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A detailed gravity study over a known Devonian carbonate buildup: the Shell Golden Reef, northwestern North Dakota

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University of North Dakota

A DETAILED GRAVITY STUDY OVER A KNOWN DEVONIAN CARBONATE BUILDUP: THE SHELL GOLDEN REEF, NORTHWESTERN NORTH DAKOTA

by

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This thesis, submitted by Stephen M. Braun in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

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Department Geology

Degree Master of Science

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Signature Stephen M. Braun

Date 4-15-91

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My wife, Susan, along with my four children, deserve the most thanks. They gave me support, stood behind me, and made countless sacrifices throughout this entire endeavor. God bless them.

ABSTRACT

A detailed gravity study was conducted over the Shell Golden reef in the northwestern North Dakota portion of the Williston Basin. The Shell Golden reef has been previously interpreted to be reefal facies within the Winnipegosis Formation (Devonian) located at a depth of about 2400 meters. Based only on information from wireline logs and core from two boreholes, the Shell Golden well #34X-34 has been previously interpreted as a pinnacle reef with 70 meters of relief and undetermined diameter. The basin regime of the Elk Point shelf created an environment that allowed the growth and development of the Shell Golden reef, numerous pinnacle reefs, and mounds in northwestern North Dakota and southeastern Saskatchewan. Carbonate buildups within the Elk Point Basin have previously been interpreted to be 70 to 105 m thick with diameters ranging from 0.5 to 5.0 km.

For this study, vertical and horizontal positions were surveyed to +/- 3 cm and +/- 1 m, respectively, providing gravity measurement accuracy of .01 mgal. Five profiles were surveyed with three east-west lines intersecting two north-south lines forming a cross over the expected center of the reef. The distance between each line was 1.6 km and gravity-station spacing along each line was 0.4 km. The additional information provided by the analysis of the residual Bouguer gravity anomalies generated in this study indicate that the Shell Golden reef consists of a north-south trending elongate carbonate buildup rather than a pinnacle reef. The length of the elongated carbonate buildup is

about 4.0 km both north and south of the location of the two drill holes, the width is between 850 and 1500 m, and the relief ranges from about 90 to 105 m. Analysis of the residual Bouguer gravity anomaly further indicates that the Shell Golden well #34X-34 is on the south flank of the reef and not on the apex.

INTRODUCTION

The carbonate buildup investigated in this study, the Shell Golden reef, was named for its discovery in the Shell Oil Company's #34X-34 well. Part of the Winnipegosis Formation (Devonian), this reef is located along the northeastern margin of the Williston Basin in Renville and Ward counties of north-western North Dakota (Figure 1). The Shell Golden reef has been defined as a pinnacle reef (Precht, 1986; Ehrets and Kissling, 1987) based on information collected from one core hole that penetrates an anomalously thick section of carbonates containing reefal material, and one hole 280 m away that penetrates a much thinner carbonate section, lacking reefal material. This reef is overlain by evaporites (predominantly halite) of the Devonian Prairie Formation (Figure 2).

The purpose of this study was threefold: 1) to determine if Devonian reefs in North Dakota can be detected using gravity methods, 2) if so, to determine the nature of the source of the gravity signal, and 3) to generate structural models that satisfy the geophysical and geologic data as well as indicate the vertical and horizontal dimensions of the reef and depth to the reef.

Carbonate reef structures in the subsurface have been detected by several workers utilizing high-precision gravity surveys (Aginich, 1949; Brown, 1949; Pohly, 1954; Ferris, 1961, 1962, 1964a, 1964b, 1965, 1968; and Haye, 1966). Many of these studies show a reef structure overlain by clastic sediments. As these clastics were deposited

Figure 1. General location of study area and survey grid lines over the Shell Golden carbonate buildup in Ward and Renville Counties, North Dakota.

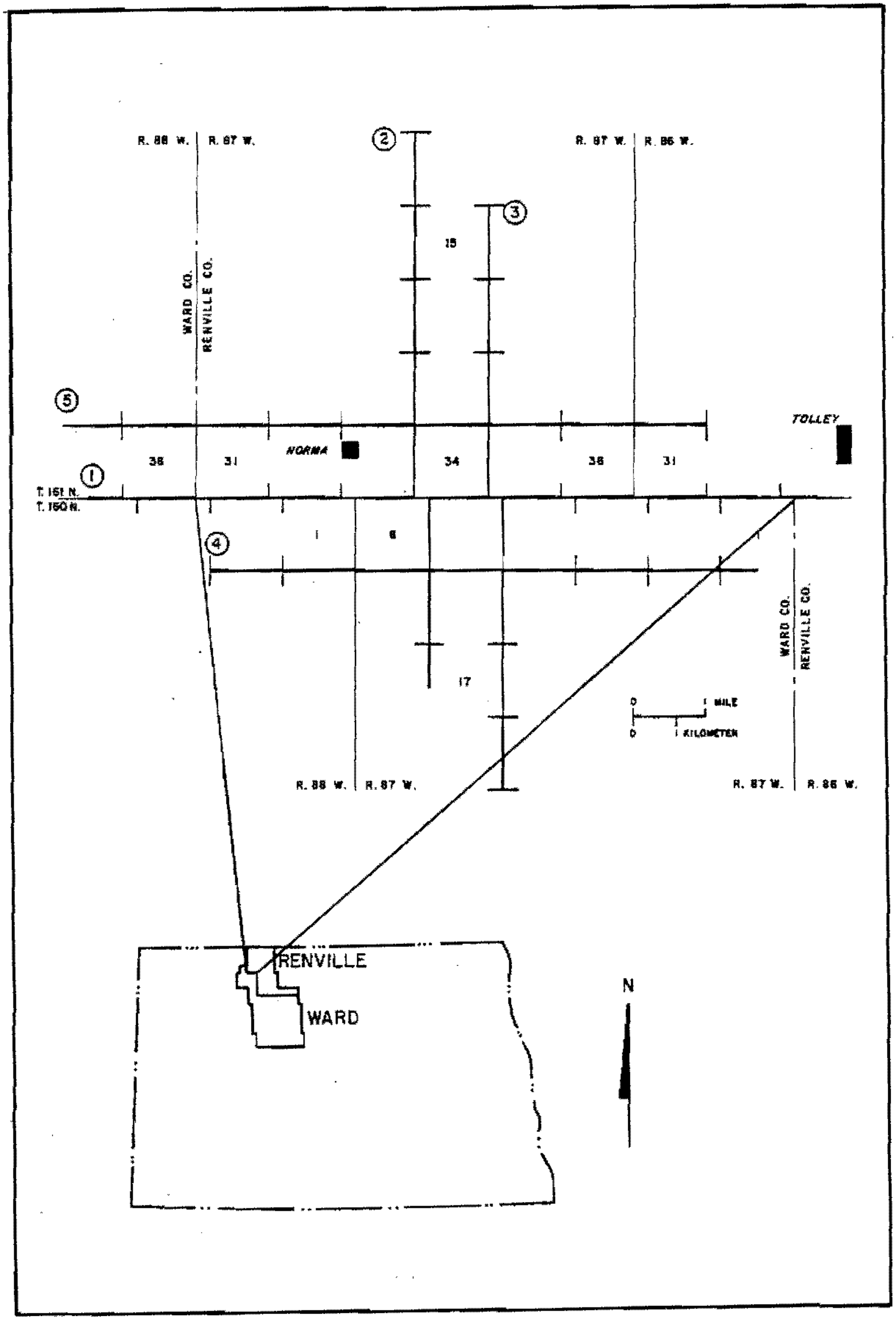

R. 88 W.
R. 87 W.
R. 87 W.
R. 86 W.
2
3
15
WARD CO.
RENVILLE CO.
5
TOLLEY
36
31
NORMA
34
36
31
1
T. 161 N.
T. 160 N.
4
1
6
17
0 1 MILE
0 1 KILOMETER
R. 88 W.
R. 87 W.
R. 87 W.
R. 86 W.
WARD CO.
RENVILLE CO.
RENVILLE
WARD
N

Figure 2. Partial stratigraphic column of North Dakota highlighting the Devonian period.

