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Gravity Measurements Over the
Cumberland Basin, N.S.

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Gravity Measurements over the Cumberland Basin, Nova Scotia

By G. D. GARLAND*

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INTRODUCTION

ALTHOUGH the presence of rock salt in the Carboniferous basin of northern Nova Scotia has been known for at least one hundred and twenty years, and salt has been mined at Malagash continuously since 1919, certain characteristics of the deposits make exploration by drilling or surface examination difficult. The surface rocks of the basin are, in general, of Pennsylvanian age, while the salt occurs in the Mississippian Windsor group. The latter rocks are brought to the surface only along anticlinal folds, or as irregular fault blocks. Because of the limited areal extent of these Windsor exposures, and their complicated internal structure, geophysical surveys, especially gravimetric, can be of considerable aid in outlining the more favourable areas.

The present paper describes the results of recent investigations by the Dominion Observatory, in co-operation with the Nova Scotia Department of Mines. It includes a regional study of that section of the Cumberland basin lying between Springhill and Malagash (Figure 1), and a much more detailed survey of the immediate vicinity of the Malagash deposit itself. This deposit had been studied by Miller (6, 7) with the torsion balance nearly twenty years before, and a direct comparison between the results given by the two types of instruments is therefore possible.

GEOLOGY OF THE AREA

The region to be studied forms part of the extensive Cumberland basin of Carboniferous deposition. It is well covered by the one mile to the inch map series of the Geological Survey of Canada, and is described fully by Bell (1) and Norman (8). This outline, which is drawn largely from publications of

TABLE OF FORMATIONS

PENNSYLVANIAN	Pictou Series	Sandstone, shale, conglomerate
	Cumberland Series	Sandstone, conglomerate, shale
	Riversdale Series	Boss Point formation: sandstone, shale. Claremont formation: conglomerate, sandstone, shale.
MISSISSIPPIAN	Middleborough form'n	Sandstone, shale
	Windsor group	Shale, sandstone, gypsum, limestone, salt
PRE-CARBONIFEROUS		Complex of sedimentary and volcanic rocks intruded by granite, etc.

the Geological Survey, is intended only to present the general nature of the formations and the structural relationships that are to be dealt with in the interpretations of the gravity anomalies.

The Cumberland basin lies between the exposed pre-Carboniferous ridge that forms the Cobequid mountains to the south, and the concealed extension, inferred from previous gravity observations (3),

of the Caledonian mountains to the north. The general sequence of rocks in the area, with the lithological nature of each series or formation, is given in the accompanying Table.

The thicknesses of the various series are rather variable over the area, but the total thickness of the Pennsylvanian strata alone is several thousands of feet. The Middleborough formation, which lies immediately above the Windsor group,

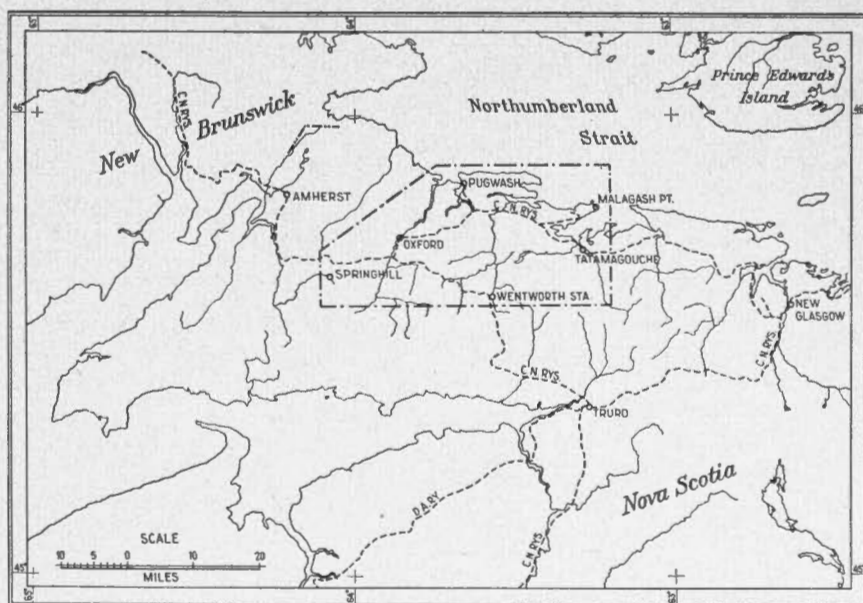


Figure 1.—Outline of the area of northern Nova Scotia covered by the regional gravity survey.

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GRAVITY ANOMALIES AND GENERAL GEOLOGY SPRINGHILL-MALAGASH AREA, NOVA SCOTIA.

