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GRAVITY AND CRUSTAL STRUCTURES IN THE

SOUTHERN BEAUFORT SEA (NORTH OF ALASKA)

by

Peter Dehlinger*

FINAL REPORT TO THE OFFICE OF NAVAL

RESEARCH ON

CONTRACT N00014-75-C-0714

WITH THE

UNIVERSITY OF CONNECTICUT

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*Marine Sciences Institute, Department of Marine Sciences, Department of Geology and Geophysics, University of Connecticut

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INTRODUCTION AND SUMMARY

The purpose of this investigation was to (1) obtain geophysical measurements in open waters of the southern Beaufort Sea (north of Alaska), (2) determine from these measurements and from other data crustal structures that extend across the continental margin and into the adjacent abyssal plain, and (3) interpret the structural features in terms of the tectonic development of the region. The field work was conducted aboard U.S. Coast Guard cutters (ice breakers) during their summer field seasons north of Alaska, when the ships were available cost free for the project measurements. Our program was, in turn, restricted to work that could be conducted aboard ice breakers.

The project was initiated on 1 April 1972 and completed 30 June 1979; field measurements were made during the summer field seasons of 1972 through 1977, as ice conditions permitted. The extent of open-waters varied greatly from year to year (and could not be estimated in advance). In 1977, ice conditions were most favorable; the southern limit of the ice pack was nearly 600 km north of the shore in eastern Alaska and we then obtained a large amount of useful measurements. In 1975 and 1976 conditions were least favorable: the ice pack extended almost to the shore and we obtained few useful measurements.

Previous geophysical work in the Beaufort Sea includes (1) a regional gravity survey (with an estimated 15 mgal uncertainty) made on sea ice over the entire Beaufort Sea (the Canada Basin) and most of the Arctic Ocean in the 1960s by a group from the University of Wisconsin (Wold and Ostenso, 1971; Wold, 1973), (2) various types of measurements conducted on drifting ice islands in the 1960s and 1970s by investigators at the Lamont-Doherty Geological

Observatory, and (3) detailed gravity and limited seismic measurements on the continental margin of the eastern Beaufort Sea (eastern margin of the Canada Basin) in the 1960s and 1970s by Canadian geophysicists (Sobczak and Weber, 1970; Sobczak et al, 1973). An excellent review of geophysical data in the Arctic region, including part of the southern Beaufort Sea, was published by the Earth Physics Branch in Canada (Sweeney, 1978).

Concurrent with our investigations, a group from the U. S. Geological Survey obtained numerous seismic reflection profiles and made a gravity survey in the southern Beaufort and the northeastern Chukchi seas. The Beaufort Sea gravity measurements that we and the USGS had obtained through 1974 were published as a jointly prepared gravity map (Boucher et al, 1977). Magnetic anomaly profiles had been flown over the Beaufort Sea by various agencies. One crustal refraction line was shot near Point Barrow, Alaska (Hunkins, 1965), one northeast of Point Barrow (Milne, 1966), and deep crustal refraction data were obtained in the central Canada Basin (Beaufort Sea), in connection with other oceanographic studies (Baggeroer and Falconer, 1981).

Our measurements emphasized shipborne gravity and bathymetry, with the expectation of including ship-towed magnetometer measurements and several crustal refraction profiles.

We used a LaCoste and Romberg gravity meter operating on a stable platform, installed near the ship's center of gravity, to obtain more than 2800 free-air gravity anomaly values between Barrow, Alaska, and the Canadian border, and from the coast out to the summer ice pack. From misties at more than 100 trackline intersections, we determined a mean anomaly uncertainty of 1.27 mgal. The gravity anomalies have a high accuracy for shipborne measurements because: (1) ship positioning was accurate to 0.4 km, (2) seas were generally calm, such that ship accelerations were low, and, (3) we discarded all questionable measurements (as are produced when the ship hit an ice flow or changed course substantially in avoiding a flow, or where ship accelerations were large).

Bathymetry was measured continuously aboard ship. Depths were not corrected for water temperature; surface temperatures were approximately 1°C to 2°C, and corrections are small. The recorded depths are considered accurate to ± 10 meters on the continental shelf, although probably less accurate in deep water.

Ship positioning was determined by the ship's satellite receiver. A relatively large number of satellites passed overhead (at these high latitudes), providing fixes with a measured uncertainty of 0.25 km. Dead reckoning provided positions between fixes.

We attempted to tow a total-field-measuring magnetometer behind the ship during the first year of operation. There were so many ice flows in the water that we had to abandon this effort, such that the anticipated magnetic measurements were not obtained. However, magnetic measurements obtained by others indicate that the anomalies in the Beaufort Sea have low amplitudes which cannot be reliably correlated.

Seismic refraction profiling was undertaken to determine crustal layering and thicknesses in critical locations. We assisted a group from Oregon State University, working aboard the same ship, in shooting numerous refraction lines along the coast in 1976 (Johnson et al, 1978). The southern limit of the ice pack necessitated shooting in shallow water, which resulted in shooting relatively short lines. Depths were obtained only down to the top of basement rocks (about 4.5 km); the anticipated long, deep-water lines could not then be shot.

A novel shooting technique was developed and successfully tested that summer. To record sonobuoy data at distances well beyond the line of sight, the ship's helicopters hovered at appropriate altitudes between ship and buoy to record the sonobuoy data. The following year (1977), open water conditions were ideal for shooting the anticipated long refraction lines with the helicopter-recording procedure. At the eleventh hour, however, we called off the shooting plans because various government agencies and public groups, when notified of the shooting plans, became alarmed that shooting would harm endangered mammalian species, particularly bowhead whales. Approximate depths to the Mohorovicic discontinuity in the abyssal plain were nevertheless available to the project from seismic refraction shooting that was, at about the same time, being conducted in the central Canada Basin (Baggeroer and Falconer, 1981).

We constructed the following maps from our measurements:

(1) Ship tracklines (Fig. 1), along which useful gravity and bathymetric data were obtained.

(2) Bathymetry (Fig. 2), with contour intervals ranging from 10 to 500 meters.

(3) Free-air gravity anomalies (Fig. 3), based on the 1967 IGA Gravity Formula (e = 1/298.47) and the International Gravity Standardization Net, 1971 (I.G.S.N. 71), which is the Revised Potsdam System, with a 5-mgal contour interval. (It is appropriate to contour with such a small interval because the anomalies have high accuracies and the tracklines are sufficiently close relative to the observed anomaly field.)