PERIOD	SEQUENCE	GROUP	FORMATION
MISSISSIPPIAN	KASKASKIA	MADISON	LODGEPOLE
DEVONIAN			BAKKEN
			THREE FORKS
		JEFFERSON	BIRD BEAR
			DUPEROW
		MANITOBA	SOURIS RIVER
			DAWSON BAY
		ELK POINT	PRAIRIE
			WINNIPEGOSIS
			ASHERN
SILURIAN	TIPPECANOE		INTERLAKE
ORDOVICIAN		BIG HORN	STONEWALL

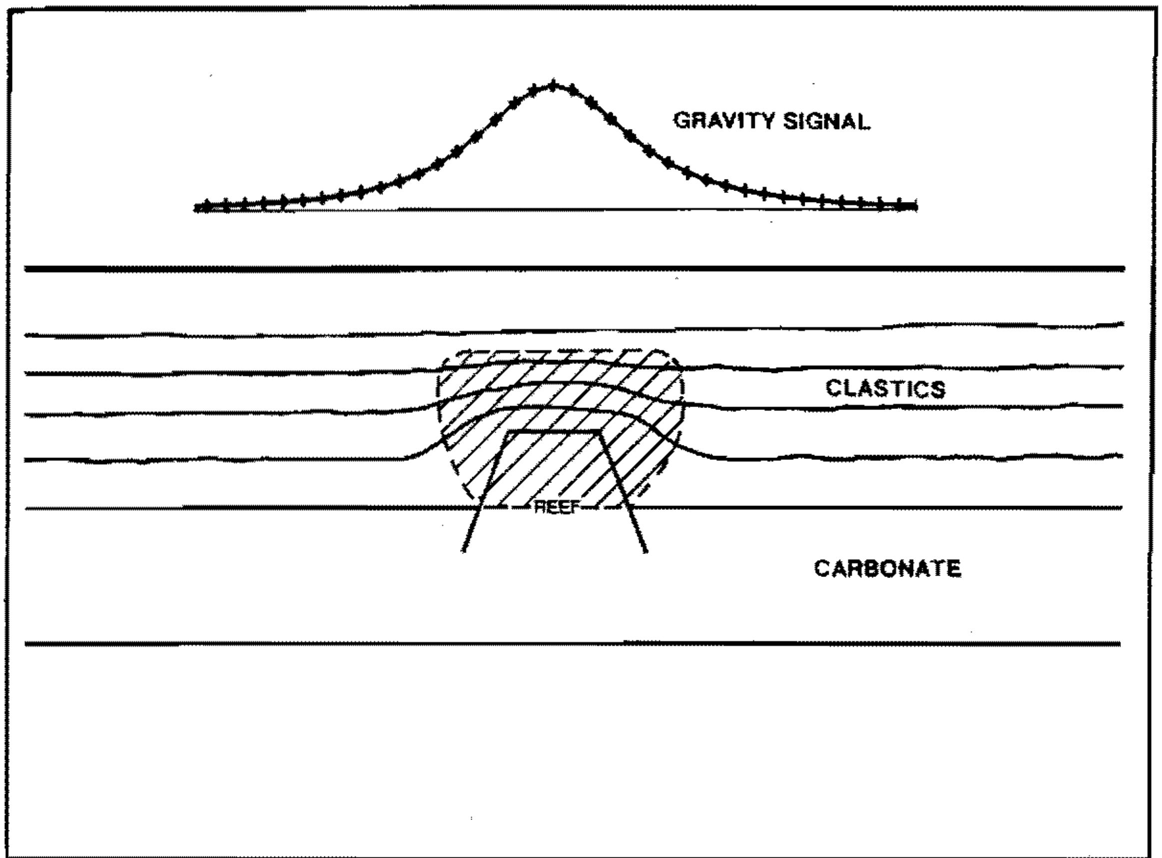
through time, compaction anticlines formed over the reefs due to the greater rigidity of the carbonate structure (Figure 3a). The primary contribution to the Bouguer gravity signal is from the clastic sediments that overlie the reefs which are compacted and more dense than the off-reef sediments.

Other reefs detected by gravity methods are not draped by clastic sediments, but evaporites instead. In the Williston Basin, the evaporites show no evidence of major flow structures around the reefs and consequently the formation of compaction anticlines is not likely and the gravity signal should arise from the reef itself (Figure 3b). The Shell Golden reef, surrounded by evaporites instead of clastics (Figure 4), fits into this latter scenario (Figure 3b).

The data used in this study were collected during the summer of 1985 under contract with Tenneco Exploration Company (TEC). The locations of the gravity traverses, spacing of the stations, and required accuracy of the gravity measurements were specified by TEC.

Figure 3a. Generalized geologic cross section of carbonate reefs with compaction anticlines. The clastic sediments are draped over the resilient reef and are preferentially compacted over the top of the reef. This phenomena generates compaction anticlines over the reef, which contributes to the source of the gravity signal. Cross-hatch depicts approximate boundary of material with greater density than surrounding material.

Figure 3b. Generalized geologic cross section of Winnipegosis carbonate buildups in the Williston Basin overlain by evaporites of the Prairie Formation. The gravity signal in this case is generated by only the reef buildup since compaction anticlines have not been noted by previous workers to exist over the reef. Cross-hatch depicts approximate boundary of material with greater density than surrounding material.