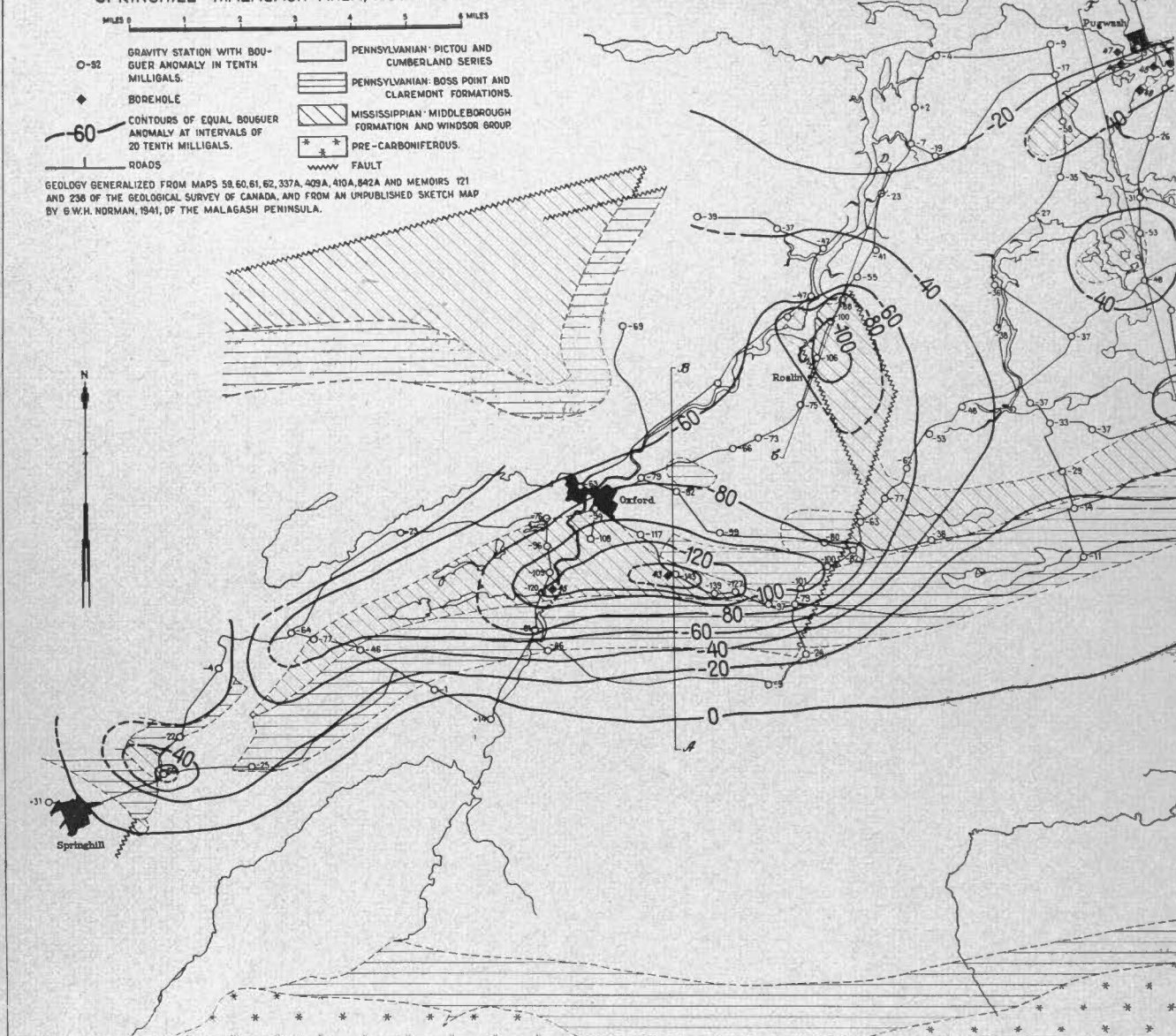


Figure 2.—Bouguer gravity anomalies and generalized geology of a portion of the Cumberland basin.

ranges in thickness from a few hundred to about three thousand feet.

A generalized section of the Windsor group itself in the area is given by Bell (1), as follows:

Red sandstone, siltstone, etc..	400 ft.
Calcareous member:	
limestone, etc.....	125 ft.
Red shale, mudstone, etc.....	800 ft.
Gypsum-anhydrite-salt member.....	500+ft.

The lowest member of the group offers little resistance to erosion, and where it has been brought to the surface the actual rock exposures are characteristically poor. Very often, its presence can only

be inferred from topographical features, such as 'sinks' and ponds, produced by solution. Where the structure of the Windsor areas can be deduced, the strata are in general found to be steeply dipping and highly contorted.

Overlying formations up to and including the Boss Point appear to have been deformed by major forces acting before the deposition of the Pictou series. Thus, although the Windsor exposures lie along the axes of anticlinal folds in this series, the dips of the Pictou strata are much more regular and gentle than those of the pre-Pictou rocks.

The actual contact relationships

between the Windsor group and younger rocks are quite varied among the different exposures. At places along the Claremont anticline, which extends from near Springhill to Malagash point (Figure 2), the Windsor beds are found to lie conformably beneath the Middleborough formation. More often, however, the areas of Windsor rocks are in fault contact with rocks as young as the Pictou series. In the case of the exposure south of Pugwash, the Windsor group is apparently bounded on all sides by overlap of the Pictou strata, and the relationships with formations older than the Pictou are not known.