The bathymetric map (Fig.2) shows that the continental margin has typical water depths in the western part of the area; the continental slope is approximately 150 km wide there, the shelf break is at a depth of about 200 meters, and the continental slope dips at approximately 4° to depths of 2000 meters. In the eastern part of the area (off Camden Bay), the continental shelf consists of an inner shelf (breaking at 60-meter depths) that is about 100 km wide, and an outer shelf (breaking at 550-meter depths) that is 50 km wide. This outer shelf correlates directly with an unusually large positive-amplitude gravity anomaly. Depths to the abyssal plain in the southern part of the Canada

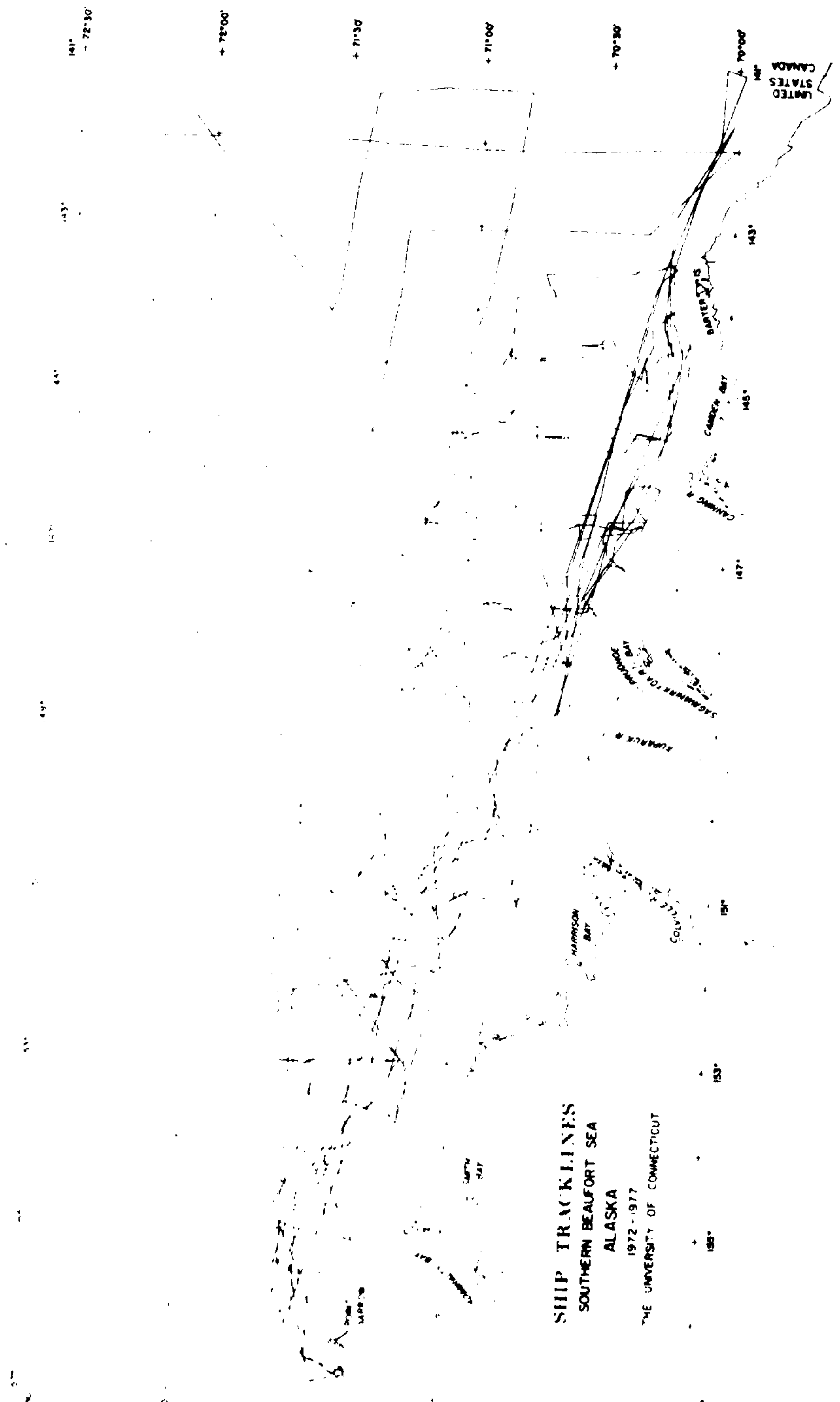

SHIP TRACKLINES
SOUTHERN BEAUFORT SEA
ALASKA
1972-1977
THE UNIVERSITY OF CONNECTICUT
UNITED STATES
CANADA
BARTER IS
CAMDEN BAY
HARRISON BAY
70°00'
70°30'
71°00'
71°30'
72°00'
72°30'
141°
143°
145°
147°
151°
153°
155°
157°

Figure 1.

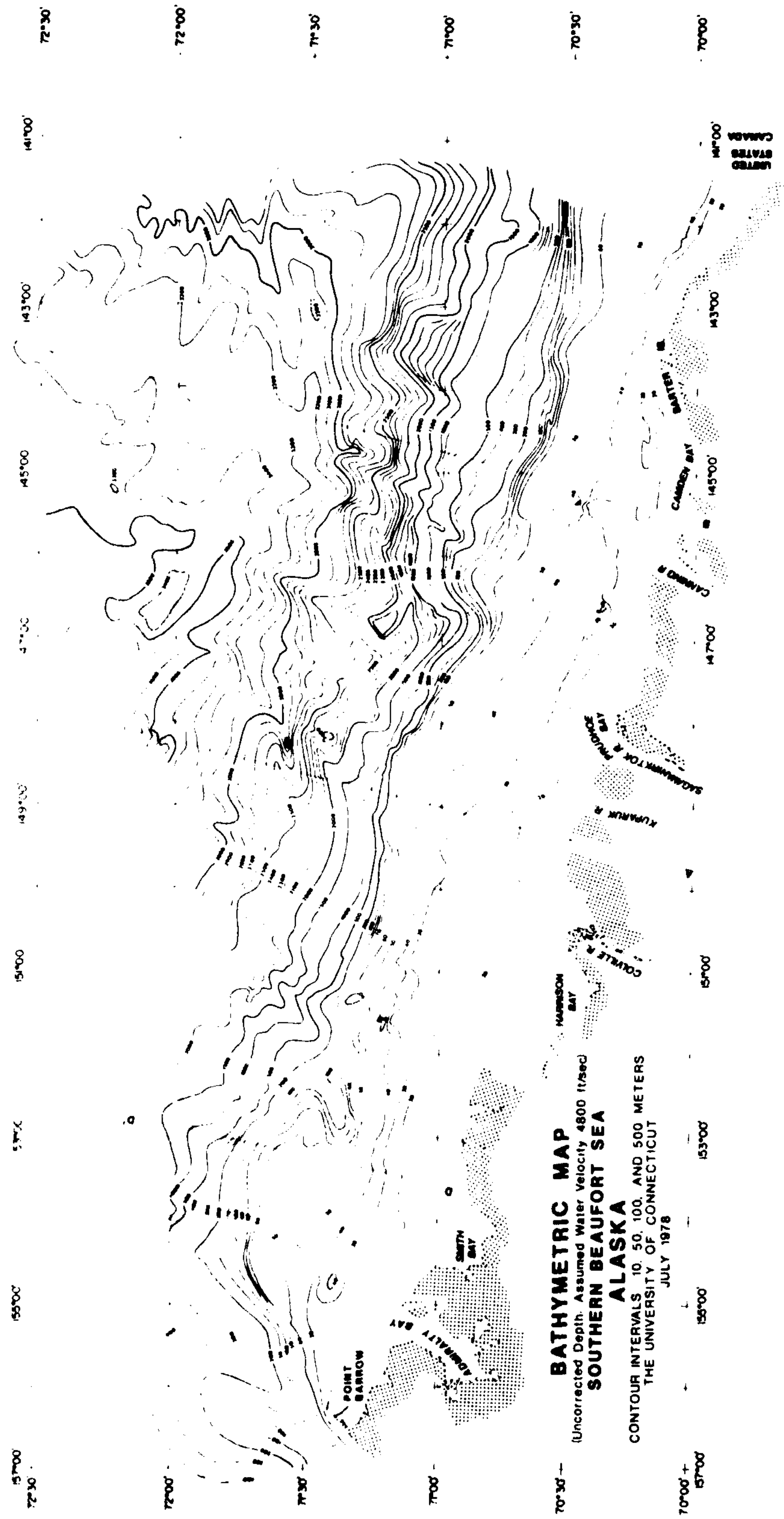

BATHYMETRIC MAP
(Uncorrected Depth. Assumed Water Velocity 4800 ft/sec)
SOUTHERN BEAUFORT SEA
ALASKA
CONTOUR INTERVALS 10, 50, 100, AND 500 METERS
THE UNIVERSITY OF CONNECTICUT
JULY 1978
POINT BARROW
ADMIRALTY BAY
SMITH BAY
HARRISON BAY
COLVILLE R
KUPARUK R
PRUDHOE BAY
SAGAVANIRKTOK R
CANNING R
CAMDEN BAY
BARTER I
UNITED STATES
CANADA

Figure 2.