GRAVITY SIGNAL
CLASTICS
REEF
CARBONATE

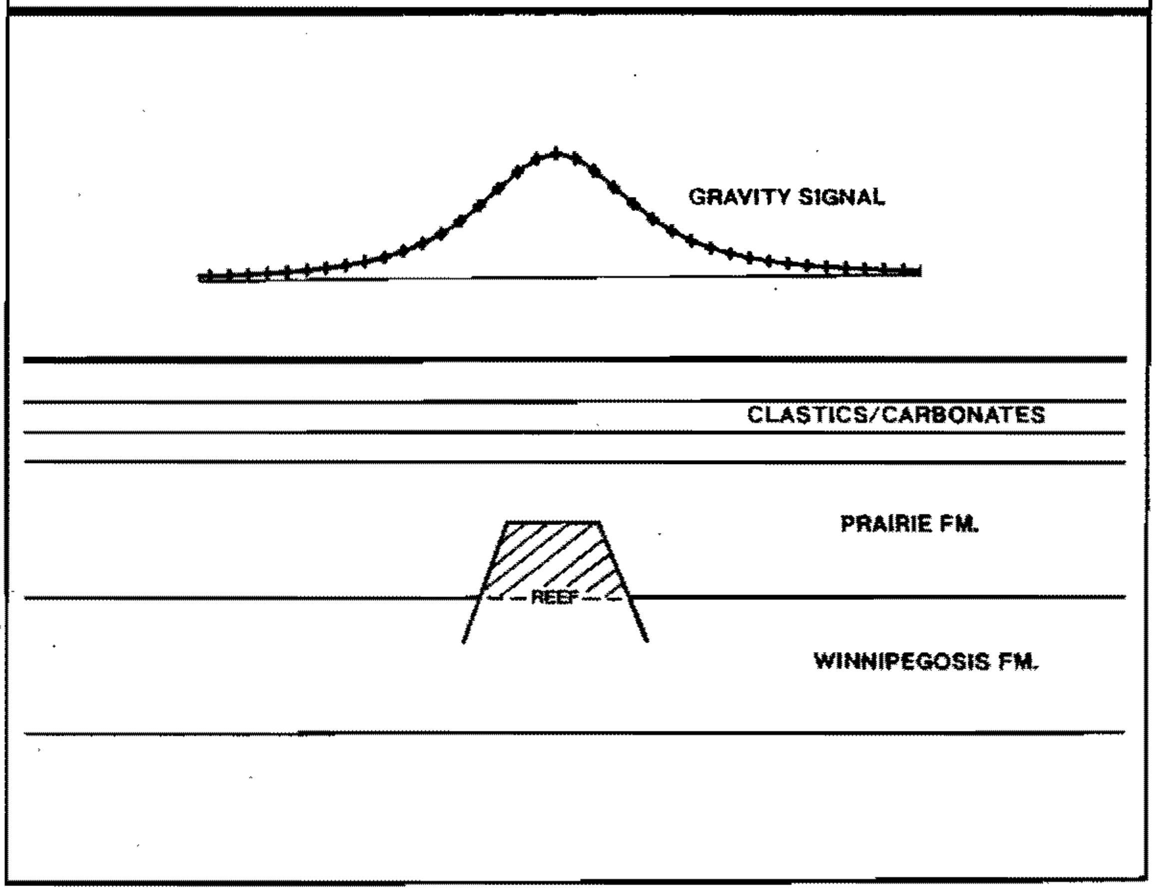
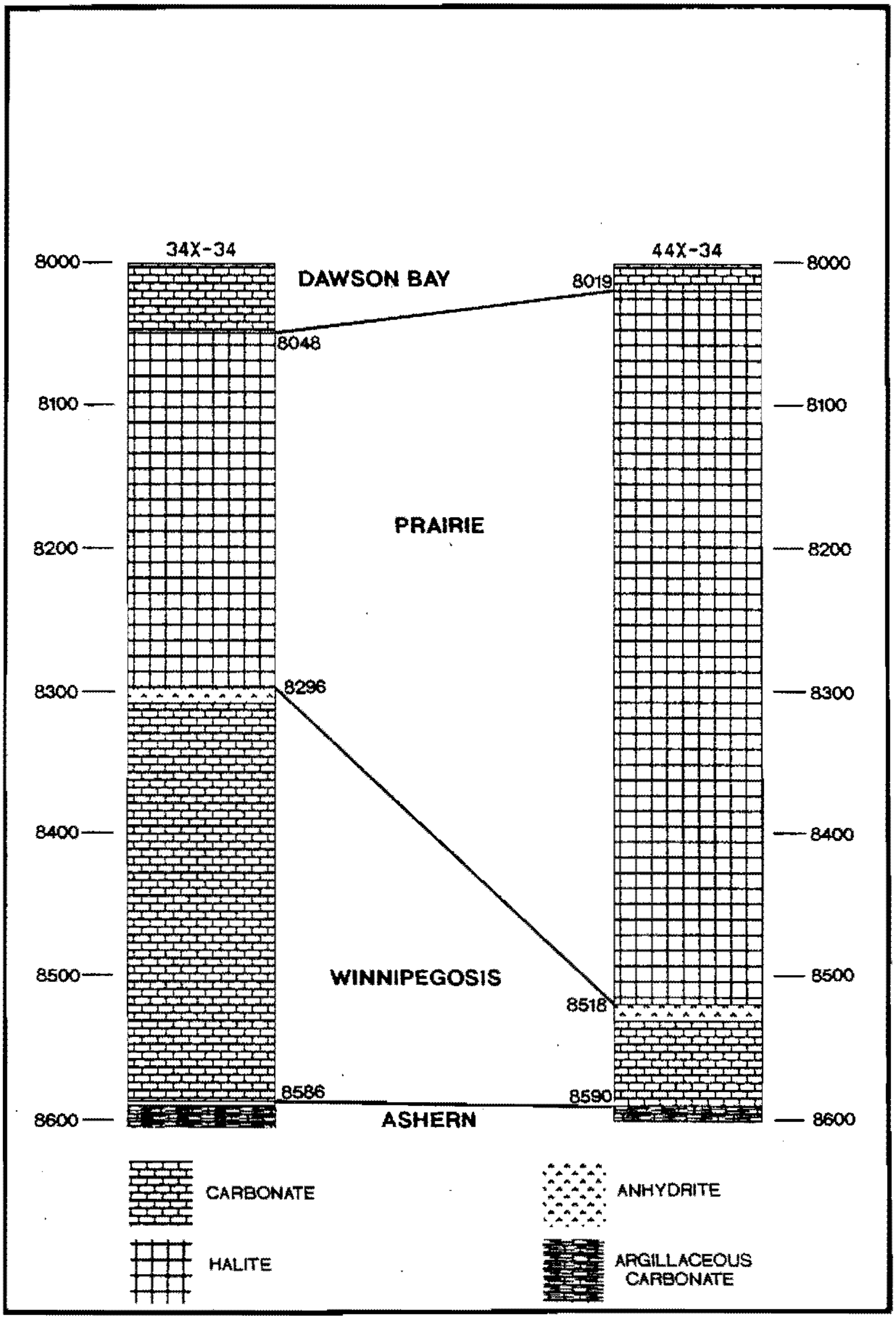

GRAVITY SIGNAL
CLASTICS/CARBONATES
PRAIRIE FM.
REEF
WINNIPEGOSIS FM.

Figure 4. Geologic cross-section of Shell Golden #34X-34 and #44X-34 based on gamma ray and compensated neutron formation density logs. Depths shown are in feet below kelly bushing.


