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by A. B. WATTS [2] AND R. T. HAWORTH

Atlantic Geoscience Centre

ABSTRACT

Bouguer gravity anomaly and magnetic anomaly maps of the area east of the Magdalen Islands, Gulf of St. Lawrence, are presented at a scale of 1:250,000. These maps, together with information from previous geological and geophysical studies provide evidence for (1) a deep sedimentary basin infilled by Carboniferous sediments between southwestern Newfoundland and the Magdalen Islands, (2) a large area of salt accumulation on the eastern Magdalen Shelf, and (3) the continuity of geological structure between the Magdalen Islands and southwestern Newfoundland.

RÉSUMÉ

Des cartes des anomalies de Bouguer et des anomalies magnétiques du secteur situé à l'est des Îles de la Madeleine, dans le golfe Saint-Laurent, sont présentées à l'échelle du 250,000^e. Ces cartes, ainsi que des données provenant d'autres études géologiques et géophysiques, indiquent la présence (1) d'un bassin sédimentaire profond de dépôts du carbonifère situé entre le sud-ouest de Terre-Neuve et les Îles de la Madeleine et (2) d'un grand secteur d'accumulation de sel dans la partie est de la plate-forme des Îles de la Madeleine ainsi que (3) d'une continuité structurale géologique entre les Îles de la Madeleine et le sud-ouest de Terre-Neuve.

INTRODUCTION

This report presents a magnetic anomaly map and a Bouguer gravity anomaly map (Fig. 1 and 2, in pocket) for the region of the Gulf of St. Lawrence east of the Magdalen Islands. These maps supplement free air gravity anomaly and total magnetic field maps, at the same scale and projection, published in the Natural Resource Map series of the Canadian Hydrographic Service (1972). A detailed discussion of the interpretation of these gravity and magnetic data in conjunction with other geophysical and geological information was presented by Watts (1972). The purpose of this report is to present the new maps, provide information on the accuracy of the data, and summarize the results of Watts (1972).

GEOPHYSICAL DATA

The geophysical data used in the preparation of Fig. 1 and 2 were obtained mainly during the Canadian Hydrographic surveys in the eastern portion of the Gulf of St. Lawrence during 1968 and 1969. The ship's tracks in the survey area are shown in Fig. 3. The ship was positioned by Low Ambiguity Decca in the range–range mode, which gives a 95% confidence in position to better than 200 m in the survey area.

[1] Bedford Institute Contribution No. 424.

[2] Present address: Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y. 10964, USA.

The magnetic field data were collected with a proton precession magnetometer towed approximately 200 m astern of the ship, and were recorded digitally at 6-s intervals. The data were edited to remove spurious values, and the remaining data were averaged to provide discrete total magnetic field values at 1-min intervals. These were then referred to the International Geomagnetic Reference Field (Cain and Cain 1968) to give the magnetic anomalies used in preparation of the contour map (Fig. 1). An analysis of 363 intersections of ship's tracks indicates an RMS error of 20 gamma (Fig. 4). The main source of error is the diurnal variation of the magnetic field. The variations monitored at Bedford Institute were applied to the marine magnetic data without phase or amplitude change. The residual diurnal correction presumably contributes significantly to the total error since the contribution through errors in navigation will be small because of the low magnetic field gradients in the study area.

The gravity data were collected with a Graf-Askania Gss-2 surface-ship gravimeter mounted on an Anschutz gyro-stabilized platform. The platform utilized during most of the survey incorporated an "oil erection" system as a vertical reference. The survey data were tied to the Canadian gravity network by connections to one of the harbor gravity base stations at Bedford Institute, Sydney, or Cornerbrook every 3 wk. Details of those base calibrations and the instrumental drift between base ties are given in Table 1 (Canadian Hydrographic Service 1972). The gravity data