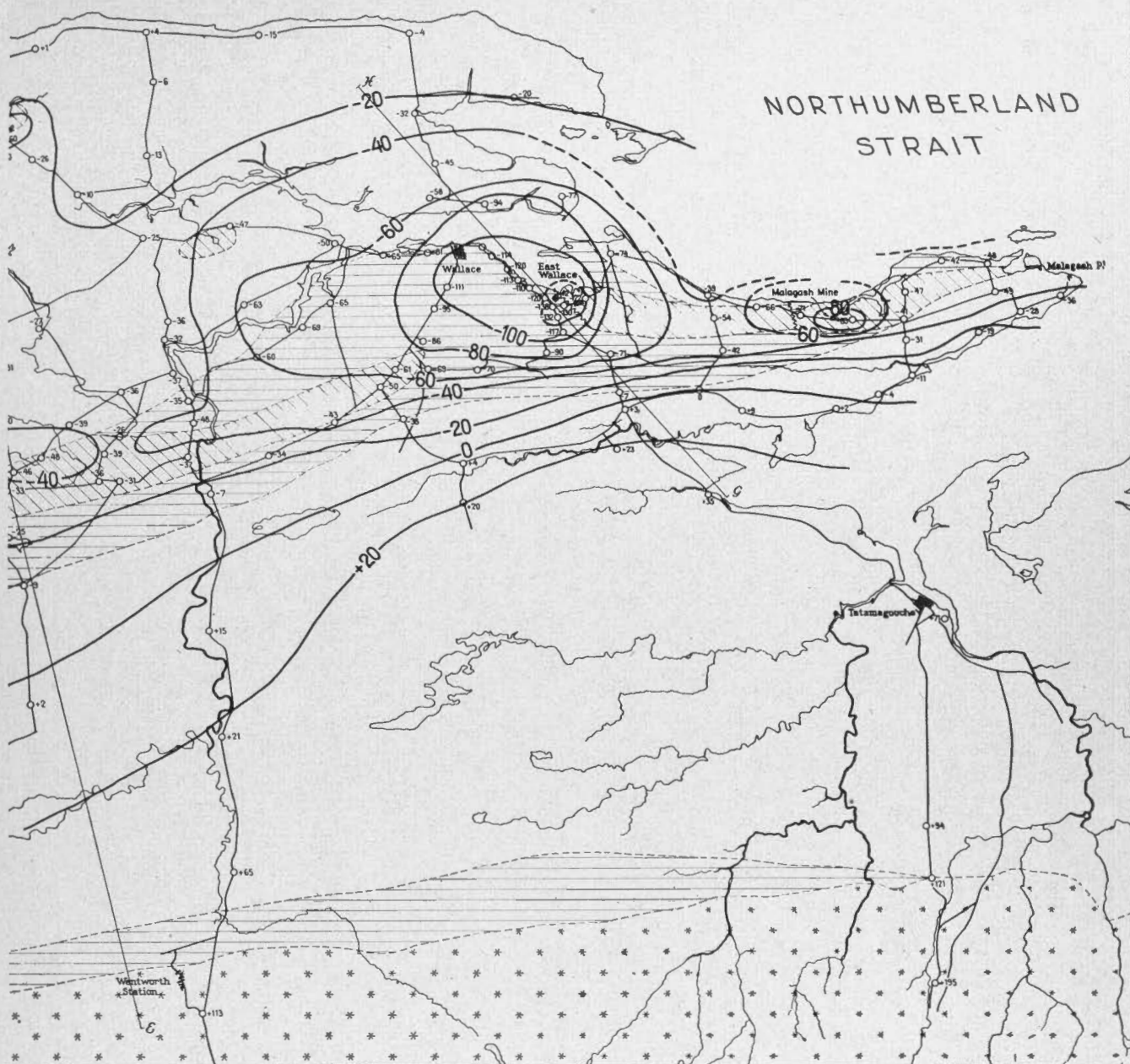


Figure 2. (For caption, see page opposite)

For the interpretation of the gravity anomalies, a knowledge of the densities of the rocks involved is of prime importance. The data available, which include values measured by Miller (6) and by the writer, are summarized in Table I.

Although the range in density between lithological units of a formation may appear to be greater than the difference between formations, certain generalities may be noted. The Boss Point formation, which is fairly thick (2,000 to 4,000 feet) throughout the area, is on the whole probably less dense than the overlying Pictou series. The Windsor group on the average is less dense than the majority of the younger

formations, as the dense limestone member it contains is quite thin. It is apparent that local concentrations of gypsum, and especially of salt, will largely control the exact density of the Windsor. These relationships suggest that the gravity observations may be applied to the problem of outlining the various Windsor exposures, and, on a more detailed scale, to the detection of salt concentrations within these areas.

THE OBSERVATIONS

Quite different field procedures were employed on the regional and detailed surveys. For the former,

stations were spaced at intervals of about half a mile along the available roads through the area. The gravity readings were taken with a North American instrument, whose scale constant was 0.2315 milligals per division. All observations were made relative to bases at Tatamagouche, Pugwash, or Oxford, which were in turn connected to a previously established main base at Amherst (3). The elevations of the majority of the stations were obtained by readings with two aneroid barometers. As control points in the form of bench marks and map elevations were plentiful throughout the area, the station elevations are probably reliable to about five feet,