34X-34
44X-34
8000
8100
8200
8300
8400
8500
8600
DAWSON BAY
8019
8048
PRAIRIE
8296
WINNIPEGOSIS
8518
8586
8590
ASHERN
CARBONATE
ANHYDRITE
HALITE
ARGILLACEOUS CARBONATE

GEOLOGIC SETTING

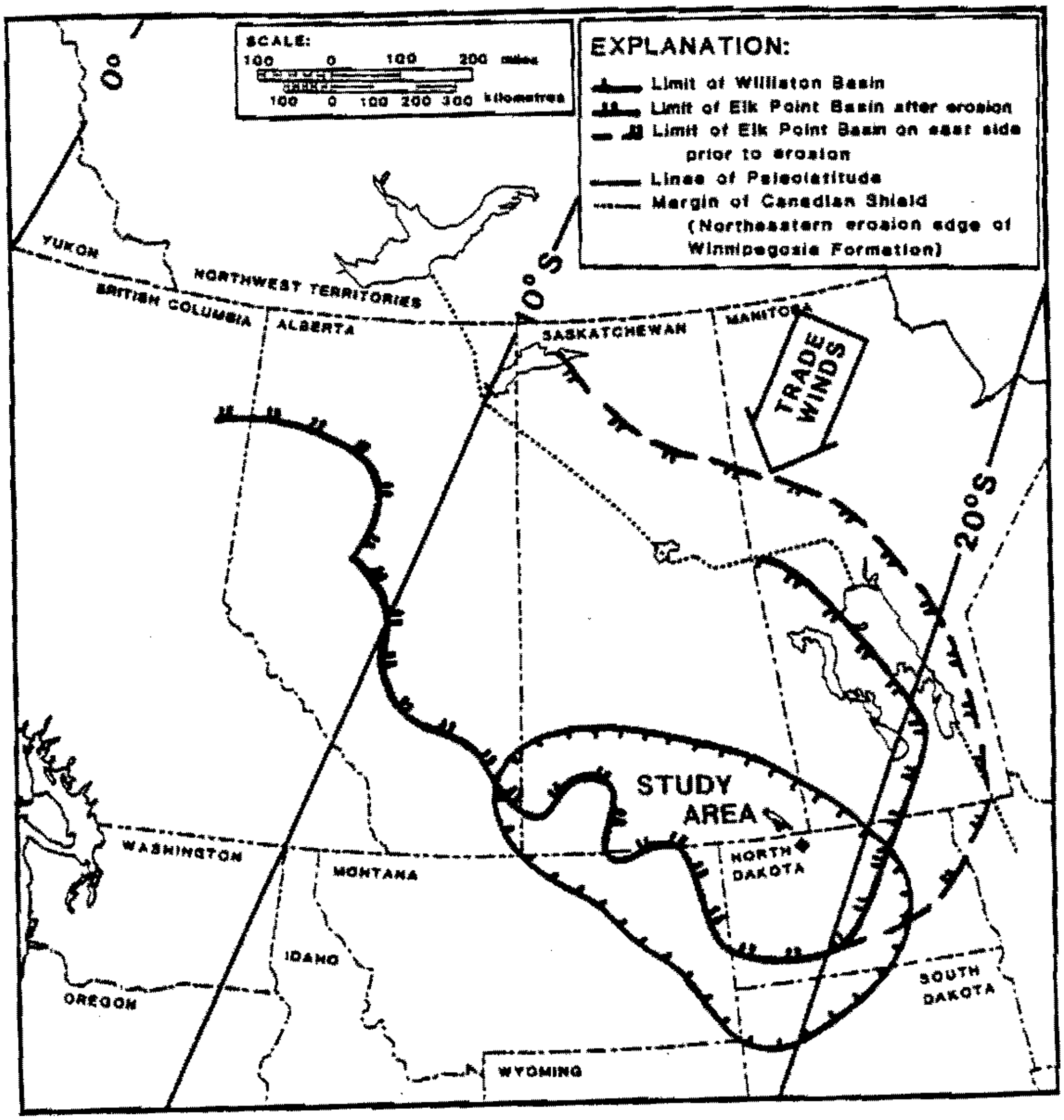
Introduction

Deposition of Devonian sediments occurred as the lower part of the Kaskaskia Sequence which represents a sea transgressing across the study area from the north and west (Carlson and Anderson, 1970). During the Devonian period, the Elk Point Basin was the dominant structural feature in the region (Figure 5). The Williston Basin was dominant before and after the Devonian (Perrin, 1987).

Deposition of the sediments that formed the Winnipegosis Formation carbonates and overlying Prairie Formation evaporites took place in the Elk Point Basin. The Elk Point Basin was an elongate, northwest-south east trending basin that covered approximately 3,900,000 sq km; its southern margin located in Montana and North Dakota (Figure 5). Seawater influx into the basin was predominantly from the north and was at times restricted by the Presqu'ile Barrier Reef in the northern end of the basin (Blatt et al., 1980). Initially, conditions in the basin favored the deposition of carbonates (Winnipegosis Formation). However, increasing restriction of seawater flowing into the basin eventually led to evaporative drawdown, the cessation of carbonate deposition, and the production of extensive evaporite deposits of the Prairie Formation (Blatt et al., 1980).

During deposition of the Winnipegosis Formation, the basin regime of the Elk Point shelf created an environment that allowed the growth and development of the Shell Golden reef, numerous pinnacle reefs, and

Figure 5. Location of study area relative to the dominant Elk Point Basin during the Devonian period. Modified from Perrin, 1987.


SCALE:
100 0 100 200 miles
100 0 100 200 300 kilometres
EXPLANATION:
Limit of Williston Basin
Limit of Elk Point Basin after erosion
Limit of Elk Point Basin on east side prior to erosion
Lines of Paleolatitude
Margin of Canadian Shield (Northeastern erosion edge of Winnipegosis Formation)
0°
10°S
20°S
YUKON
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
TRADE WINDS
STUDY AREA
WASHINGTON
MONTANA
NORTH DAKOTA
IDAHO
OREGON
SOUTH DAKOTA
WYOMING

mounds (carbonate buildups) in northwestern North Dakota and southeastern Saskatchewan. Carbonate buildups within the Elk Point Basin were interpreted to be 70 to 105 m thick with diameters ranging from 0.5 to 5.0 km (Ehrets and Kissling, 1987).

Stratigraphy

The Ashern Formation (Figures 2 and 4) comprises the lowest Devonian beds in the study area. The Ashern is predominantly medium to very dark gray argillaceous dolomite and locally consists of anhydrite and anhydrite nodules (Bluemle et al., 1986). The lower portion of the Ashern contains a reddish weathered zone (Carlson and Anderson, 1970) presently labelled as the "Third Red" (Bluemle et al., 1986). Fischer and Burke (1987) determined from gamma ray and compensated neutron formation density logs that the Ashern is 18 to 19 m thick both under the Shell Golden reef structure and off the reef. The maximum thickness of the Ashern in the Williston Basin is about 55 m (Bluemle et al., 1986).

Conformably overlying the Ashern Formation is the Winnipegosis Formation which is dominated by limestone, dolomite, and anhydrite (Carlson and Anderson, 1970). The Winnipegosis rocks are generally gray, dense, and contain some shale (Bluemle et al., 1986). The thickness of the Winnipegosis off-reef facies (NDGS #7976, Shell Golden #44X-34) adjacent to the Shell Golden reef was determined to be 22 m (Figure 4) as interpreted from gamma ray and compensated neutron formation density logs. The total thickness of the Winnipegosis, including reef facies (NDGS #7976, Shell Golden 34X-34), was determined from the same type of logs to be 90 m. The maximum thickness of Winnipegosis carbonates in the Williston Basin is generally 65 m, but it is known to have marked thickness variations due to the development of reef and inter-reef facies (Bluemle et al., 1986).