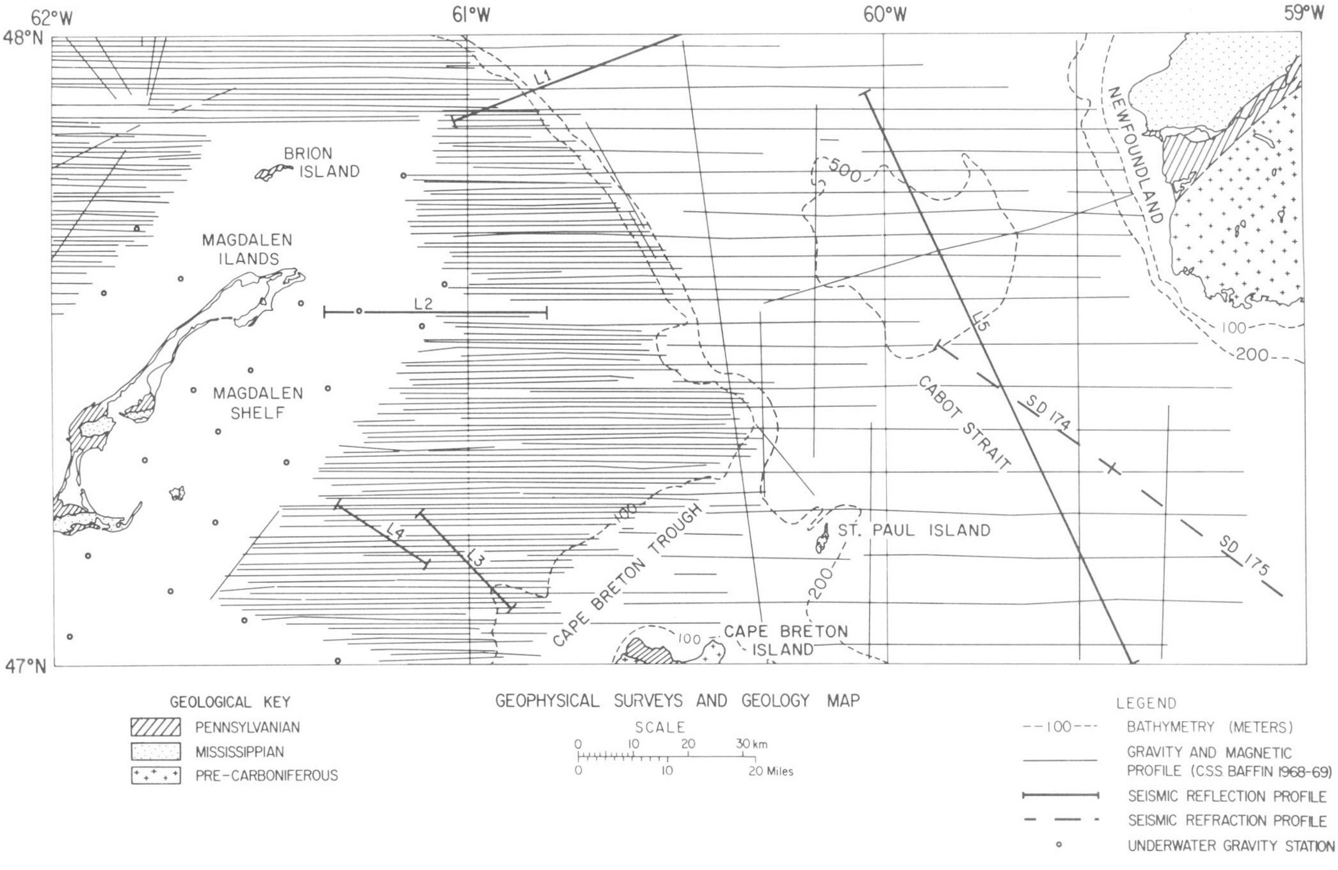

FIG. 3. — Geophysical surveys and geology map of study area. Seismic refraction profiles from Sheridan and Drake (1968); seismic reflection profiles L1 and L5 from Loring (1973) and L2, L3, and L4 from Loring (unpublished profiles); underwater gravity stations from Goodacre et al. (1969); geology based on Sanschagrin (1964), Baird and Coté (1964), Phinney (1963), and Bell (1944).

were recorded digitally at 1-min intervals and processed to remove the effects of the long period damping of the sea gravimeter (Haworth and Loncarevic 1974).

Analysis of 202 intersections of ship's tracks indicates an RMS error of 3.1 mgal (Fig. 4). Less than about 10% of the discrepancies were greater than 5.5 mgal.

The main sources of error in the gravity measurements were attributed to horizontal and vertical accelerations acting on the ship and to uncertainties in the Eötvös correction due to irregularities in the ship's track.

The gravity data were reduced to Bouguer anomalies using an infinite slab correction and an assumed crustal density of 2.67 g/cm^3. A Bouguer anomaly map of the study area contoured at 5-mgal intervals is presented as Fig. 2 (in pocket).

MAGNETIC ANOMALY MAP (FIG. 1)

The Magdalen Shelf north and east of the Magdalen Islands is associated with positive magnetic anomalies (Regions N and M, Fig. 5). The positive anomaly N, north of the Magdalen Islands, trends approximately northwest–southeast and reaches a maximum amplitude of about 160 gamma. The positive anomaly M, east of the islands, trends northeast–southwest and reaches a maximum amplitude of about 120 gamma. We call anomaly M the East Magdalen magnetic "high." A smaller negative region with similar trend and reaching a minimum of about -110 gamma occurs northwest of anomaly M.

A broad belt of positive anomalies extends between Cape Breton Island and southwest Newfoundland (Region P, Fig. 5). The positive anomalies are generally short-wavelength and locally reach maximum amplitudes of up to 600 gamma.

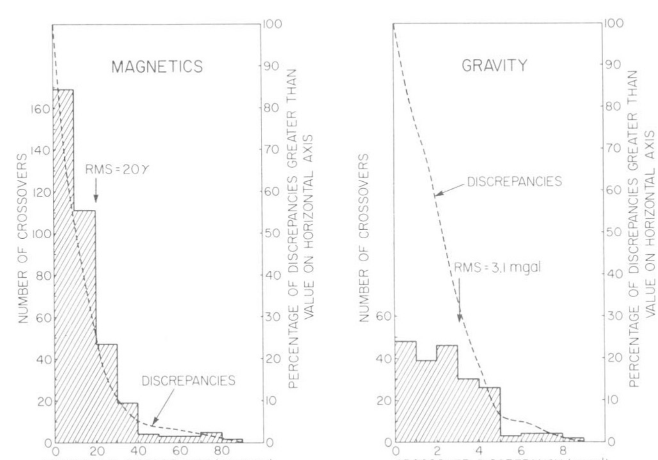

FIG. 4. — Crossover analysis of magnetic anomaly and gravity anomaly data in the study area.

