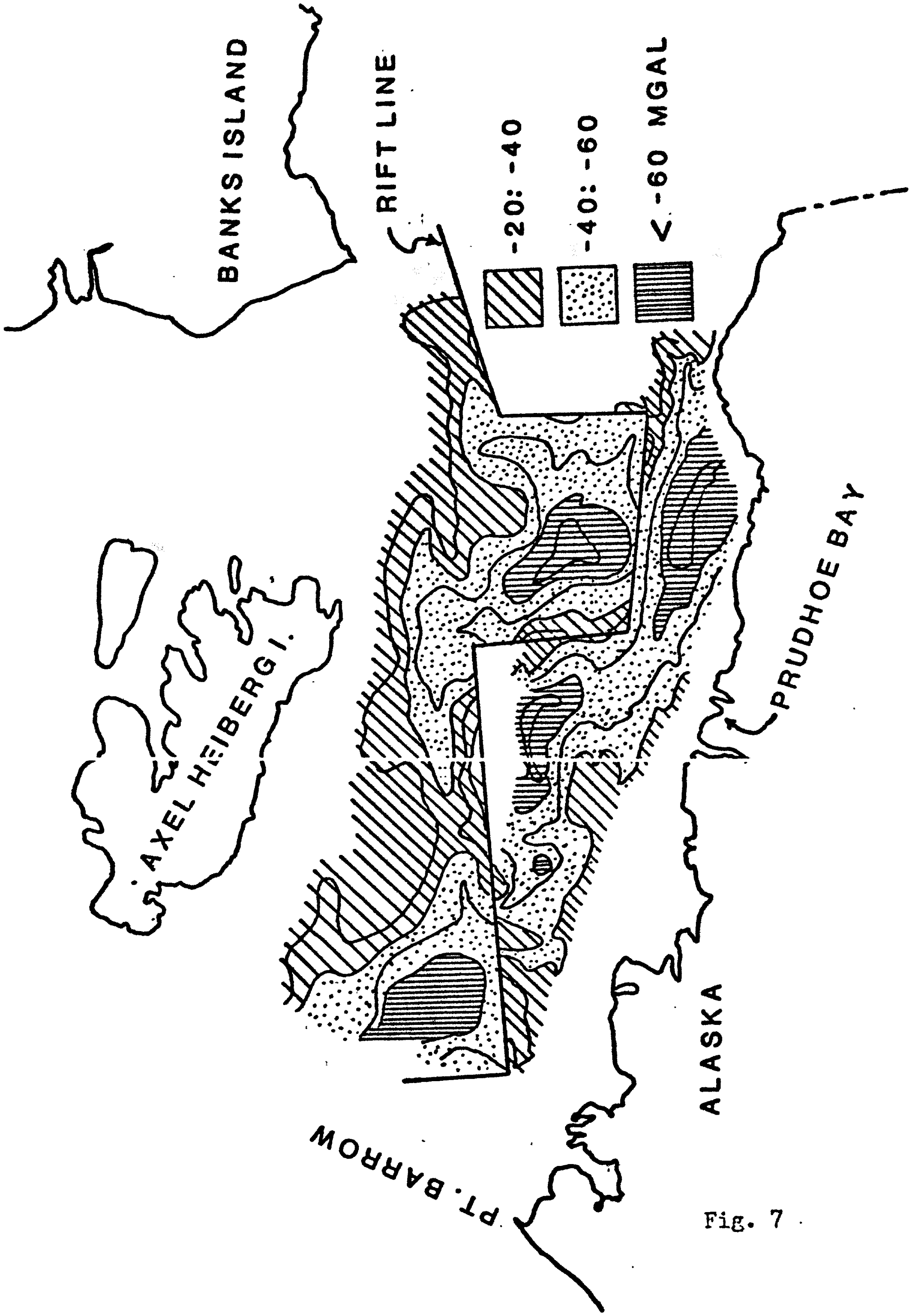
BANKS ISLAND
RIFT LINE
-20: -40
-40: -60
< -60 MGAL
AXEL HEIBERG I.
PRUDHOE BAY
ALASKA
PT. BARROW

Fig. 7