TABLE I.—DENSITIES OF CARBONIFEROUS ROCKS OF THE CUMBERLAND BASIN

ROCK TYPE	DENSITY Gm. per cc.	OBSERVER
PICTOU:		
Sandstone.....	2.48	G.D.G.
Sandstone.....	2.45	A.H.M.
Conglomerate..	2.36	A.H.M.
BOSS POINT:		
Sandstone.....	2.35	G.D.G.
Sandstone.....	2.33	A.H.M.
Red shale.....	2.56	A.H.M.
CLAREMONT:		
Conglomerate..	2.42	G.D.G.
MIDDLEBOROUGH:		
Shale.....	2.44	G.D.G.
Sandstone.....	2.47	G.D.G.
WINDSOR:		
Red shale.....	2.42	G.D.G.
Red shale.....	2.50	A.H.M.
Yellow shale..	2.17-2.30	A.H.M.
Anhydrite.....		G.D.G.
Gypsum.....	2.3	(Smithsonian Tables)
Salt.....	2.16	A.H.M.
Limestone.....	2.69	G.D.H.

and the error from this cause in the Bouguer 'anomalies' is about 0.5 milligals (*i.e.*, 5 parts in the last figure of the quantities plotted on the map, Figure 3). In computing these anomalies, a density of 2.67 was adopted for the rocks above sea-level, so that the values would be directly comparable to those on the gravity map of the Maritime Provinces (3). It is apparent that this density is rather high for the particular region, but very few of the stations are as much as 200 feet above sea-level, and the resulting uncertainty for these highest stations is not greater than 0.5 milligals. The Bouguer anomalies are plotted on the map in units of 0.1 milligal (0.0001 cm. per sec.²), and are contoured at intervals of twenty of these units.

In the case of the detailed survey of the Malagash area, a rectangular grid of 300 feet was used (Figure 3). Gravity observations were taken with a Worden gravimeter, scale

constant 0.1114 milligals per division. The observations were made on short loops out from base stations distributed along the main east-west road. They are believed, on the basis of repeat observations at certain stations, to be accurate to about 0.02 milligals. Elevations for all stations were obtained by spirit levelling with a Zeiss auto-level. The mean closure error on levelling circuits was about 0.05 foot. The Bouguer anomalies were computed for a density of the surface material of 2.0 grams per cubic centimeter. This figure was adopted as a mean between the soil density of 1.7 and the rock densities of 2.3 to 2.4. The land surface is fairly level over much of the area, except for minor undulations in the glacial drift. Toward the southern limit of the survey, however, it rises gradually to about 150 feet above the sea. Since a rise in the bed-rock surface is assumed beneath this higher ground, a density intermediate between that of rock and soil was adopted.

The topography, as mentioned above, is flat or gently rolling over most of the area. However, the western section of the coastline is in the form of an almost vertical cliff, rising forty to fifty feet above the sea. Terrain corrections were applied to stations in the vicinity of this feature by calculating the effect, at various distances, of a vertical, 50-foot scarp of infinite strike length. These corrections became quite negligible at a distance of 200 feet from the cliff, and only at about ten stations did the corrections significantly change the contouring. This method of treating terrain features was suggested by Hubbert (6). The final Bouguer anomalies are plotted on the map in units of 0.01 milligal (0.00001 cm. per sec.²), and are contoured at intervals of twenty of these units.

DISCUSSION OF THE RESULT OF THE REGIONAL STUDY

The accompanying map (Figure 2) indicates that the Bouguer ano-

malies range from +113 units at the extreme south of the area to -143 in the vicinity of Oxford. The positive values along the southern border are due to the dense pre-Carboniferous rocks of the Cobequid complex. There is a fairly rapid decrease in anomaly near the edge of the Carboniferous basin, but from a few miles north of the basin edge to the shores of Northumberland Strait any effect of the pre-Carboniferous basement rocks must be very small and slowly varying in comparison with the sharper effects of near-surface density variations. The most striking feature of this region is the series of negative anomalies along the axis of the Claremont anticline and over the Windsor exposures near Roslin and Pugwash. This correlation of negative anomalies with the uplifted areas confirms the hypothesis that the Windsor and possibly other pre-Pictou formations are less dense than the overlying Pictou series.

The different Windsor areas will now be examined in detail, in order to suggest what may be deduced from the gravity field regarding the structural relations and internal composition of these areas.

Oxford Area

The largest single exposure of Windsor strata within the region studied is that which occupies the axial portion of the Claremont anticline from near Springhill to the transverse fault about five miles east of Oxford. Traverses across the western section of the area indicate a rather broad area of lower anomaly, conforming to the boundaries of the Windsor series with the overlying, denser formations. East of Oxford, however, there is a narrower, more intense negative anomaly, suggestive of a concentration of low-density material within the Windsor rocks. The nature of the anomaly, as indicated by the profile along the line AB, Figure 4, suggests that the effect of a local, near-

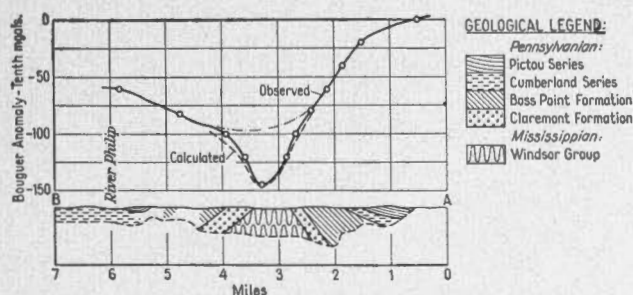


Figure 4.—Gravity anomaly profile and geological section along the line AB, Figure 2. (Regional survey)