Overlying the Winnipegosis Formation, the Prairie Formation consists mainly of halite with some carbonates and anhydrite (Carlson and Anderson, 1970). Bluemle et al. (1986) summarize the Prairie as consisting of evaporites, both potassium and sodium salts, interbedded with anhydrite beds. The Prairie was deposited during evaporative drawdown of the Elk Point basin at the close of Winnipegosis deposition (Ehrets and Kissling, 1987). The thickness of the Prairie Formation is interpreted to be 155 m adjacent to the reef in Shell Golden #44X-34 and 80 m over the reef in Shell Golden #34X-34 (Figure 4).

The Dawson Bay Formation overlies the Prairie Formation and consists mainly of gray to brown limestone and dolomitic limestone (Bluemle et al., 1986). According to Gendzwill (1978), seismic surveys over Winnipegosis reefs on the Canadian side of the Elk Point Basin have revealed possible salt-solution features over the reefs. The solution of salt was caused by water circulating through the mound thereby creating subsidence, which lowered the base of the Dawson Bay directly over the reef (Figure 4). Gendzwill (1978) also discussed several other mechanisms which may have caused or at least contributed to the subsidence over the reef. These include volume shrinkage due to dolomitization, compaction of the mound itself if originally very porous, settling and compaction of the platform due to the weight of the mound, and dehydration of carnallite.

Winnipegosis Reef Morphology

The basin regime of the Elk Point shelf created an environment that allowed the growth and development of the Shell Golden reef and numerous pinnacle reefs in northwestern North Dakota and southeastern Saskatchewan (Ehrets and Kissling, 1987). Carbonate reef structures in the Winnipegosis of the Williston Basin have been described as buildups (Martindale and MacDonald, 1989), mounds (Gendzwill, 1978), and as pinnacle reefs (Precht, 1986; Perrin, 1987; Ehrets and Kissling, 1987; and Fischer and Burke, 1987).

Martindale and MacDonald (1989) analyzed seismic data over the Tableland area located on the west margin of the Elk Point Basin about 14.5 km north of the U.S.-Canada border. Their results indicate an elongate northwest-southeast trending Winnipegosis carbonate buildup about 2.2 km long and 0.8 km wide. Eight locations adjacent and over the buildup have been drilled and support the seismic data (Martindale and MacDonald, 1989).

Gendzwill (1978) used seismic data to model Winnipegosis carbonate mounds about 50 km southeast of Saskatoon, Saskatchewan. The results indicate the mounds are flat-topped, 70 to 100 m high, and 1 to 8 km wide and long (Gendzwill, 1978).

Ehrets and Kissling (1987) describe pinnacle reefs in northwestern North Dakota and southeastern Saskatchewan as ranging from 0.5 km to nearly 5 km across and between 45 m and 105 m thick. The proportional thickness of the reef facies correspond to distance from the basin platform.

The dip of the carbonate reef peripheries obtained from reefs throughout the Elk Point Basin show a wide variation in values. Martindale and MacDonald (1989) describe dips from 20 to 50 degrees. Dips of 15 to 40 degrees were observed in the Shell Golden reef core (#34X-34) by Ehrets and Kissling (1987). Although the American Geological Institute dictionary defines a pinnacle reef as having 45-90 degree beds, reefs in the Winnipegosis with dips less than 45 degrees (i.e. Ehrets and Kissling, 1987) have been called pinnacle reefs.

In summary, the geometries of many reefs within the Winnipegosis in the Williston Basin seem to vary from location to location. The reefs have been interpreted to be isolated circular buildups to elongate features ranging from 1 to 8 km wide and long. Dips of the beds within these reefs also vary and range between 15 and 50 degrees. In addition, many reefs that have been called "pinnacle" by previous workers may not be true pinnacle reefs at all.