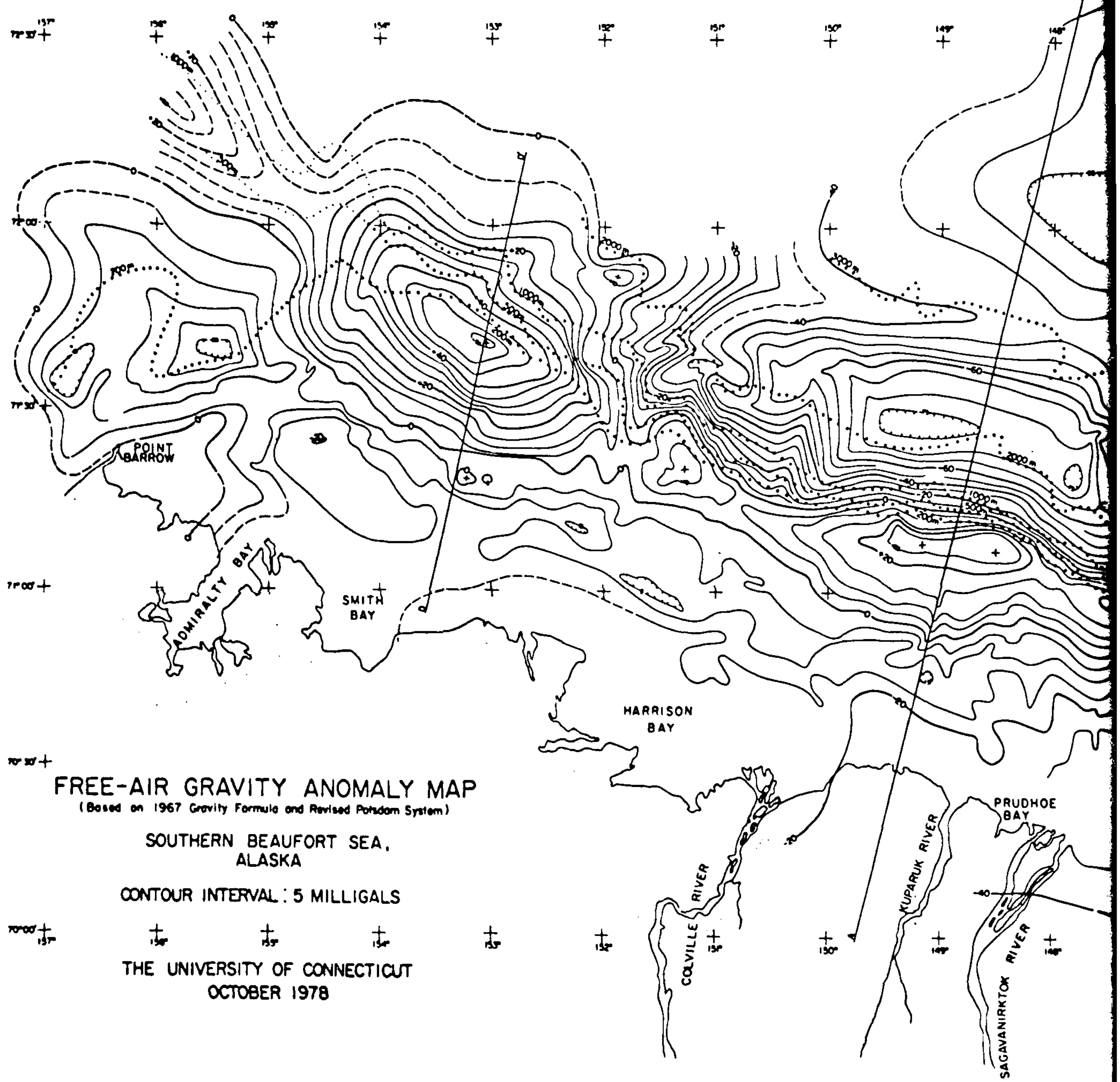
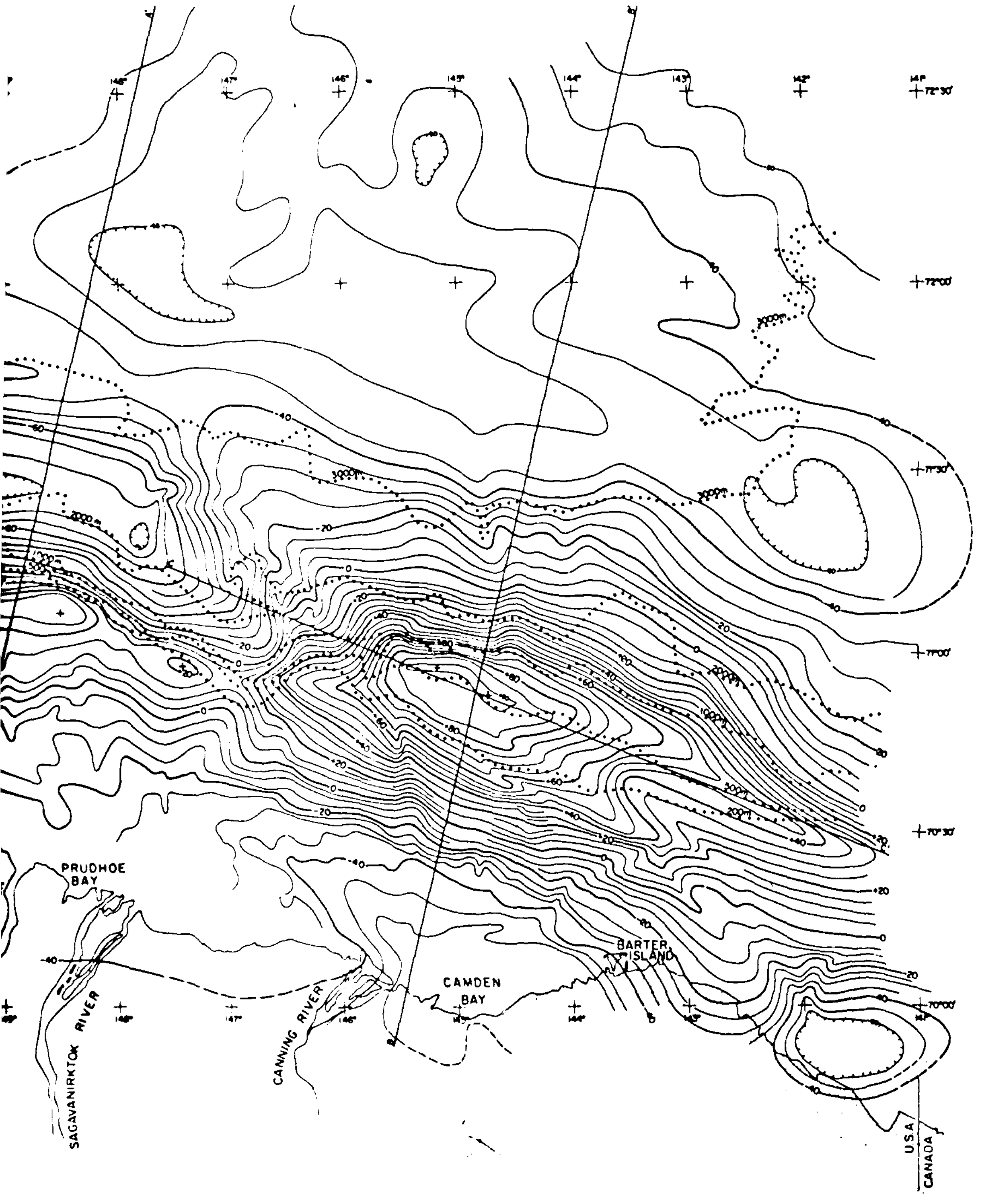