A broad belt of negative magnetic anomalies extends between the Magdalen Shelf and southwest Newfoundland (Region A, Fig. 5). The negative anomalies trend generally northeast–southwest and reach minimum values of about −200 gamma. There is no indication that these anomalies are interrupted between the Magdalen Shelf and Cabot Strait. The minimum negative anomalies correlate with the deepest part of Cabot Strait.

The magnetic anomaly patterns outlined in the study area have also been outlined in aeromagnetic maps published by the Geological Survey of Canada.

BOUGUER ANOMALY MAP (FIG. 2)

The most striking feature of the Bouguer anomaly map of the study area is a belt of generally negative anomalies between the Magdalen Islands and southwest Newfoundland (Region A, Fig. 6). The negative anomalies were first outlined from measurements using underwater gravimeters by Goodacre and Nyland (1966). Detailed surface-ship measurements have outlined the negative anomalies in more detail. The negative anomalies reach a minimum of about −60 mgal near the center of Cabot Strait and are bounded by steep marginal gradients of up to 11 mgal/km. The steepest gradients occur on the northwest, southeast, and southwest margins of the main negative anomaly. A relatively gentle gradient occurs between the center of the negative anomaly belt and the coast of Newfoundland. We call this region of negative anomalies the Cabot Strait gravity "low."

Surface-ship measurements have shown that southwest of the Cabot Strait gravity low is a region of circular and elongate negative anomalies (Regions C to I, Fig. 6). The negative anomalies reach a minimum of −44 mgal (Region D, Fig. 6) and are bounded by steep gradients of up to 5 mgal/km. We call these circular and elongate negative anomalies the East Magdalen gravity lows.

The belt of negative anomalies is bordered by a broad belt of positive anomalies (Regions J and K, Fig. 6) north of the Magdalen Islands and between Cape Breton Island and southwest Newfoundland. The positive anomalies reach maximum values of about 20 mgal.

TABLE 1. HARBOR GRAVITY STATIONS AND CONNECTIONS.

Harbor station			Base reference		
Location	g_h(*mgal*)	Connection (g_b–g_h)	Location	EPB** Station no.	g_b(*mgal*)
Bedford Institute Pier	980,578.76	—	Bedford Institute Pier	#9861–62	980,578.76
Cornerbrook CN Terminal	980,982.13	+0.46	Cornerbrook CN Terminal	#9201–64	980,982.59
Sydney Government Pier	980,737.68	+0.29	Sydney RCMP Pier Building	#9895–62	980,737.97

N.B.The values of gravity quoted above are those to which the data presented on Fig. 2 have been referred. Because of possible changes in the national reference system to which these stations are connected, these values should not be used as the basis for further surveys or instrument calibration without first verifying the values with the Earth Physics Branch** (Gravity Division), Department of Energy, Mines and Resources, Ottawa, from which the descriptions and gravity values of all gravity base reference stations may be obtained.

Harbor connection		Connection			Number of observations used in compilation	
Station	Date	Gyro erection system	Closure error (*mgal*)	Drift *mgal/day*		
Bedford Institute	27/6/68					
Sydney Pier	13/7/68	Electric	+3.11	+0.194	133	5.1%
Cornerbrook CN	4/8/68	Electric	−2.58	−0.118	122	1.4%
Bedford Institute	1/9/68					
Sydney Pier	27/9/68	Electric	+0.23	+0.007	125	1.4%
Cornerbrook CN	11/10/68	Electric	+0.30	+0.022	131	1.5%
Bedford Institute	27/5/69					
Sydney Pier	13/6/69	Oil	+1.20	+0.071	163	1.8%
Cornerbrook CN	5/7/69	Oil	−8.70	−0.395	4459	50.3%
Cornerbrook CN	15/7/69	Oil	+2.70	+0.263	1869	21.1%
Sydney Pier	25/7/69	Oil	+1.80	+0.187	1866	21.0%
					8868	100.0%