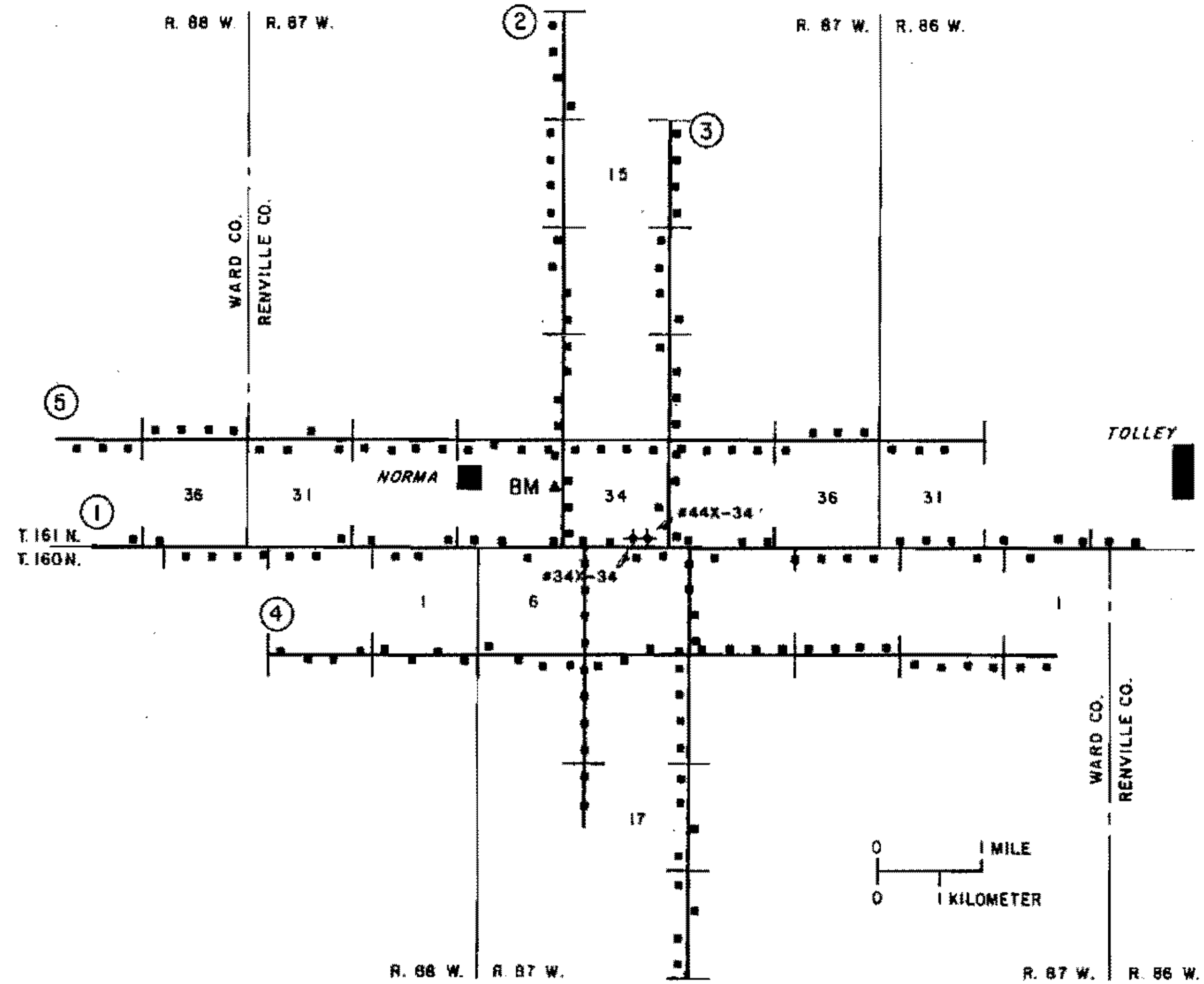
METHODOLOGY

Establishment of Survey Lines

Tenneco Exploration Company (TEC) specified a survey line spacing of 1.6 km, a northsouth/eastwest survey line orientation, and a length and location designed to extend beyond the assumed horizontal dimension of the reef. A gravity station interval of 0.4 km along each survey line was also specified by TEC. The gridwork of survey lines over the Shell Golden reef (Figure 6) was developed to optimize detection of the anticipated gravity anomaly resulting from lithologic differences between carbonates and halite. Minimum thickness differences in lithology were based on cores and geophysical logs from two boreholes, Shell Golden #34X-34 which penetrated the reef, and Shell Golden #44X-34 which did not penetrated the reef. The grid selected by TEC was designed on the assumption that the high frequency gravity signals generated by the Winnipegosis reef structure could be detected at the surface.

Precision gravity measurements of relatively low magnitude gravity signals from great depths require highly accurate determination of position. An accuracy of 3 cm in vertical and horizontal control was needed to detect the anticipated gravity anomaly. This was accomplished by using a digital theodolite and electronic distance meter (EDM) to survey gravity stations. The relative elevation of each station was based on a benchmark (BM) located within the grid (Figure 6).

Figure 6. Detailed location map of the gravity stations along each survey line and wells #34X-34 and #44X-34. The towns of Norma and Tolley, North Dakota, are also shown for reference.


R. 88 W.
R. 87 W.
R. 87 W.
R. 86 W.
WARD CO.
RENVILLE CO.
15
34
36
31
36
31
NORMA
BM
TOLLEY
#44X-34
#34X-34
T. 161 N.
T. 160 N.
1
6
1
17
0
1 MILE
0
1 KILOMETER
WARD CO.
RENVILLE CO.
R. 88 W.
R. 87 W.
R. 87 W.
R. 86 W.
1
2
3
4
5

Gravity Measurement

The instrument used to obtain field gravity values (Appendix A) was a Lacoste and Romberg Model D gravity meter. This meter has the capability to detect down to 0.001 milligal (mgal) with the thousandths place interpolated, the accuracy required by TEC.

The acquisition of the gravity data was accomplished by taking a reading at a base station, collecting data at other gravity stations for a maximum of two hours, and then reoccupying the base station for another reading. By repeating this procedure throughout each day, changes in base station gravity readings were noted and used to remove the effects of earth-tides and meter drift from the field data (drift correction). A linear drift relationship was assumed to occur between base station readings.

Individual gravity meters have mechanical characteristics which may generate different gravity readings for the same gravity signal. Therefore, each gravity meter has a meter constant that is determined and supplied by the manufacturer. When multiplied by the meter constant (0.02774), the field gravity signal is corrected to a value duplicated by other meters.

Data Reduction

The standard corrections of meter, latitude, free-air, Bouguer, and drift were calculated to reduce the data to a usable form. The application of these corrections to the raw field data result in a Bouguer gravity anomaly value for each station. A Bouguer gravity anomaly map (Figures 7 and 8) was generated by contouring the corrected anomaly values.

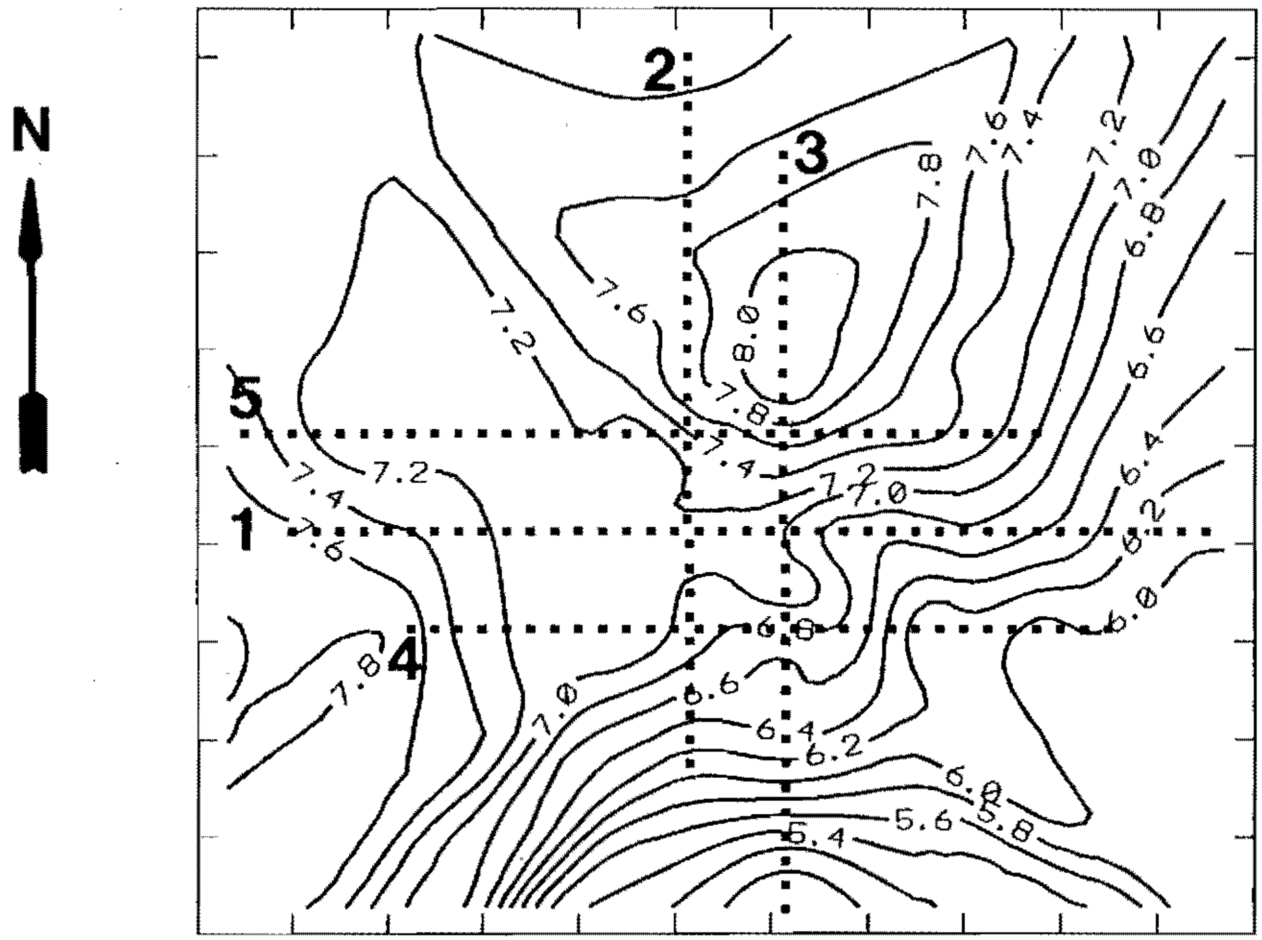
The effects of long wavelength features (Precambrian basement in this study) tend to mask or obscure the shorter wavelength features of interest (reefs in this study). Therefore, the regional gravity effects of the basement were removed by calculating a second order trend surface of the Bouguer gravity anomaly (Figure 9) and subtracting it from the Bouguer gravity anomaly data. A second order trend surface was used because the regional curve of the northsouth lines appear parabolic in nature, while the eastwest lines appear linear. The result is a residual Bouguer gravity anomaly map (Figures 10 and 11) which more clearly defines the anomalies of interest.