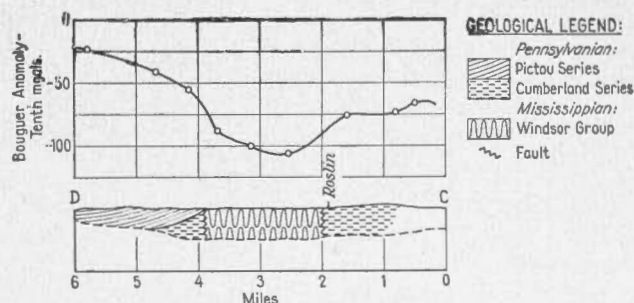


Figure 5.—Gravity anomaly profile and geological section along the line CD, Figure 2. (Regional survey)

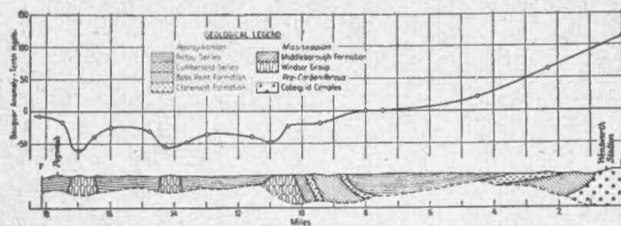


Figure 6.—Gravity anomaly profile and geological section along the line EF, Figure 2. (Regional survey)

surface structure is superimposed on the broader negative anomaly caused by the general anticlinal structure. For comparison, the illustration includes the calculated anomaly due to a shallow, horizontal cylinder, with a radius of 2,500 feet, and a density deficiency of 0.2 grams per cubic centimeter. One interpretation would be that a concentration of low-density material, including salt strata, could be present along the axis of the anticline between Phillip river and the fault mentioned above.

However, the results of recent drilling suggest that any body of commercial salt must be rather restricted in size. The log of borehole 43 (Figure 2) of the Malagash Salt Company indicated steeply dipping red clay or soft shale from the surface to a depth of about 250 feet. From there to about 380 feet, both red and green shale containing stringers and crystals of coloured salt, with a few bands of clear salt, were encountered. Below 380 feet, to the end of the hole at 412 feet, the salt content was found to decrease. Similar conditions were found in borehole 45 at the opposite side of the anomaly peak. These findings do not entirely rule out the possibility of there being a dome-like concentration of salt in the area between the drill holes.

The negative anomaly ends abruptly at the transverse fault east of Oxford, although Windsor or Middleborough rocks continue to occupy the axial region of the anticline. Only near Wallace river, some eight miles to the east, does a pronounced negative reappear over the anticline. It appears safe to conclude that the intervening area holds little promise of important near-surface salt accumulations.

Roslin Area

The block of Windsor rocks near Roslin forms an interesting structure, as it is apparently bounded on three sides by faults and on the fourth side by an overlap of Pictou strata (Bell 1944 and G.S.C. Map

842A). The Windsor group is highly distorted and steeply dipping, and is known to contain gypsum at several localities. Its gravitational effect is clearly seen on the anomaly map as a closed negative anomaly decreasing to about -100 units. An oblique profile across the block is shown in Figure 5. Although the negative anomaly is quite pronounced, it is less intense than that considered above, and it appears to result from the block as a whole, rather than from any concentration within it.

A more detailed network of stations over the area might give quite a different picture, but for the present no specific deposit can be pointed out. One interesting feature that may be seen from the anomaly map is the steep gradient northwest of the block, just inside the overlapping Pictou strata. This suggests that the contact between the Windsor group and younger pre-Pictou strata, presumably along a fourth fault, is not far northwest of the actual exposure.

Wentworth-Pugwash Profile

In Figure 6 is shown a profile extending from near Wentworth Station, on the pre-Carboniferous rocks, to the coast of Northumberland strait, near Pugwash. The profile indicates that, apart from the rise toward the southern edge of the basin, the anomaly level over areas of Pictou rocks is quite uniform. Three areas of Windsor strata produce negative anomalies, although none of these is very intense. However, it should be pointed out that the distribution of stations over the two northern areas is rather sparse, as they are difficult of access. The Windsor exposures near Pugwash are largely covered by an inlet of Northumberland strait, while the central area on the profile, known as the Canfield Creek area, is low-lying and traversed by few roads. In the three cases, the Windsor rocks are exposed on the axes of

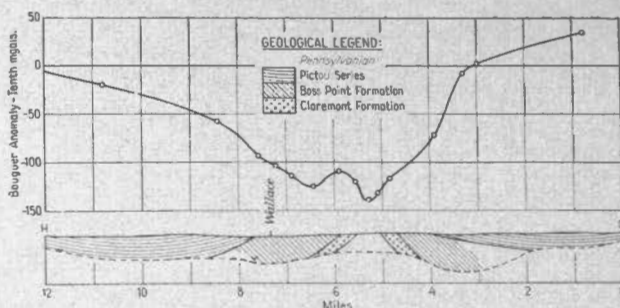


Figure 7.—Gravity anomaly profile and geological section along the line GH, Figure 2. (Regional survey)

anticlinal structures in the Pictou series, but the Mississippian formations are characteristically more severely folded than the Pictou.