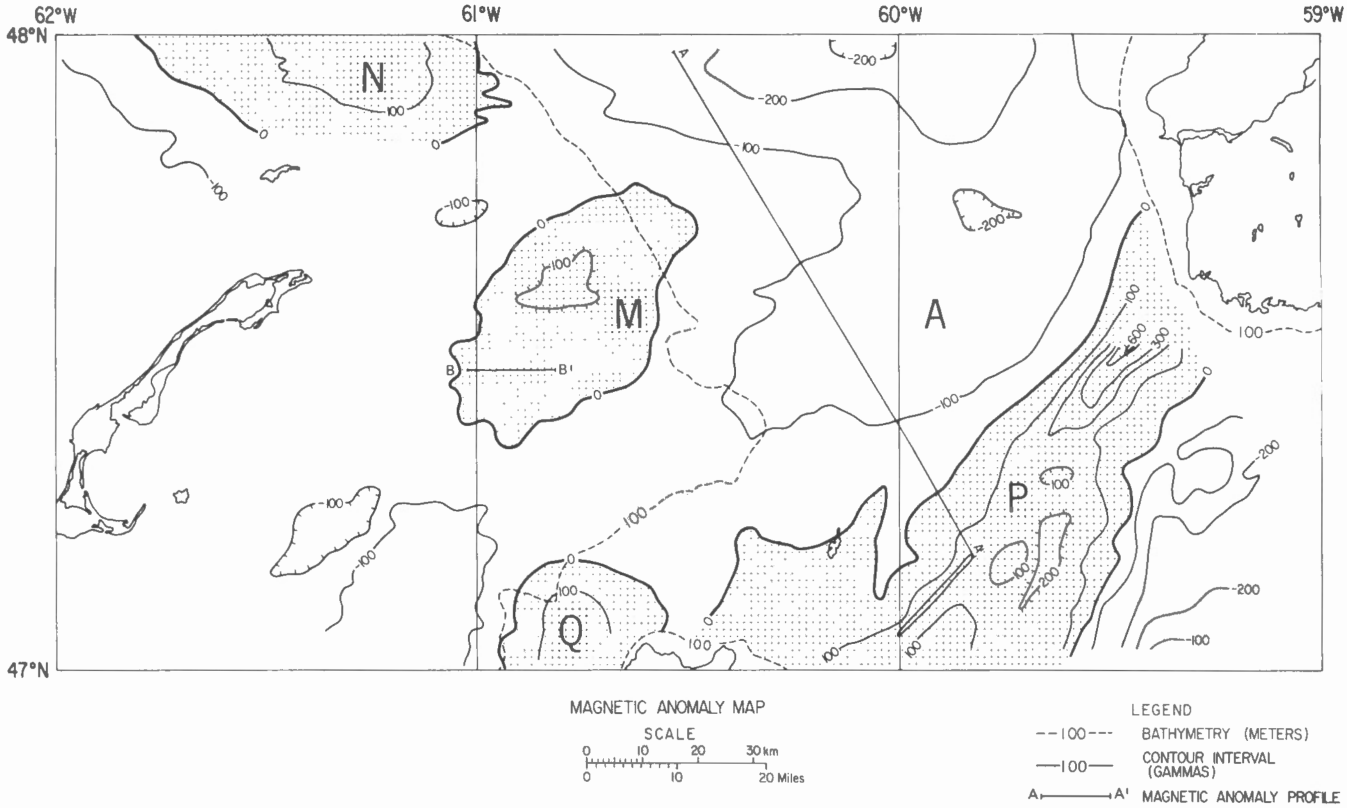

FIG. 5. — Summary magnetic anomaly map of the study area. Positive anomalies are stippled. Letters refer to regions referenced in the text.

GEOLOGICAL INTERPRETATION

Full details of the interpretation of the geological and geophysical data in this region will be found in Watts (1972). A summary of the interpretation of the major features is included here, followed by a synthesis of the structural elements.

The Cabot Strait gravity low (Region A, Fig. 6) represents one of the most extensive and largest amplitude negative Bouguer gravity anomalies identified offshore eastern Canada.

The clearest insight into the cause of the gravity low has come from seismic refraction measurements in the region. Sheridan and Drake (1968) and Hobson and Overton (1973) have used the seismic data to construct subsurface structure maps of the southern Gulf of St. Lawrence. These maps show a broad basin associated with seismic layer velocities of 1.7–4.0 km/s which exceeds 2 km in depth north and northeast of the Magdalen Islands. The maps also show a broad basin associated with seismic layer velocities of 4.5–5.6 km/s which exceeds 9 km in depth about 40 km east of the Magdalen Islands. There is general agreement (Sheridan and Drake 1968; Hobson and Overton 1973) that the sediments infilling these broad basins are Permo-Carboniferous or younger in age. There is a close correlation between the extent of these basins, collectively called the Magdalen Basin, and the Cabot Strait low.

Bouguer gravity anomaly and magnetic anomaly profiles AA′ across the Cabot Strait low are shown in Fig. 7. The approximate position of seismic refraction stations SD 174 and SD 175 (Sheridan and Drake 1968) are shown below the profiles. Profiles SD 174 and SD 175, located south of the low, show an upper 1–2 km thick layer with velocities 2.2–4.0 km/s. At Profile 175 the upper layer overlies the seismic basement with a velocity of about 6.5 km/s. At profile SD 174, however, the upper layer is separated from the seismic basement by a lower layer 2–4 km thick with a velocity of about 4.5 km/s. The Bouguer anomaly decreases by only about 20 mgal between profiles SD 175 and SD 174. Thus, the underlying low density mass contributing to the main part of the gravity low occurs north of profile SD 174. This suggests the low could be caused by either a thickening of the upper and/or lower layer north of profile 174 or an increase in depth to the seismic basement north of profile SD 174. Alternatively, the low could be caused by lateral density changes in these layers or in the seismic basement. There are two observations which limit the possibilities. First, seismic refraction data show that the upper layer, which has been interpreted as Pennsylvanian and younger in age, does not appear to exceed 2.5 km in thickness in the Gulf of St. Lawrence (Hobson and Overton 1973). However, at East Point, Prince Edward Island, a bore hole has encountered 3.5 km of Pennsylvanian sediments (R. D. Howie personal communication). Even so, computations using acceptable density contrasts between the Pennsylvanian and younger layer and the underlying layers suggest that a thickness of about 7 km would be required to fully explain the low. Second, the steepness of the boundary gradients of