Only the gravity anomalies within and along the survey lines can be interpreted without making assumptions regarding the extent and trends of the anomalies. Therefore, analysis and interpretation of the residual Bouguer gravity anomaly map (Figure 10) should include only those residuals within the field data collection area (Figure 12).

Modelling

The three-dimensional computer technique (Appendix B) used to model the residual gravity data was developed from the geometric shape models found in Telford et al. (1976). Rather than using a sphere, slab, or cylinder to generate hypothetical gravity anomalies, stacked discs with specified thicknesses (t), radii (r), depths (z), and distances to the disc centers (R) were used (Figure 13). A stacked disc geometry was chosen to model the carbonate structures because it

Figure 7. Bouguer gravity anomaly contour map generated by making standard corrections to the field gravity data. Gravity stations are denoted along each survey line by a filled square. Contour interval is 0.2 mgals.



SCALE 1 Inch = 3.2 KILOMETERS

Figure 8. A 3-dimensional surface of the Bouguer gravity anomaly map shown in (Figure 7). The view is looking from the southwest toward the northeast.

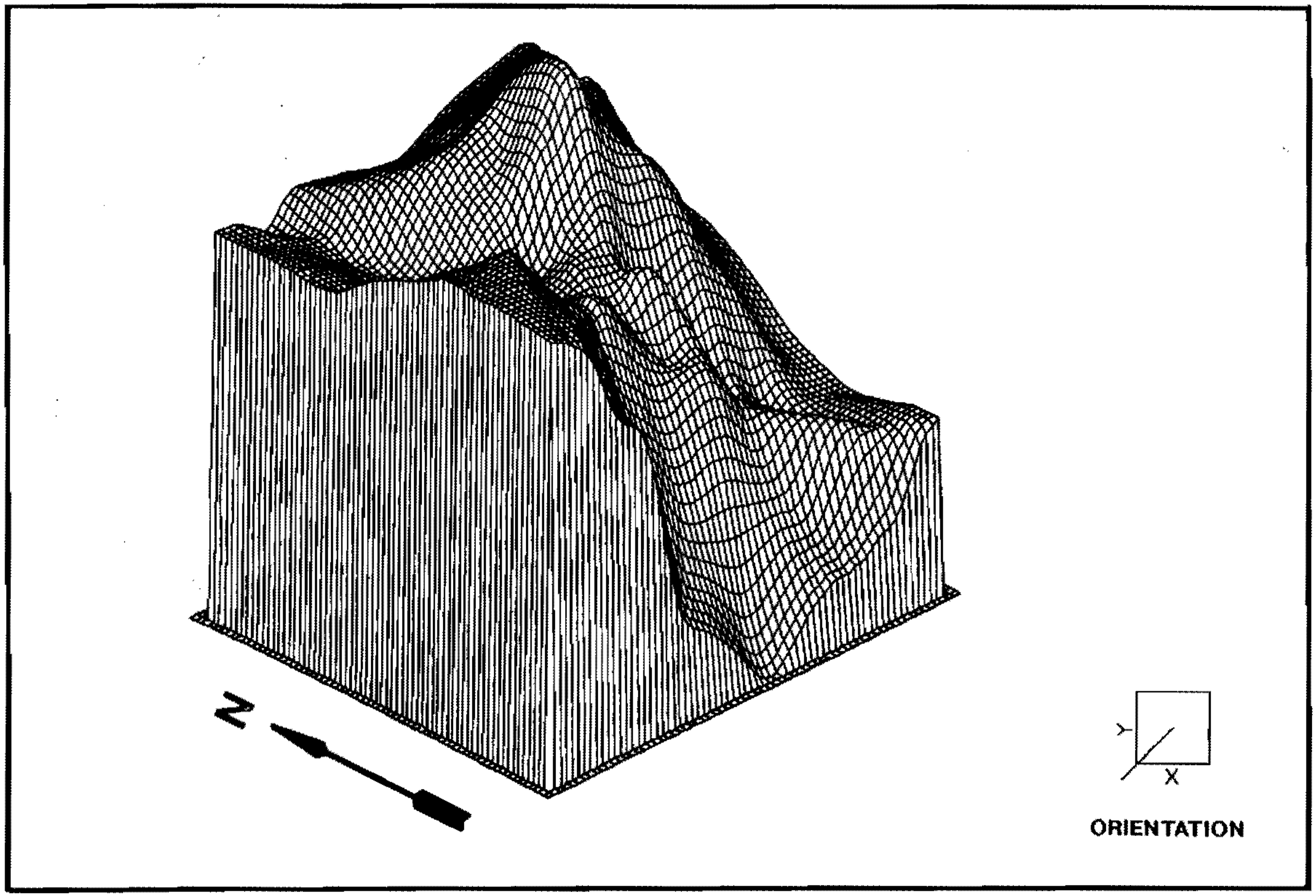

N
Y
X
ORIENTATION

Figure 9. The second order trend surface of the Bouguer gravity anomaly surface (Figures 7 and 8). Bouguer gravity values have been reduced by 4500 mgals for convenience.