FREE-AIR GRAVITY ANOMALY MAP
(Based on 1967 Gravity Formula and Revised Potsdam System)
SOUTHERN BEAUFORT SEA, ALASKA
CONTOUR INTERVAL: 5 MILLIGALS
THE UNIVERSITY OF CONNECTICUT
OCTOBER 1978
POINT BARROW
ADMIRALTY BAY
SMITH BAY
HARRISON BAY
PRUDHOE BAY
COLVILLE RIVER
KUPARUK RIVER
SAGAVANIRKTOK RIVER
2000m
1000m
500m
200m
-60
-40
-20
20

Figure 3.



148°
147°
146°
145°
144°
143°
142°
141°
72°30'
72°00'
71°30'
71°00'
70°30'
70°00'
3000m
2000m
1000m
500m
200m
PRUDHOE
BAY
SAGAVANIRKTOK RIVER
CANNING RIVER
CAMDEN
BAY
BARTER
ISLAND
USA
CANADA

Basin (southern Beaufort Sea) are 3300 to 3500 meters, which is shallow for an oceanic province.

In the southern abyssal plain free-air anomaly amplitudes (Fig. 3) are -40 to -50 mgals. A thick sedimentary layer blankets this relatively shallow, closed ocean basin. The negative anomalies imply that the region is not in complete isostatic equilibrium; either the lithosphere is able to support a moderate mass deficiency, or sub-crustal movements occur beneath the Canada Basin.

The free-air map shows that the continental margin north of Alaska is essentially in isostatic equilibrium (as is the Alaskan North Slope), except for the eastern part, which is characterized by the outer shelf mentioned above. Anomalies in the western margin are typical of a passive continental margin: relatively small positive amplitudes along the continental side of the shelf break and larger negative amplitudes near the base of the slope.

In the eastern margin, off Camden Bay, a 90-mgal positive-amplitude anomaly extends for about 300 km along the break of the outer continental shelf; its width extends from the coastline out to the abyssal plain. Similar-shaped large gravity anomalies also occur along the shelf edge off Canadian Islands in the Eastern Beaufort Sea (Sobczak et al, 1973), although such anomalies are not commonly observed on other continental margins.

To investigate the source of this large anomaly, two crustal sections were constructed across the continental margin and into the abyssal plain. One is across a typical margin (Fig. 4, along line AA' in Fig. 3), consisting of a normal transition zone from continental to oceanic crusts. This sections includes known sediment thicknesses (obtained from reflection profiles) and known geologic layering beneath the Alaskan North Slope, a reported 14-km depth to Moho in the central Canada Basin, and an estimated 30 km depth to Moho beneath the North Slope (which is in isostatic equilibrium).

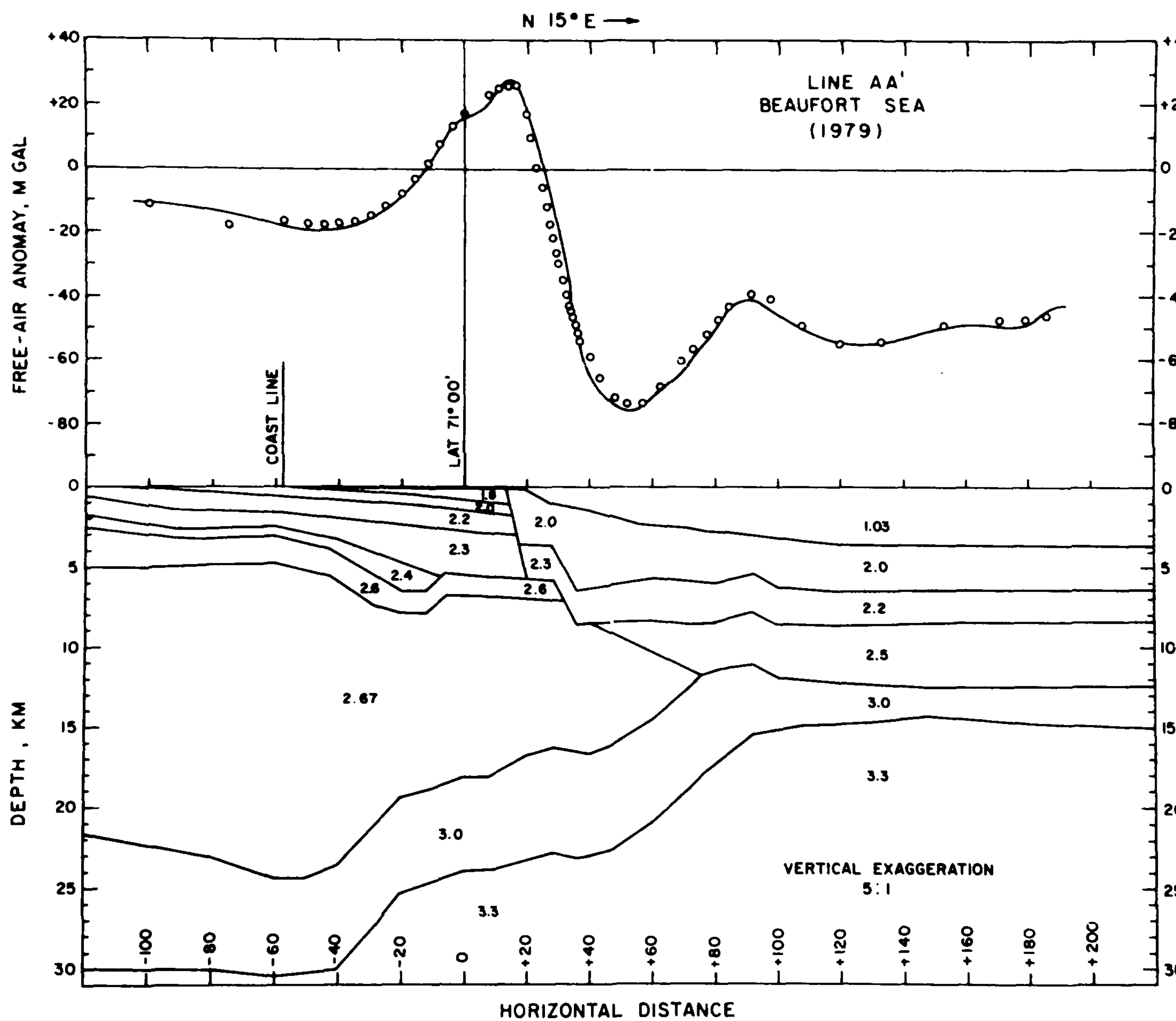


Figure 4. Crustal-subcrustal section along line AA' in Figs. 2 and 3. Numbers in the section indicate density, g/cm^3. Values of observed free-air anomalies are indicated by solid line, and those of the computed section by circles (adjusted with constant bias).