On the basis of magnitude of anomaly only, none of the Windsor areas on this profile would appear as favourable as those near Oxford or East Wallace. However, this criterion alone is hardly satisfactory, as the most intense negative anomalies may indicate areas of extreme crumpling and piling up of the light Mississippian strata, in which bands of relatively pure salt cannot be satisfactorily traced. In any case, preliminary drilling of the more moderate anomaly near Pugwash suggests that it is underlain by a somewhat less distorted block of Windsor strata, containing definite salt horizons. Borehole 48 is apparently located near the axis of the structure, for it passed immediately into gypsum and anhydrite, intersecting salt between about 360 and 540 feet. The northern limit of the Windsor rocks is either a fault or a steeply dipping unconformity passing between boreholes 46 and 47. In the former hole, the salt was found at a depth of somewhat over 600 feet, while the total depth of the latter hole, almost one thousand feet, lay in Pictou strata. The steep nature of this northern boundary is indicated also by the gravity gradient over it.

Wallace Area

In the vicinity of East Wallace, the axis of the Claremont anticline changes rather abruptly from northeasterly to east-west. Here, also, the north limb of the anticline is more gently dipping, in contrast to the overturned north limb, which may be observed a few miles to the east, near Malagash. Over this section of the structure, which is evidenced on the map by the wide exposure of the Boss Point formation, there is a broad area of low gravity, extending roughly as far west as Wallace river. Superimposed on this

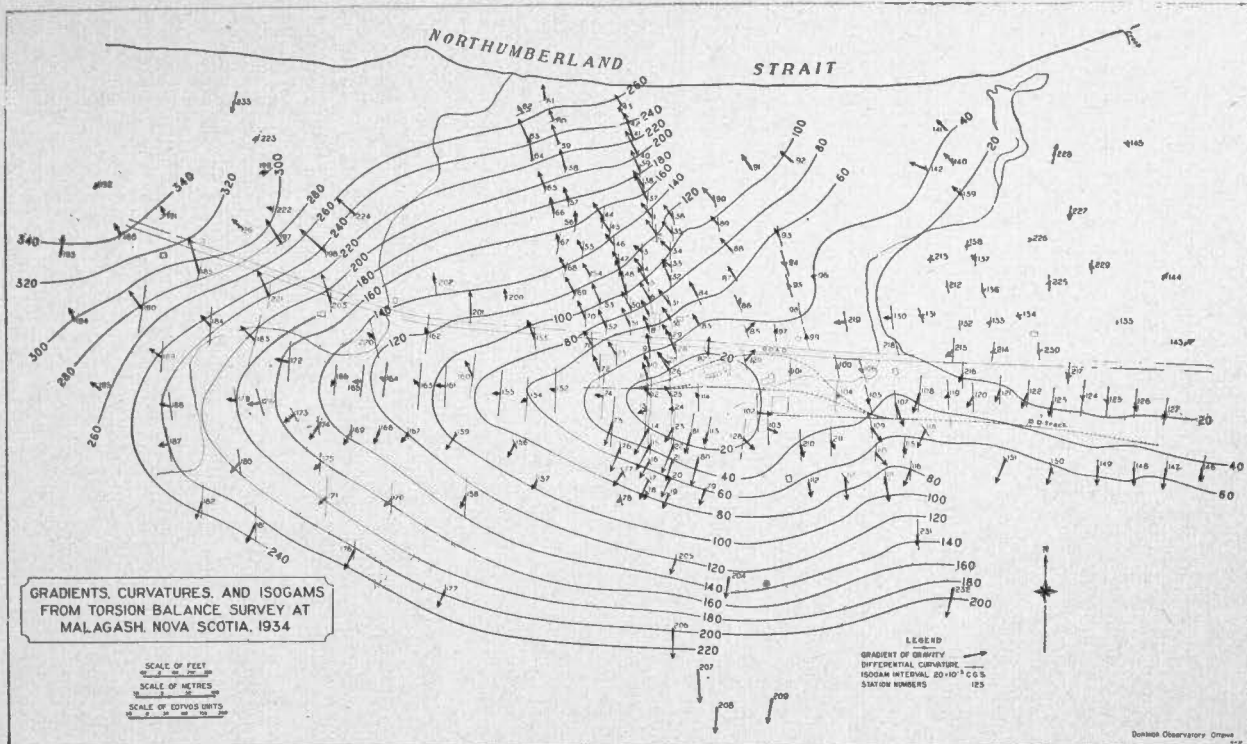


Figure 8.—Torsion balance survey of the Malagash mine area.

broad effect is a sharp circular negative anomaly near East Wallace. The general low area may be a reflection of the wider exposure of pre-Pictou (less dense) formations (*e.g.*, the Boss Point) on the north side of the anticline, or it may indicate a deep concentration of evaporite. In any case, the local anomaly near East Wallace must be due to a relatively shallow body, and is therefore of importance. The general relation between the anomaly profile and the geological section is shown in Figure 7. Comparisons with calculated profiles suggest that the anomaly could be caused by a structure in the form of a vertical cylinder with upper surface near the earth's surface, if the radius of the cylinder is taken as 1,000 feet and the density contrast with the surroundings as 0.2 grams per cubic centimeter. Actually, the rocks exposed along the axis of the anticline within the area of the anomaly are Claremont strata (Bell 1944, p. 38), the nearest Windsor exposures lying about 1,200 feet to the north-east.