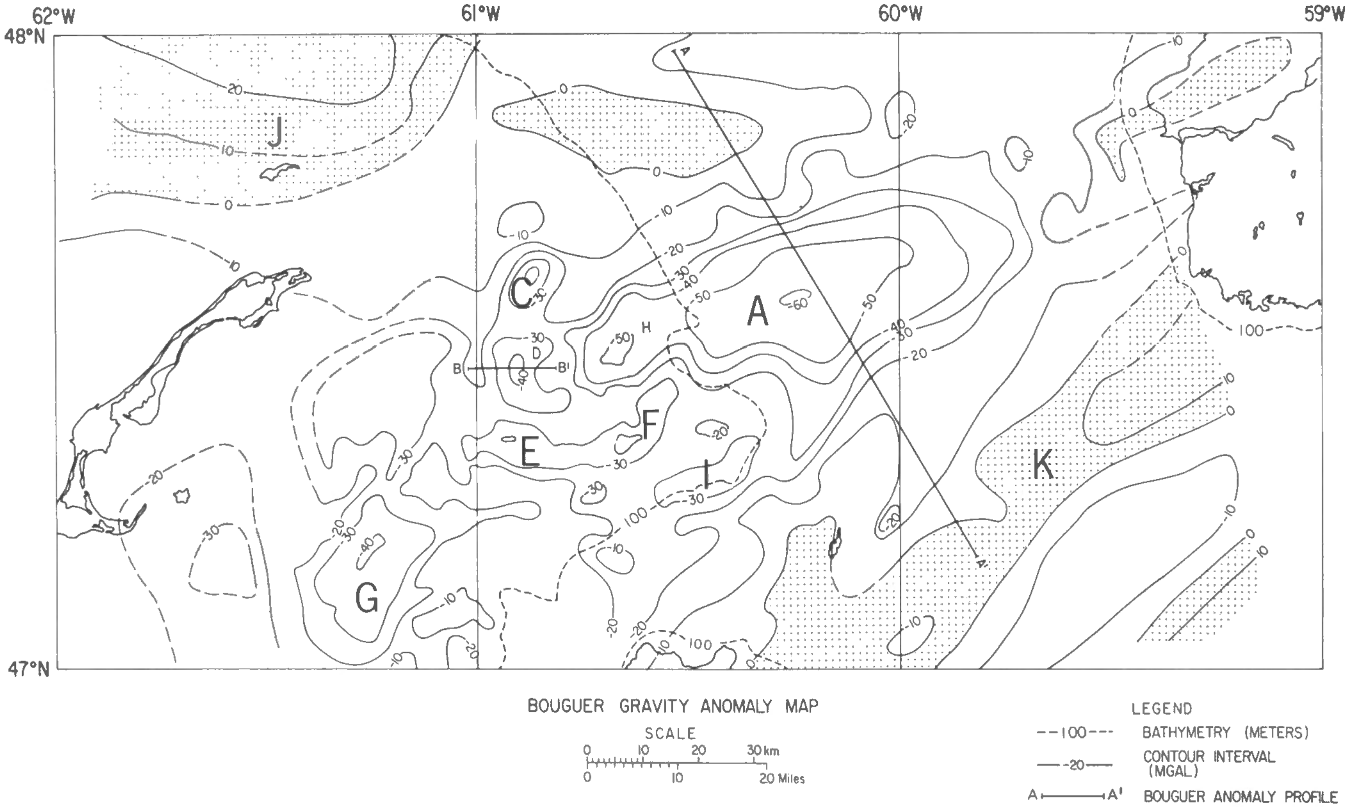

FIG. 6. — Summary Bouguer gravity anomaly map of the study area. Positive anomalies are stippled. Underwater gravity data (Goodacre et al. 1969) were used to extend the contours of Fig. 2 inshore. Letters refer to regions referenced in the text.

the Cabot Strait low requires that the causative body be relatively shallow. If the upper layer does not change significantly in thickness north of profile 174, then the upper surface of the causative body must be located at shallow depths beneath it.

The geological interpretation of profile AA′ that is shown in Fig. 7 assumes two-dimensionality and an upper layer with average density of 2.45 g/cm³ which does not change significantly in thickness north of profile SD 174. The main contribution to the low arises from an underlying layer about 4 km thick with an average uniform density of 2.2 g/cm³. A smaller contribution arises from an increase in depth by about 2 km in an underlying basement layer with an average uniform density of 2.75 g/cm³. Thus the Cabot Strait low is interpreted as caused mainly by a northward lateral change in density of the lower layer at profile SD 174. Computations show that for an upper layer about 2 km thick a uniform density contrast of at least about −0.45 g/cm³ is required to explain the low.

Goodacre and Nyland (1966) and Watts (1972) have interpreted the low density sediments causing the main part of the Cabot Strait low as Late Mississippian in age. In particular, they have correlated the low density rocks with evaporites. In New Brunswick, Nova Scotia, and the Magdalen Islands evaporites occur in the Windsor Group of Upper Mississippian age (Gussow 1953; Bell 1944). The density of the lower layer used in the interpretation of profile AA′ is similar to measured rock densities from evaporites in Nova Scotia (Miller 1940).