The second section (Fig. 5, along line BB' in Fig. 3) crosses the large gravity anomaly. The difference between the two sections represents the anomaly source. The anomaly width of about 170 km suggests a deep source. A shallow source, as would be produced by a section of sediments becoming progressively thicker from the coast to the outer shelf break, and from there thinning progressively to the abyssal plain, is hardly possible since seismic profiles show that sediment thicknesses across the anomaly are about the same as in adjacent areas. The most reasonable source structure consistent with known data involves an upper part of a continental crust overriding the edge of an oceanic crust (or oceanic crust shoved beneath the upper part of the continental crust).

Because this large anomaly is strikingly similar to several others observed to parallel the shelf edge off Banks and Queen Elizabeth islands in the eastern Beaufort Sea (Sobczak et al, 1973), one suspects that all of these unusual anomalies have a common type of origin. Either identical or very similar tectonic processes have occurred along the borders of both the southern and eastern parts of the Canada Basin, or the anomalies are remnants of a single structural feature which has been torn apart by plate rotations. A 70° anti-clockwise rotation of Alaska has been proposed by Carey (1958), Tailleur (1969), Churkin (1973) and others, although disputed by some. Boucher (1978) has suggested that the positive gravity anomalies along the southern and eastern Canada Basin may be manifestations of such a rift. If the anomalies are part of the same rifted structure, they would have had to exist at least since the rotation began. Other localities, as the Hawaiian Islands, support the concept that large loads can be supported by the lithosphere for long durations. Hence, it seems quite possible that these anomalies may be remnants of earlier rifting. Such rifting would explain the similarities in size, shape,

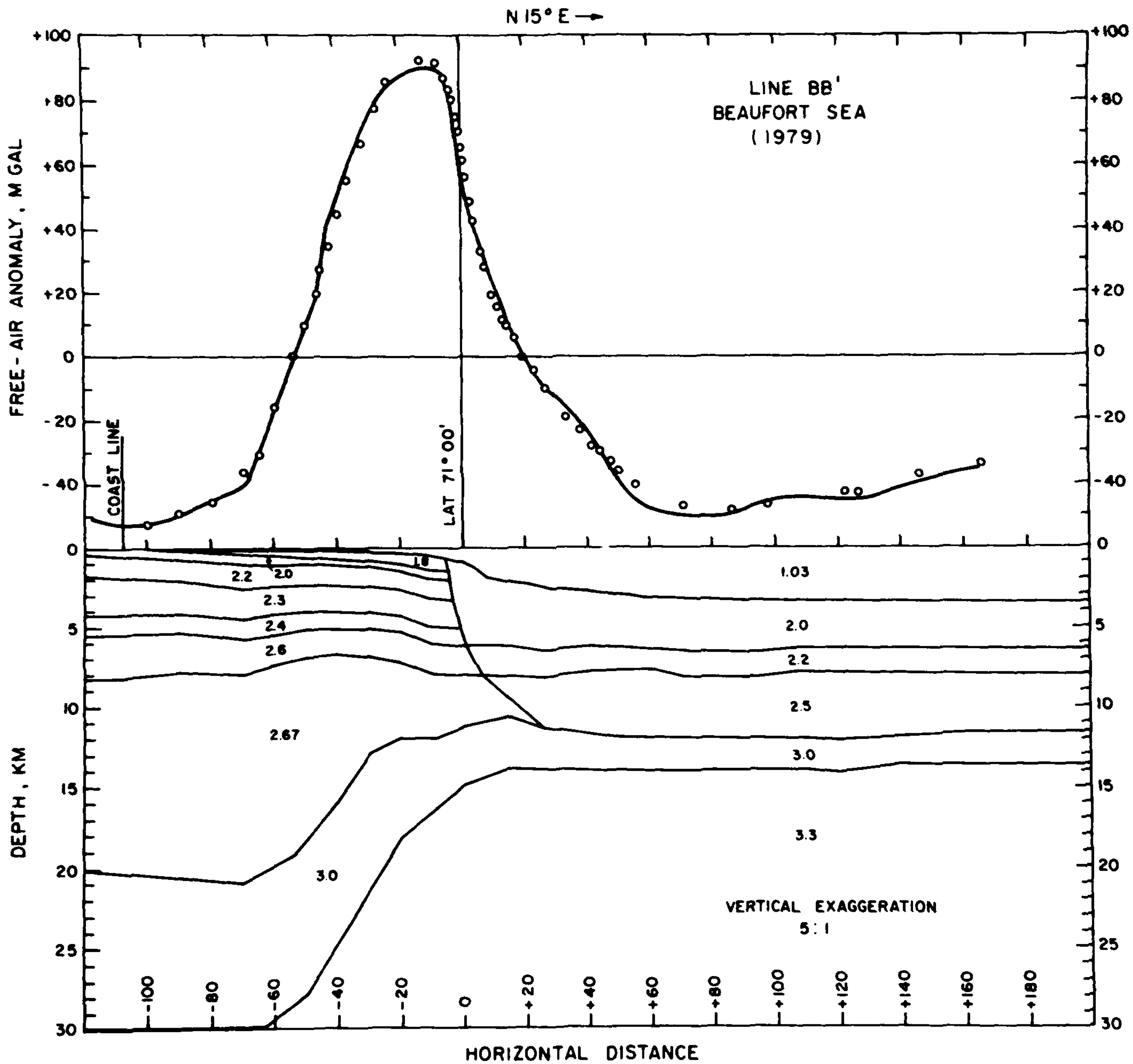


Figure 5. Crustal-subcrustal section along line BB' in Figs. 2 and 3. Numbers in the section indicate density, g/cm^3. Values of observed free-air anomalies are indicated by solid line, and those of the computed section by circles (adjusted with a constant bias).

and locations of the anomalies better than other origins that have been considered.

It is concluded that the gravity anomalies in the southern Beaufort Sea are consistent with a passive continental margin and the formation of the Canada Basin about 70 m.y.a. Furthermore, they are consistent with the concept of a large structural feature having existed along the Canadian islands which was torn apart by a plate rotation in which northern Alaska rotated anticlockwise as the Canada Basin was forming concurrently with the formation of the Atlantic Ocean basins. The gravity anomaly map also provides accurate numbers to which other measurements in the area can be tied, such as satellite geoids, satellite gravity, local undulations of the geoid, and deflections of the verticle.

PROJECT PERSONNEL

Principal Investigator: Dr. Peter Dehlinger, Professor of Geophysics

Co-investigator: Dr. E. F. Chiburis, Associate Professor of Geophysics

The principal investigator participated throughout the project, the co-investigator from 1 April 1972 to 31 July 1977, when he accepted employment at another institution. (The principal investigator constructed contour maps, crustal sections, supervised the data interpretation, and coordinated the final year's field program. The co-investigator coordinated the field programs through 1976, supervied the data reduction, and wrote computer programs.) Other personnel (all part time) included gravity-meter operators aboard ship, a computer analyst, a draftsman, graduate students working aboard ship, and a graduate assistant during each school year.

FIELD PROCEDURES

Field procedures included the logistics for working aboard U.S. Coast Guard icebreakers, installing the necessary equipment aboard ship before departing from its West Coast home port, and making geophysical measurements in the Beaufort Sea as ice conditions permitted. In the early years of the project, we also made measurements to and from the Beaufort Sea (including the Chukchi Sea), although these measurements were not continued in the last several years.