However, the Windsor group, according to Bell (1944), is there contained between two thrust faults, and, if the more southerly of these is of low angle, the Windsor group could be expected at a moderate depth beneath the centre of the anomaly. Gussow (4) has described several cases of salt accumulation in New Brunswick, some of which

apparently are related to thrust faulting. This fact, together with the intensity of the East Wallace anomaly, and its location over a possible deep accumulation of salt, suggested that the area was worthy of further investigation.

A drill hole, number 42 as shown on Figure 2, was put down near the centre of the anomaly by the Malagash Salt Company. This hole passed through steeply dipping, soft, red shale, with many zones of gouge-like material, suggestive of faulting. Some gypsum was encountered between 591 and 614 feet. From 614 feet to the bottom of the hole at 655 feet the strata consisted of shale containing numerous small cubical cavities from which salt had been leached, together with larger cavities which caused the drill stem to drop several feet at a time. It was concluded that most of the salt originally present had been leached by water circulating through the fault zone. The effect of the cavities would, of course, be to decrease the density of the rocks, and this may contribute to the pronounced local anomaly. The single drill hole does not conclusively indicate that salt is not present within the anomalous zone, but it does suggest that much of the area would be unsuitable for mining operations in any case, because of the broken, faulted strata.

To the east of the feature described above, the course of the Claremont anticline is marked only

by a rather weak gravity minimum, except in the immediate vicinity of Malagash. The detailed examination of the conditions there will form the subject of the following section.

DETAILED STUDY OF THE MALAGASH AREA

The Malagash salt deposit has been described in detail by Hayes (5), Norman (8), and others. In 1934, a torsion-balance survey of the area was conducted by A. H. Miller of the Dominion Observatory (7 and 8), the results of his survey being reproduced in Figure 8. A comparison between this map and the results of the present survey (Figure 3) shows a remarkable similarity. Even though the terrain correction for the torsion balance averaged 25 per cent of the measured gradients, that instrument appears to have outlined the main deposit as faithfully as the gravimeter.

As the rock exposures in the area are limited to the shore of Northumberland strait and to the mine workings, the precise boundaries of the Windsor block containing the deposit were not known before the gravity survey. A fault, with downthrow to the west, was known to exist at the shore west of the mine, and its extension was believed to form the western limit of the Windsor group. The northerly boundary was believed to be formed by fault contact with younger strata (Bell

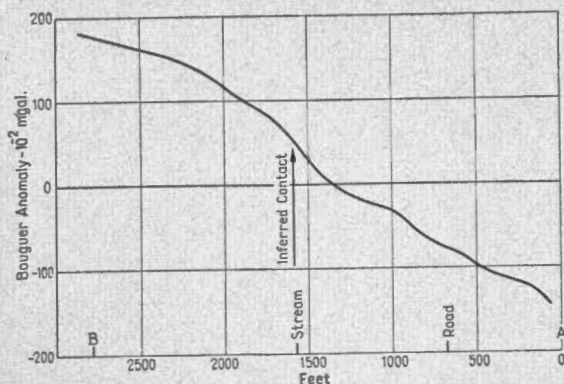


Figure 9.—Gravity anomaly profile along the line AB, Figure 3. (Detailed survey)

1944, p. 36), along the line indicated on Figure 3. The southern and eastern boundaries were also thought to be faults.

The gravity map indicates a broad area of low gravity, bounded on the northwest by a steep gradient near the presumed fault and on the southwest by a similar gradient. This area of low gravity extends almost to the eastern limit of the surveyed area. The eastern boundary of the low-density rocks would appear, from the gravity contours, to be along a north-south line, about 4,500 feet east of the main shaft. Within these limits, the broad area of low gravity is assumed to indicate the presence of the salt-bearing Windsor member, that is, interbedded salt, gypsum, anhydrite, and low-density shales. Concentrations of salt within this member should be indicated by more local gravity minima within the general low area.

The profile shown in Figure 9, taken along the line AB on the map, extends from the region of the main deposit northwesterly to the shore, crossing the northern boundary of the Windsor block. The main contact would appear to be indicated by the steepest portion of the curve, which coincides with the line of the assumed fault shown on the map. North of this line, the strata presumably belong to the Claremont, and, nearer the shore, to Boss Point formations. The major fault, which trends southeasterly from the shore, would appear to be evidenced on the gravity map in two ways. Near the shore, rocks of the Pictou series to the west are down-faulted against the Boss Point formation. The profile of Figure 10, along the line CD, shows the anomaly produced by this relationship. For comparison, the calculated effect of a vertical fault at 500 feet displacement, and density contrast 0.1 grams per cubic centimeter, is also shown. The good

agreement between the curves indicates that the assumed density differential between the Boss Point and Pictou strata is consistent with Norman's (8) estimate of the throw on the fault. Farther south, the western extremity of the area of low gravity appears to be displaced southward along the line of the same fault. This would suggest that the horizontal displacement on the fault is to the south on the west side, a hypothesis consistent with Hayes' (5) observations at the shore line.