The main part of the Cabot Strait gravity low between the Magdalen Islands and southwest Newfoundland correlates with a broad region of negative magnetic anomalies (Region A, Fig. 5 and 6). The quantitative interpretation of the magnetic low is complicated because of a lack of constraints on the configuration and magnetic properties of the causative body. In the interpretation shown in Fig. 7 the low is assumed to be caused only by changes in relief of a two-dimensional uniformly magnetized basement. The total magnetization is assumed to be 0.0013 emu/cm³ and to be oriented in the direction of the present earth's field. The assumptions of magnetic rock properties used in the computations generally agree with values obtained from pre-Carboniferous metasediments, granites, plutonic and volcanic rocks in New Brunswick and Nova Scotia (McGrath et al. 1973). These rocks have susceptibilities as high as 0.01 emu/cm³ and small Königsberger ratios. In the model the depth to the interpreted basement increases from about 2 km in the vicinity of seismic refraction profile SD 175 to about 12 km in the vicinity of the low density sediments that cause the main part of the gravity low. North of the interpreted region of low density sediments the magnetic basement shallows to about 10 km depth. The magnetic basement in this region may be a northeastern extension of the shallow basement ridge interpreted by Watts (1972) east of the Magdalen Islands.

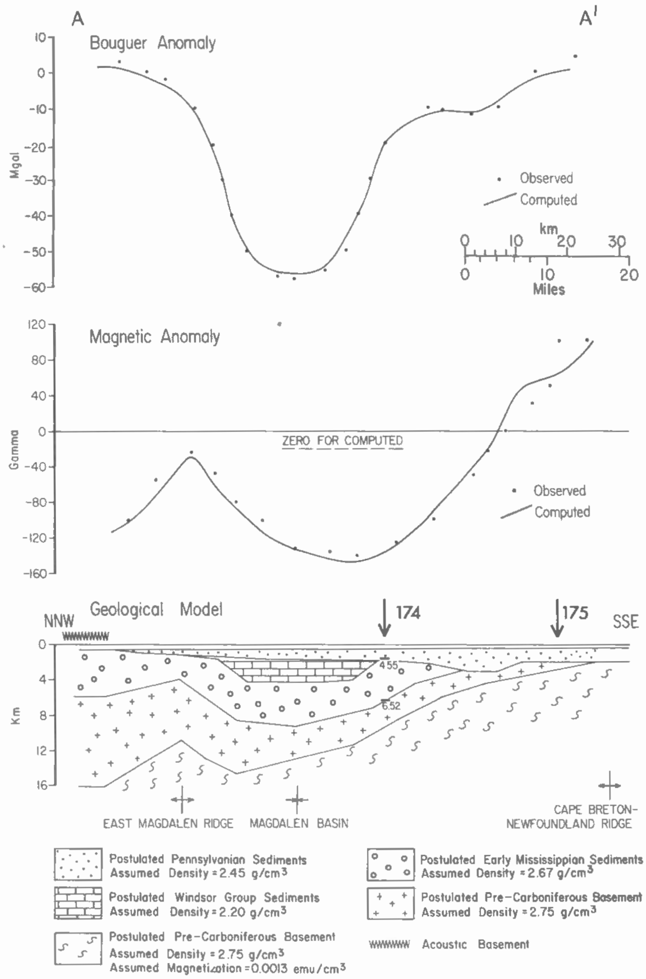

FIG. 7. — Geological interpretation of Bouguer anomaly and magnetic anomaly profile AA′ (Fig. 5 and 6) of Cabot Strait. The computed gravity and magnetic effects of the model have been determined for the assumed density and magnetization distribution shown. The magnetization of the pre-Carboniferous basement is assumed aligned to the direction of the present earth's field. The acoustic basement is indicated where it has been identified on adjacent seismic reflection profile L5 (Fig. 3).

The interpreted magnetic basement in the geological model of Fig. 7 is somewhat deeper than the seismic basement with velocities greater than 5.6 km/s. The difference is about 2 km at profile 175. This suggests that relatively dense, but weakly magnetic rocks, such as Early Mississippian and/or pre-Carboniferous sediments may infill the basin.

A striking feature of the southwest part of the Cabot Strait gravity low in the vicinity of the Magdalen Shelf is the number of circular and elongate gravity lows (C to I, Fig. 6).

A gravity anomaly profile across one of the circular lows (Region D, Fig. 6) is shown in Fig. 8. Computations show that the low can be explained to better than 2 mgal by a steep outward-sloping body with a flat upper surface. For an assumed upper surface of the body at the sea bottom a 3 km thick body is required for an assumed uniform density contrast of -0.25 g/cm^3 or about 2 km for -0.30 g/cm^3.

The computations clearly indicate that the cause of the circular lows must be relatively shallow, suggesting from geological and geophysical evidence on the Magdalen Islands and the Magdalen Shelf (Loring et al. 1969; Hobson and Overton 1973) that the cause of the lows is confined to the upper part of a thick sequence of Permo-Carboniferous sediments.