The measurements were made on the U.S. Coast Guard Cutter Glacier or Burton Island (as available), between Barrow, Alaska, and the Canadian border, and out to the summer ice pack. Along tracklines the ship maintained constant speed and as straight a heading as possible while at the same time dodging ice flows. Where the number of flows was large, ship speed was reduced; where ice was extensive, the ship was stopped for still readings, usually at 5-km intervals.

Navigation

The ship's permanent AN/SRN-9 satellite receiver and computer provided satellite fixes, which were obtained at average rates of approximately two per hour in these northern latitudes. The mean error of the fixes is taken as ± 0.25 km (± 800'), based on multiple fixes obtained on a single, three-day anchored station in the Beaufort Sea (Chiburis and Dehlinger, 1974). Dead reckoning provided positions between fixes (adjusted to adjacent fixes), with an estimated position uncertainty of ± 0.4 km.

Bathymetric Measurements

The ship's wide-beam transducer (echo sounder) and fathometer provided essentially continuous depth recordings. Echo times were converted to depths for an assumed sound velocity of 4800'/sec (1.46 km/sec). These depths were not corrected for water temperature, the corrections in these cold waters being small enough for us to ignore.

Gravity Measurements

Continuous gravity measurements were made by a LaCoste and Romberg meter mounted on a stable platform operating near the ship's center of gravity. We used different gravity meters in different years, as they were available to us (loaned by the National Ocean Surveys of NOAA, Oregon State University, and the U.S. Geological Survey).

Conventional gravity base-station ties were made along side the ship at its West Coast home-port, at middle latitudes, just before ship departure and on its return. Although the ties at the end of a cruise usually agreed well with those at the beginning, there was a distinct possibility that readings in the high latitudes of the Beaufort Sea included a bias. Ship piers have not been constructed in that region because of winter ice movements. To obtain a base-station check in the Beaufort Sea area we devised a new technique. The ship rammed an ice pack or large flow until it was lodged in the ice. With engines turned off, we took a LaCoste and Romberg geodetic gravity meter (these meters have almost negligible drift rates and large reading ranges) out on the ice, about 0.5 km from the ship, to obtain a gravity reading. Later, when the ship was near Barrow, Alaska, one of the ship's helicopters flew the meter to U.S.G.S. base station BARA for a tie measurement. W.F. Barnes of the U.S.G.S. determined the following base-station data (August, 1976):

Location: Point Barrow, Alaska — Designation: BARA

Latitude: 71° 20.16'N. — Elevation: 4 meters

Longitude: 156° 38.72'W.

Old adjusted gravity: 982,699.75 mgals; Woollard & Rose (1963) Datum

New adjusted gravity: 982,685.20 mgals; I.G.S.N. (1971) Datum

Description: at the old terminal and control building (No. 134) on the Point Barrow military airfield.

This method for tying gravity measurements on the ice in the Beaufort Sea to a local base station was used once during each but the first field season. The first year's (1972) measurements were later shown to contain a 13 mgal bias; these data have been corrected accordingly.

When the ship sideswiped iceflows along tracklines, the resultant horizontal accelerations caused the meter to hit its stops. It was therefore necessary to skirt flows, but this introduced variations in the Eötvös correction that applies to an average trackline. Approximately true Eötvös corrections were calculated by incorporating data from the ship's course recorder. Insofar as possible, changes in headings were kept to less than 10°.

Magnetic Measurements

We brought a towed magnetometer along during the first field season (1972), but there were so many ice flows in the water as to create a danger of losing it. Hence, the magnetometer was not put into the water.

Seismic Refraction Measurements

We wished to shoot several long, reversed, seismic refraction profiles to obtain control data on crustal layering and crustal thicknesses. The profiles were to be longer than line-of-sight distances from sonobuoy to ship, particularly when shooting on the continental shelf (up to 150 km). To record at larger distances, we deployed the ship's helicopters to hover at appropriate altitudes between ship and sonobuoy while one of the helicopters recorded the sonobuoy transmissions. This recording technique is useful for short lines, but imposes operational delays on long lines where the helicopter must refuel before the shooting is completed.

As indicated in the Introduction and Summary, this recording technique was successfully employed in 1976 when the icepack was near the coastline and shooting was restricted to shallow water. The numerous profiles shot were all short and penetrations were shallow.

In 1977 equipment and explosives were aboard ship to shoot four long reversed refraction lines, two on the shelf and two in the abyssal plain. Last minute alarms were raised by various government agencies and private groups claiming that the proposed shooting would harm endangered mammalian species, particularly bowhead whales; we therefore felt compelled to cancel this rather important part of our program.

DATA ANALYSIS

Analysis of the data included:

(1) Plotting detailed ship tracklines,

(2) Reducing the gravity measurements and calculating free-air anomaly values,

(3) Constructing a bathymetric contour map,

(4) Constructing free-air gravity anomaly maps,

(5) Constructing hypothetical crustal sections across selected parts of the continental margin.

Gravity Reductions

Gravity reduction procedures included correcting for frequent dodging of ice flows. We plotted all local course changes, which required hand calculating the anomaly values. We retained only those anomaly values for which the uncertainty in estimated Eötvös correction, due to course excursions, was less than about two milligals. It is to be noted, however that Eötvös corrections are relatively small at these high latitudes, particularly at reduced ship speeds.

For reducing gravity measurements obtained between 1972 and 1975, we initially used the 1930 Internatinal Gravity Formula (e = 1/297) and a base value tied to the Old Potsdam base station (see, e.g., Dehlinger, 1978, pp. 34 and

35 for descriptions). The resultant anomaly values were contoured (as illustrated in Dehlinger, 1978, pp. 265 and 266), and were also combined with free-air values obtained by a group at the U.S.G.S. and published separately as U.S.G.S. MAP MF-851 (Boucher et al, 1978).

We reduced gravity measurements obtained in 1977 to free-air values tied to the 1967 IGA Gravity Formula (e = 1/298.47) and the I.G.S.N. 1971 or Revised Potsdam System (see e.g., the above Dehlinger reference), and also recalculated previously determined anomalies, tying them to the same reference system. The resultant free-air values (more than 2800) and associated data are now on file in the National Geophysical and Solar-Terrestrial Data Center (Boulder, Colorado).

Accuracies of the Free-Air Values

We determined the accuracy of the gravity anomalies from misties at 107 intersecting ship tracklines (Fig. 1); the mean mistie is 1.79 mgals. On the assumption that a mistie is distributed equally between the two intersecting lines, the mean uncertainty per anomaly value is $1.79/\sqrt{2} = 1.27$ mgals. At 105 of these intersections, the mean uncertainty was less than 5 mgal; the other two uncertainties were 5.5 and 7.1 mgals.

This is an unusually high accuracy for ocean gravity-anomaly determinations, verifying that uncertainties resulting from ship excursions around ice flows produced only minor errors in those anomaly values accepted as reliable. Reasons for this high accuracy are mentioned in Introduction and Summary.

Gravity values were usually calculated at 10- to 15- minute intervals along ship tracks; however, in areas where ship accelerations were large, we determined anomalies wherever a gravity reading was constant over at least a 15-minute interval.

Maps

We read water depths at 15-minute intervals, converting fathoms to meters. These depths, with locations, are now also on file at NGSDC. Plotted depths were contoured (Fig. 2) on 10-meter intervals on the continental shelf, 100 to 500-meter intervals on the slope, and 100 meter intervals on the continental rise and in the abyssal plain.

Fig. 3 is our final free-air anomaly map, based on anomaly values along tracklines in Fig. 1. The 5-mgal contour interval is small for an oceanic province, but is justified by the data.