Turning to the examination of local minima within the favourable area, it is seen that the anomaly over the known deposit is much the most prominent. However, the appearance of this feature, which might seem to suggest the presence of a circular salt dome, is probably misleading. The anomaly undoubtedly owes much of its form and prominence to its location near the beginning of the steep gradients due to the boundaries of the Windsor block, and to the mass deficiency caused by the removal of material from the upper levels of the mine workings. Actually, the salt beds at the mine occur as steeply dipping strata, striking generally east-west, but contorted into a number of cross-folds. The dip of the beds is toward the south, and becomes more gentle with depth. A total thickness of about 300 feet of salt strata is present, but salt of commercial quality is limited to a relatively few seams, which are thickest along the axes of the cross-folds. The mine

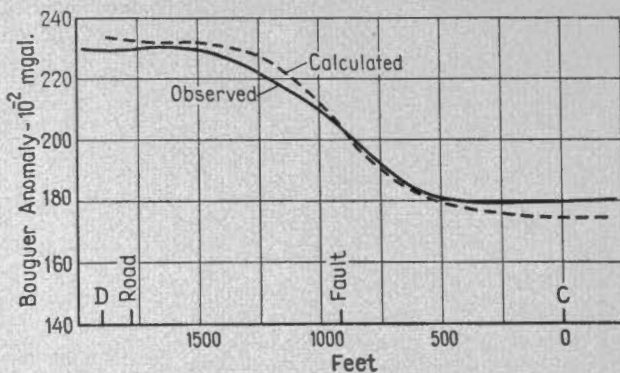


Figure 10.—Gravity anomaly profile along the line CD, Figure 3. (Detailed survey)

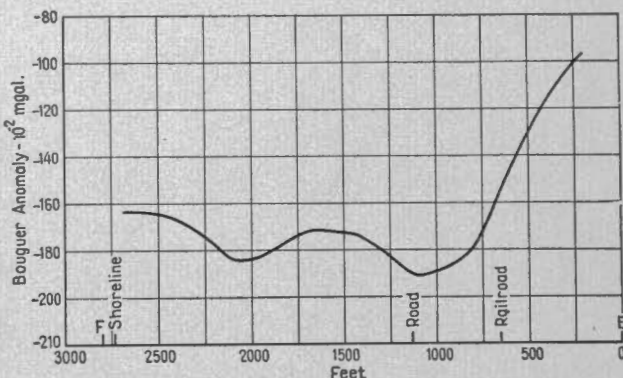


Figure 11.—Gravity anomaly profile along the line EF, Figure 3. (Detailed survey)

workings extend for about 1,000 feet down the dip of the beds, and for about the same distance along the strike, between the two shafts (Figure 3).

The torsion balance survey extended about 2,500 feet east of the main shaft, and indicated the extension of the broad area of low gravity in this direction. The gravimeter observations show two partially merged minima within this area, one on strike with the known deposit, and a similar one about nine hundred feet north of the first. These local minima are rather weak but, as the entire area is believed to be underlain by low-density strata, any lowering of the general anomaly level must be considered significant. A profile across the two features is shown in Figure 11. The fact that the effects along the line of the profile are quite distinct puts a definite upper limit on the depth of the source, for any structures deeper than about 800 feet would not have produced resolvable anomalies (Elkins and Hammer 1938). Actually, the bodies responsible for the minima are probably much shallower, judging from the form of the curves. These two anomalies, apart from the known deposit,

would appear to be the only promising areas within the block of Windsor rocks.

CONCLUSION

The regional gravity survey has been found to indicate the presence of lower-density Mississippian rocks upfolded or upthrust into the overlying Pennsylvanian formations. In particular, the Claremont or Malagash anticline has been traced from near Springhill to Malagash point. Along the axis of the anticline, intense negative anomalies were indicated near Oxford and East Wallace, but the latter of these occurs over a fault zone where the Windsor strata are badly broken and leached of salt. By contrast, a more regular structure, with better possibilities for development, has been indicated by drilling beneath the moderate anomaly near Pugwash.

The detailed investigation of the Malagash area has shown that the anomaly over the main deposit, as measured with the gravimeter, agrees very closely with the results of the torsion balance survey of 1934. The area covered by the gravimeter was extended to include the presumed boundaries of the upfaulted Windsor block in which the salt occurs (except the northern boundary, concealed beneath Northumberland strait), and these limits have been confirmed by the gravity anomalies. Two possible areas of salt-bearing strata have been indicated to the east of the known deposit. However, in view of the findings at the Malagash mine that salt

of commercial grade forms only a small percentage of the total deposit, it must be remembered that gravimetric surveys can only be expected to suggest favourable areas for more detailed, sub-surface investigation. There is a good possibility that some, at least, of the anomalies discussed are due to accumulations of salt-bearing rocks, but of the detailed chemical and physical nature of the salt nothing can be told.

ACKNOWLEDGMENTS

The detailed investigation of the Malagash area was undertaken at the request of the Nova Scotia Department of Mines. With the co-operation of Mr. J. P. Messervey, Deputy Minister of Mines of Nova Scotia, surveyors of that Department located the positions of the stations for the detailed survey. This very materially aided the progress of the gravity work. Officials of the Malagash Salt Company, namely, Messrs. J. L. Cavanaugh, John MacQuarrie, and C. M. Thurgood, provided many kindnesses to the party in the field. All observations with the Worden gravimeter were made by Mr. J. A. Robinson, while the elevations were determined by Mr. W. P. Eames and Mr. D. F. Young.

I should like also to express my thanks to the Malagash Salt Company for permission to outline the results of recent drilling, and to Mr. L. H. Cole, consultant to the Company, for helpful discussions.

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