The most satisfactory interpretation of the outward-sloping bodies is that they are low density salt structures. In southeastern New Brunswick, northern Nova Scotia, and the Magdalen Islands salt occurs as part of an evaporite sequence in the Windsor Group (Gussow 1953; Bell 1944; Sanschagrin 1964). Detailed gravity surveys in Nova Scotia (K. Howells personal communication) show that some of the evaporite structures are characterized by small amplitude gravity lows. Recent studies (Webb 1973; Keen 1970; King and MacLean 1970) suggest evaporite structures may also occur in offshore regions of eastern Canada. Salt has been

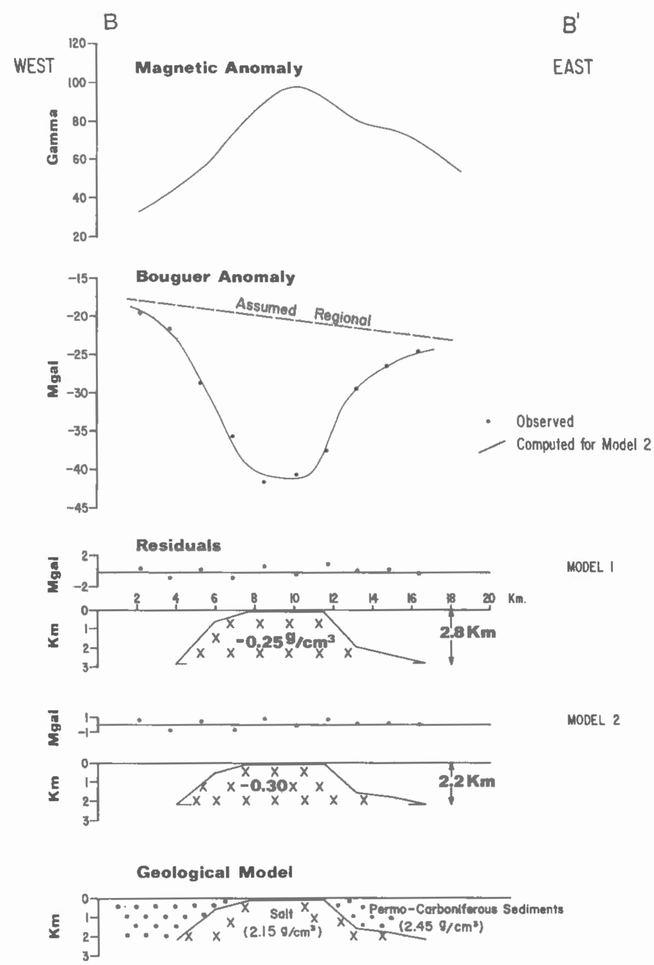

FIG. 8. — Geological interpretation of Bouguer anomaly profile BB′ (Fig. 5). The geological model has been deduced for the regional field shown. A uniform density contrast of -0.30 g/cm^3 is assumed between salt and Permo-Carboniferous sediments. Note the steep outward slopes and flat upper surfaces of the models.

drilled on the Grand Banks south of Newfoundland (Bartlett and Smith 1971) and in the study area east of the Magdalen Islands (Swift and Evans 1966).

The density of 2.15 g/cm^3 assumed for the salt in the model shown in Fig. 8 is in agreement with measured values from the Malagash area, Nova Scotia (Miller 1940). A uniform density of 2.40 g/cm^3 has been assumed for Permo-Carboniferous sediments. This model, which fits the observed low to better than 2 mgal, suggests a thickness of 2 km for the salt.

STRUCTURAL ELEMENTS OF THE AREA

A summary map showing the main structural elements in the study area is presented in Fig. 9. The map shows the approximate extent of the Magdalen Basin, the Cape Breton–Newfoundland Ridge, and the East Magdalen Ridge, which are shown in section AA′ (Fig. 7). Additional control for this regional picture was provided by interpretation of section II′, which is described by Watts (1972).

The main structural elements of the study area compare closely to the regional geological structure of southwest Newfoundland. The Cape Breton–Newfoundland Ridge extends into a region of pre-Carboniferous basement rocks southeast of the Long Range Fault. The axis of the interpreted Magdalen Basin aligns with a broad syncline in Carboniferous sediments (Bell 1948) northwest of the fault. The extension of the East Magdalen Ridge northwest of the Magdalen Basin into southwest Newfoundland is less certain. The ridge aligns approximately with the trend of the Anguille and Barachois anticline (Bell 1948) in Carboniferous sediments northwest of the fault. However, it is possible the ridge may not be continuous in the region between profile AA′ and the coast of southwest Newfoundland.

The general continuity of the structural elements of the study area with southwest Newfoundland is good evidence that Cabot Strait is itself not structurally controlled. Rather, the processes forming the strait have apparently transected the general trend of post-Devonian structural elements underlying the southern Gulf of St. Lawrence.

RESOURCES AND FUTURE WORK

The marine geophysical data presented cannot be used to assess the resources of the study area with any certainty. However, even within the limitations of the interpretation, there are two important implications.