Cross Sections

To analyze structures which produce the observed gravity field, we constructed two hypothetical geologic cross sections that extend from the coastline out to the abyssal plain. Fig. 4 is a section across a typical part of the continental margin (along AA' in Fig. 3), and Fig. 5 a section across an atypical part (along BB' in Fig. 3).

We used available control data in the constructions, including known sediment thicknesses on the margin, known thicknesses of sedimentary rocks landward of the coastline, a known Moho depth in the central part of the Canada Basin, and a known Moho depth at Point Barrow and a value at the coastline which is in accord with isostatic equilibrium.

Numerous seismic reflection profiles which a group at the U.S.G.S. obtained (A. Grantz, personal communication, 1977-1979) showed that sediments on the shelf, slope, and abyssal plain are from 5 to 7 km thick, and that these thicknesses are fairly uniform. Short seismic refraction lines shot along the coastline in the western shelf area confirm this thickness (Johnson et al., 1978), and a long refraction profile near the central Canada Basin (Baggeroer and

and Falconer, 1981) confirms the thicknesses in the abyssal plain.

Both geological studies (Grantz and Kirschner, 1975; Grantz et al, 1975) and bore hole data in the Prudhoe Bay area indicate that the sedimentary rocks beneath the North Slope have thicknesses of about 4.5 km, the lower part consisting of Paleozoic carbonates. Depth to Moho in the central Canada Basin is 14 km (Baggeroer and Falconer, 1981), and beneath the isostatically balanced North Slope it is taken to be 30 km. No information is available on the thickness of the granitic (upper) part of the continental crust, but this thickness is not critical here.

Crustal sections in Figs. 4 and 5 are two dimensional, conforming with known bathymetry and the above-mentioned constraints. Using numerical methods developed by Talwani et al (1959) to approximate line integrals around assumed structures (as illustrated for crustal structures in Dehlinger, 1978, pp. 245 and 246), we computed two-dimensional gravity profiles that are produced by the sections. The sections were adjusted until they provided good fits with the observed free-air profiles along lines AA' and BB' in Fig. 3.

Clearly, while the sections in Fig. 4 and 5 conform with known data, they are not to be interpreted literally. They indicate mass distributions which exactly fit observed gravity profiles and at the same time portray likely structures. Fig. 4 is considered to be a good representation of the two-dimensional transition from continental to oceanic crust; Fig. 5, on the other hand, is not a good two-dimensional section, because the large gravity and bathymetric features (Figs. 3 and 2) are relatively wide for their lengths. However, the section shows minimum sized structures, since a three-dimensional feature would have to be vertically larger than a two-dimensional one producing the same anomaly (Fig. 5). Actual crustal structures that produce the positive-amplitude gravity anomaly must therefore be larger than those shown (Fig. 5).

RESULTS

From this study we produced a new bathymetric and an accurate, detailed, free-air gravity anomaly map of the southern Beaufort Sea, and constructed realistic models of crustal sections across two distinctly different parts of the continental margin. We also developed and applied two field techniques that can have application in projects elsewhere.

Bathymetric Map

Fig. 2 shows the bathymetry in the southern Beaufort Sea, based on data along tracklines (Fig. 1). The depths, although uncorrected for water temperatures, have an estimated accuracy of 3%.

We see that the continental shelf is a relatively smooth feature, approximately 150 km wide, covered by deposits from the silt-laden rivers draining the Alaskan North Slope. The continental margin exhibits a significant morphological change near 146° W. longitude. To the west there is a simple shelf and slope, the shelf breaking at a depth near 200 meters, and the slope dipping at approximately 4° down to the continental margin at a depth near 2000 meters. East of 146° W. longitude (off Camden Bay and Barter Island in Fig. 2), the shelf consists of an inner shelf, breaking at a depth of 60 meters, and an outer shelf, breaking at 550 meters, with a slightly steeper dipping slope than in the western area. It will be shown that this outer margin has a deep-seated origin and is not an expression of sediments dumped beyond an older shelf break.

The abyssal plain in the northeastern part of the area undulates gently at depths of 3300 to 3500 meters,which is near the reported depths (3.8 km) for the central Canada Basin (Wold and Ostenso, 1971). The plain is shallow for an oceanic province. It contains about 5-km of sediments (A. Grantz, from unpublished seismic reflection data; Baggeroer and Falconer, 1981), which have been deposited there by the Mackenzie and other rivers draining the northern part of North America.

Free-Air Anomaly Maps

Fig. 3 shows that the continental margin north of Alaska is essentially in isostatic equilibrium, except for the large, positive-amplitude anomaly off Camden Bay which overlies the outer shelf feature mentioned above. West of longitude 146° W., the anomaly pattern characterizes a typical passive transition from a continental to oceanic crust. A small positive amplitude extends along the shelf edge, a little landward of it, and a larger negative anomaly occurs along the base of the slope. The negative trend has a greater magnitude than the positive one, primarily because of the effect of the thick sediments along the slope (see illustration in Dehlinger, 1978, p. 232). The near-zero anomalies at the coastline and on the shelf are indications of a passive margin.

The large positive anomaly off Camden Bay continues for nearly 300 km along the outer shelf break and is more than 170 km wide, extending from the inner shelf out to the abyssal plain. Such an anomaly is quite uncommon along the edge of a continental shelf, and its structural origin is therefore of particular interest. Near Camden Bay, landward of the feature, anomaly values are lower (-50 mgals) than elsewhere, and across the continental rise, positive free-air values overshadow the normally negative values that should occur there. This region is clearly out of isostatic equilibrium.

The question is asked whether the source of the large anomaly is deep (e.g., in the lower crust or mantle), or shallow (as due to sediment deposits beyond the normal shelf edge or excessive sediments above the regional basement depth). Crustal sections along lines AA' and BB' (Fig. 3) were investigated to answer this question.

Anomalies in the abyssal plain range from -40 to -55 mgals; these values agree with the generally negative values for the Canada Basin obtained by Wold and Ostenso (1973). The abyssal plain is characterized by an oceanic crust with a thick sediment section and a moderate mass deficiency.

Crustal Sections

Fig. 4 illustrates a rather typical transition from continental to oceanic crust; Fig. 5 a similar transition, but superimposed upon it the feature producing the large gravity anomaly.

If the large anomaly results from excessive sediment depositions, where deposition beyond the shelf edge may or may not be accompanied by a subsiding outer shelf, the sediments would need to become progressively thicker from the coast out to the outer shelf, and from there become progressively thinner out to the abyssal plain. Such increased sediment thicknesses are not observed. Moreover, they would not likely account for the negative (-50 mgals) anomaly values at the coast (in the Camden Bay area). The large anomaly (Fig. 5) quite clearly requires a deep origin. Discounting special features such as ore deposits (an iron deposit with an average density of $5 g/cm^3$ would have to be more than 500 meters thick, tapering off laterally), the most reasonable source which includes given sediment thicknesses at sea and sedimentary rocks on land appears to consist of an upper continental crustal section that extends out over an oceanic crust. The converse is an oceanic crust shoved beneath the upper part of a continental crust. As mentioned previously, the actual structure producing the anomaly must be larger than that shown in Fig. 5 (since the length to width of the anomaly is about 2:1, and a two-dimensional approximation requires a ratio of at least 4:1). For an interpretation of the source, see Discussion.

Tying Gravity Reading in Ice-Covered Ocean to Local Base Station

The method in Field Procedures for tying a gravity reading at an ice station (ship ramming up on the ice) to that at a local base station is recommended in areas where the ship cannot dock in the general latitude of the survey. This procedure will prevent small errors from creeping into the data due to possible errors in the meter calibration factor when a reading is tied to a base at a significantly different latitude.