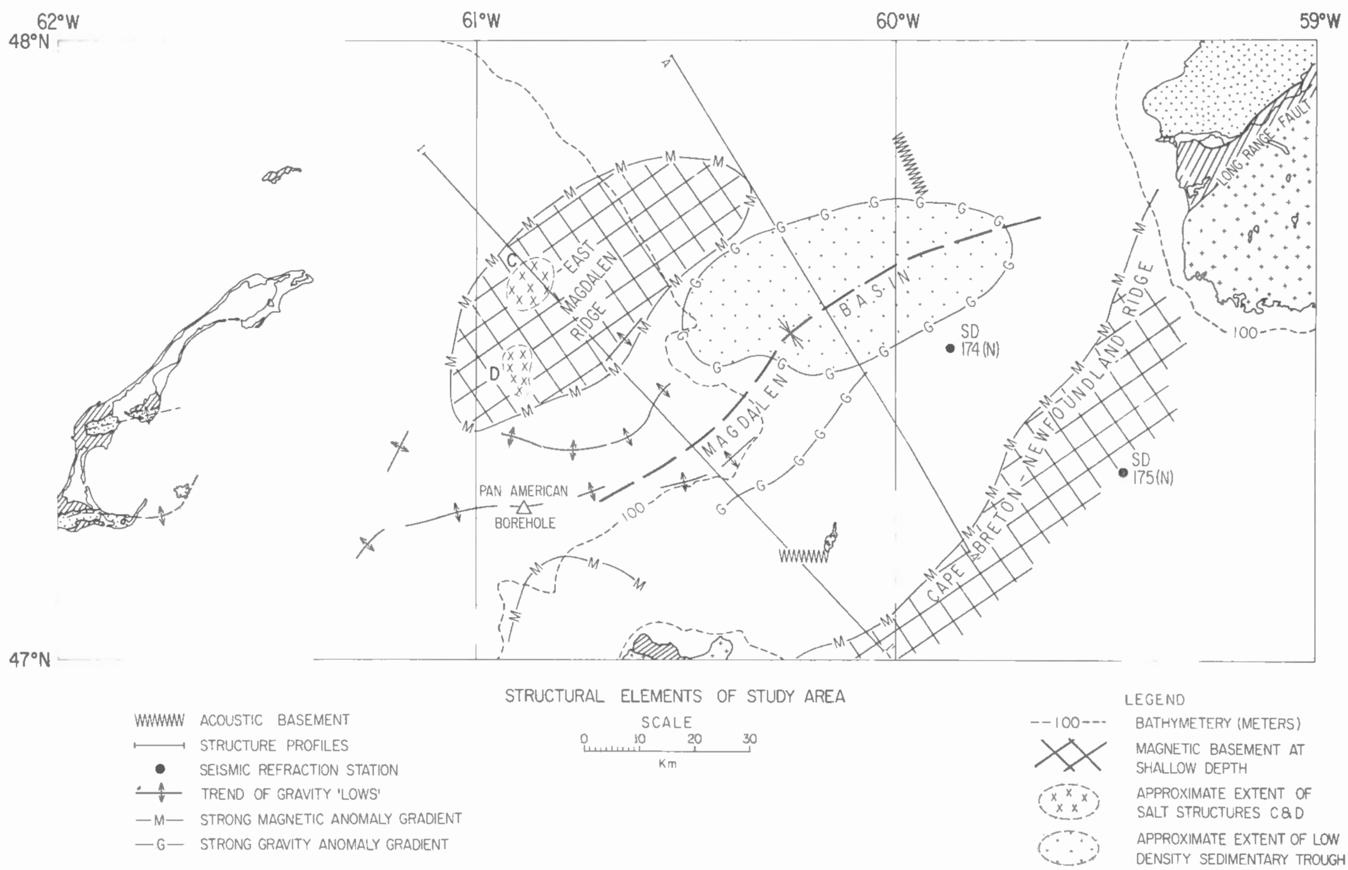

FIG. 9. — Structural elements of the study area. An interpreted geological section (Profile AA′) of Cabot Strait is shown in Fig. 7. Geological key is based on Fig. 3. The approximate trends of anticlinal structures in the Magdalen Islands (Sanschagrin 1964) are shown as light broken lines and the interpreted synclinal axis of the Magdalen Basin is shown as heavy broken lines. The position of the Pan American core hole mentioned in the text which drilled salt at a depth of 0.27 km (Swift and Evans 1966) is shown as an open triangle.

First, there is the possibility that the central part of the Magdalen Basin may be underlain by Early Carboniferous sediments. This is suggested by the substantial differences in depth estimates between the base of the low density (? Late Mississippian) sediments and the strongly magnetic (? pre-Carboniferous) basement. Early Carboniferous sediments, which include the Horton Group, have been well studied in southeastern New Brunswick and northern Nova Scotia for sources of petroleum (Gussow 1953; Bell 1958). The occurrence of folded Horton Group and Windsor Group sediments overlain by a post-Windsor Group sediment cover is regarded a good petroleum possibility in land areas (Bell 1958). Similar geological sections may occur at the margin of the Magdalen Basin.

Second, there is the presence of an extensive evaporite field east of the Magdalen Islands. Two types of evaporite structures have been postulated (Watts 1972). These are (1) piercement-type evaporite structures characterized by large amplitude, circular gravity lows and (2) evaporite structures in the crests of Mississippian/Pennsylvanian anticlines characterized by small amplitude, elongate gravity lows. There is no direct evidence indicating which of these types of evaporites underlines the sea area. However, the large density contrasts required to explain the circular gravity lows suggest salt may form a major part of these structures. The salt structures themselves may be useful on their own account for oil and gas storage after the salt has been extracted. However, their presence in the vicinity of potential petroleum source rocks in the Magdalen Basin makes them likely sites for petroleum accumulation.

Clearly, further detailed work is required to examine more carefully these possibilities. Future work could include (1) more detailed surveys at edges of the Magdalen Basin and (2) more detailed seismic surveys of the evaporite field east of the Magdalen Islands.

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