It is necessary to determine the accuracy of the ice-station to base-station ties. The tie method has limited accuracy, estimated to be one milligal under favorable conditions. For good results the meter drift rate must be negligibly small and the time interval between ice and base-station readings as short as practicable.

A reliable survey requires making at least several such gravity ties. We obtained one tie during each field season (except the first). The small gravity misties obtained at intersections of tracklines run in different years demonstrates that our base-ties are indeed reliable. Had the survey been made in a single field season, three or more ties would have been made.

Recording Sonobuoy Data in Hovering Craft

We have demonstrated that hovering craft, as a ship's helicopter, can effectively record sonobuoy data at distances beyond line-of-sight transmission. The method is practical where the helicopter can stay aloft (usually one to two hours) for the duration of shooting. Most helicopters must refuel when shooting long lines, however, and the resultant delay would impose practical limitations. Other techniques may then be more effective (e.g., using antennas held aloft by balloons above the ship).

DISCUSSION

The Arctic Basin is generally believed to have opened up in Early Cretaceous time (70 m.y.a.), and the Canada Basin in Late Cretaceous time (50 m.y.a.). Less is known about the Canada than the Arctic basin, although we do know several important things.

We know that the North Slope-Canada Basin area is aseismic, that the continental margin is passive, that much of the margin is in isostatic equilibrium, and that a thick sediment section covers the margin and the abyssal plain. The depth to Moho is approximately 30 km at Barrow, Alaska (Hunkins, 1965), which is also its probable depth along the northern Alaska coastline. The depth to Moho is approximately 14 km in the Canada Basin (Baggeroer and Falconer, 1981). Magnetic anomalies in the southerr Canada Basin exhibit low amplitudes and are difficult to correlate.

Our best knowledge of crustal structures across the continental margin stems from the gravity and bathymetric measurements interpreted in the light of known sediment thicknesses and the few approximately known Moho depths.

Regional Arctic Tectonics

Sweeney et al (1978) provide an excellent summary of Arctic tectonics, based on geophysical measurements. The general view (e.g., Sweeney et al, 1978) is that the early opening of the North Atlantic about a pole of rotation in northern Greenland produced compressions between the Arctic-Alaska plate (northern Alaska and the Chukotsk Peninsula in northeastern Siberia) and the Furasian plate. The effect was to rotate the Arctic-Alaska plate approximately 70° anticlockwise away from Arctic Canada in Early Cretaceous time, forming the Arctic Ocean. Paleomagnetic measurements of Neumann et al (1977) indicate that Carboniferous rocks in the Brooks Range (northern Alaska) have been rotated about 70° anticlockwise. Such a plate rotation had been proposed earlier by Carey (1955), Tailleur (1969), Churkin (1973), and others, although some investigators question whether the rotation applies to central and southern Alaska.

In Late Cretaceous-Early Tertiary time the pole of rotation forming the North Atlantic moved into eastern Siberia, causing North America to split away from Greenland (Pitman and Talwani, 1972). Tensional structures thus formed in the Arctic , producing the accreting Nansen-Gakkel Ridge, the Arctic extension of the Mid-Atlantic Ridge. The Lomonsov Ridge is a continental crust believed to have been rifted from the polar shelf of Eurasia, becoming the northern boundary of the Canada Basin.

The low-amplitude magnetic anomalies in the Canada Basin are evidence that the crust there was formed during Cretaceous time when there was a magnetic quiet period. During the Tertiary the Canada Basin was bordered on the south and east by crusts containing Paleozoic and Mesozoic sedimentary layers. Sediments from the adjacent lands continued to be deposited to the present thicknesses on the continental shelf and on the slope, where slumping is commonly observed (Grantz, personal communication, 1979), and also in the abyssal plain.

Structures in the Southern Beaufort Sea

The passive continental margin north of Alaska west of 146°W. longitude, as evidenced by the free-air anomaly map (Fig. 3), is consistent with the development of the Canada Basin 50 to 70 m.y.a., and the possible rotation of northern Alaska 70 m.y.a. Moreover, the approximately 5-km thickness of sediments in the abyssal plain attests to a long existence of the basin. A 5 km thickness accumulated in 50 m.y. amounts to an average sedimentation rate of 1cm/century, which appears to be reasonable for silt-laden rivers dumping their loads into a closed basin.

The mass deficiency producing the -45 mgal anomaly in the abyssal plain (and over most of the Canada Basin, according to Wold and Ostenso, 1971) has been attributed to downward flexuring in response to sediment loading (Sobczak, 1975). This could not occur if the basin were originally in isostatic equilibrium, however. In that event, sedimentation would produce flexuring that will either lag behind sediment loading, resulting in positive anomalies, or be in phase with loading, resulting zero anomalies. Negative anomalies here mean that flexuring leads the loading. Such flexuring implies either deep-seated movements or that, as the basin sinks, isostatic readjustment lags behind basin formation.

The magnitude of the laterally uniform mass deficiency can be estimated as a negative Bouguer slab. The slab formula

$$\Delta g = 2\pi G \Delta\rho \Delta h$$

in which Δg is the gravity anomaly, G is the gravitational constant, $\Delta\rho$ the density contrast, and Δh the slab thickness, reduces to

$$\Delta\rho \Delta H \approx -1$$

for Δg = -42 mgals, $\Delta\rho$ in g/cm^3, and ΔH in kilometers. For example, a 6-km thick slab with a density contrast of -0.17g/cm^3 would produce the observed anomaly.

The slab mass deficiency is more likely to originate in the lower crust or upper mantle than in the sediments, suggesting that the basin may have been down-flexed, possibly since its early development. Some evidence indicates that the mass deficiency may occur in the lower crust. Baggeroer and Falconer (1981) find that oceanic layer 3 is absent or very thin (although the sub-Moho velocity is normal). Hunkin's (1965) refraction data also indicate a thin or missing layer 3 northeast of Point Barrow. A lower velocity usually correlates with a lower density, which, in this case, means a more acidic lower crust.

If the density of a 6-km-thick lower crust is 2.8 g/cm^3 instead of the more typical 3.0g/cm^3, one would expect the observed negative anomaly. A modified ocean crust could have significant implications on the formation of the Canada Basin.

The large, positive-amplitude anomaly off Camden Bay may provide additional information on the development of the basin. Several similar-shaped anomalies with the same magnitude were mentioned to trend northerly along the continental margin off Banks and Queen Elizabeth islands (Sobczak and Weber, 1970; Sobczak 35 al, 1973). Boucher (1978) pointed out that if northern Alaska is rotated 70° clockwise about a point near 69°N. latitude, 131°W. longitude, these large anomalies will be aligned. If the anomaly off Alaska is produced by a single structure that was once aligned along the Canadian islands, the present structures and anomalies would have had to exist for the last 70 m.y. That large structures can be supported by the lithosphere for long durations is illustrated by the northwestern part of the Hawaiian Islands, which have been supported by the lithosphere for more than 80 m.y.

Other explanations for the large anomalies off Alaska and the Canadian islands have been considered (e.g., Herron et al, 1974), but it is difficult to conceive of processes which will produce the strikingly similar anomalies (which are, as mentioned before, unusual along a continental margin) in two different directions and in different localities. The origin and locations of the anomalies indeed neatly support the concept of a 70° anticlockwise rotation of northern Alaska.

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PUBLICATIONS

Various results of this investigation have been presented in the following publications (listed chronologically):

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