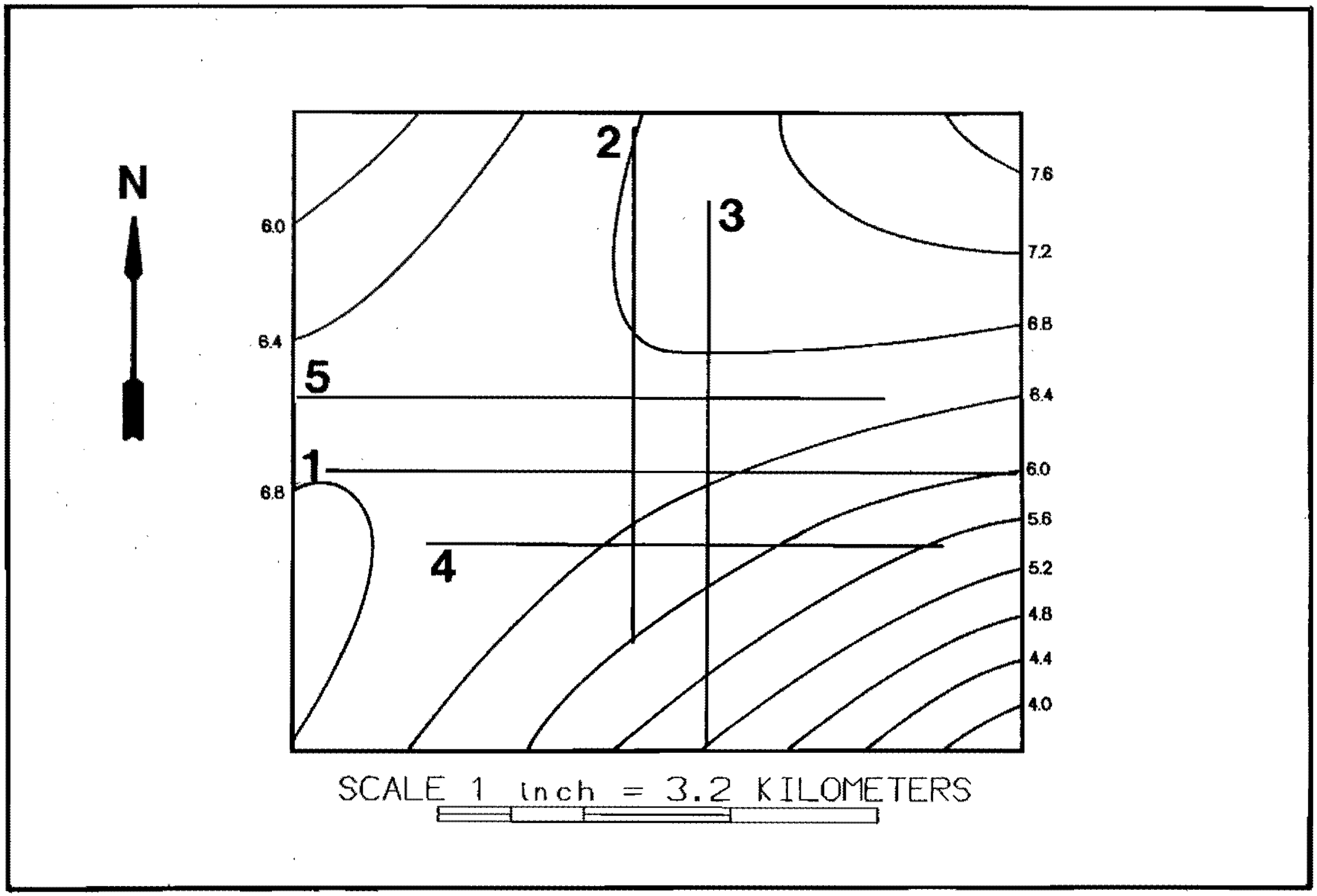
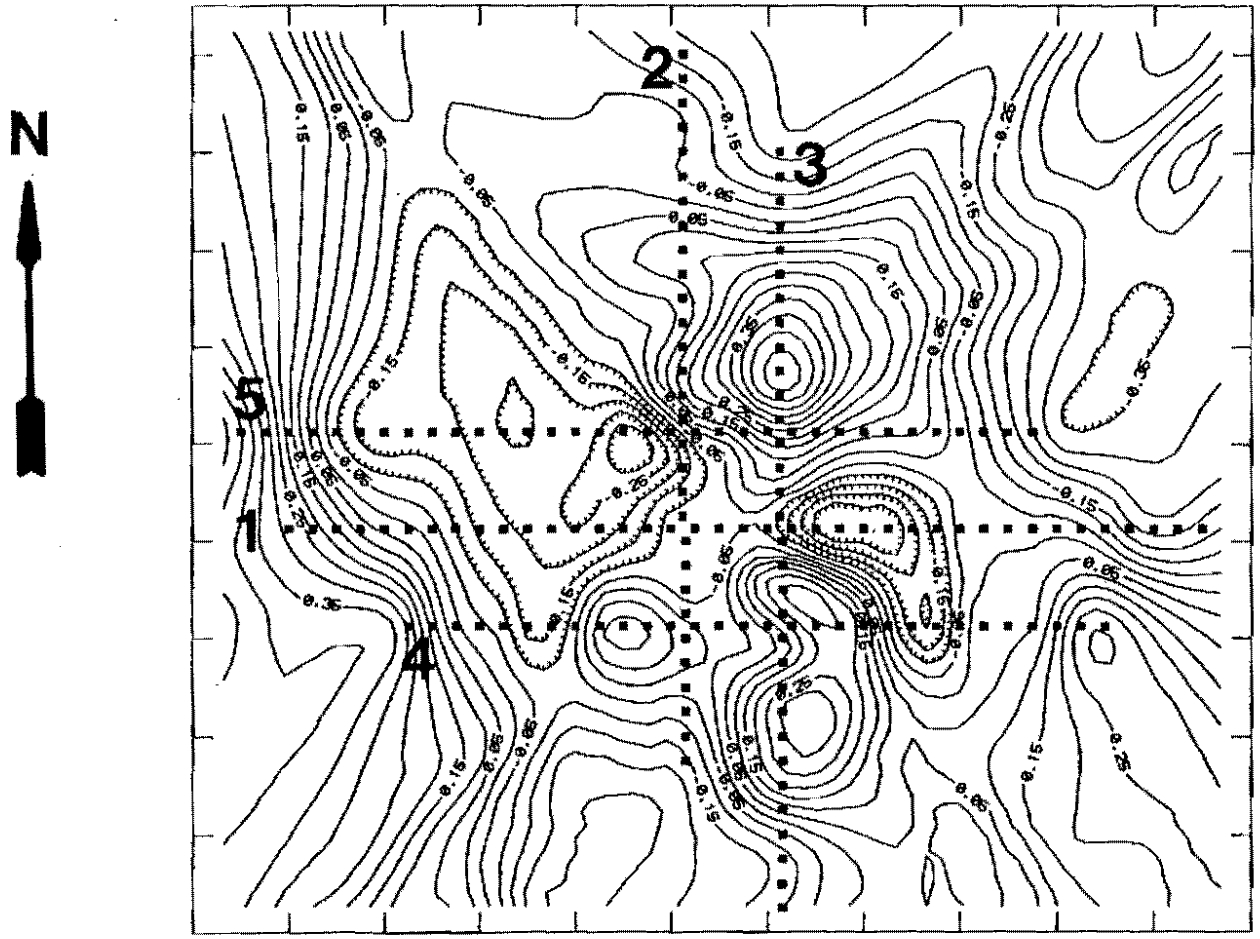

N
2
3
5
1
4
6.0
6.4
6.8
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
SCALE 1 inch = 3.2 KILOMETERS

Figure 10. Residual Bouguer gravity anomaly map generated by subtracting the second order trend surface (Figure 9) from the Bouguer gravity anomaly surface (Figures 7 and 8). Contour interval is 0.05 mgals.



SCALE 1 inch = 3.2 KILOMETERS

Figure 11. A 3-dimensional surface of the residual Bouguer gravity anomaly map (Figure 10). The view is looking from the southeast toward the northwest.

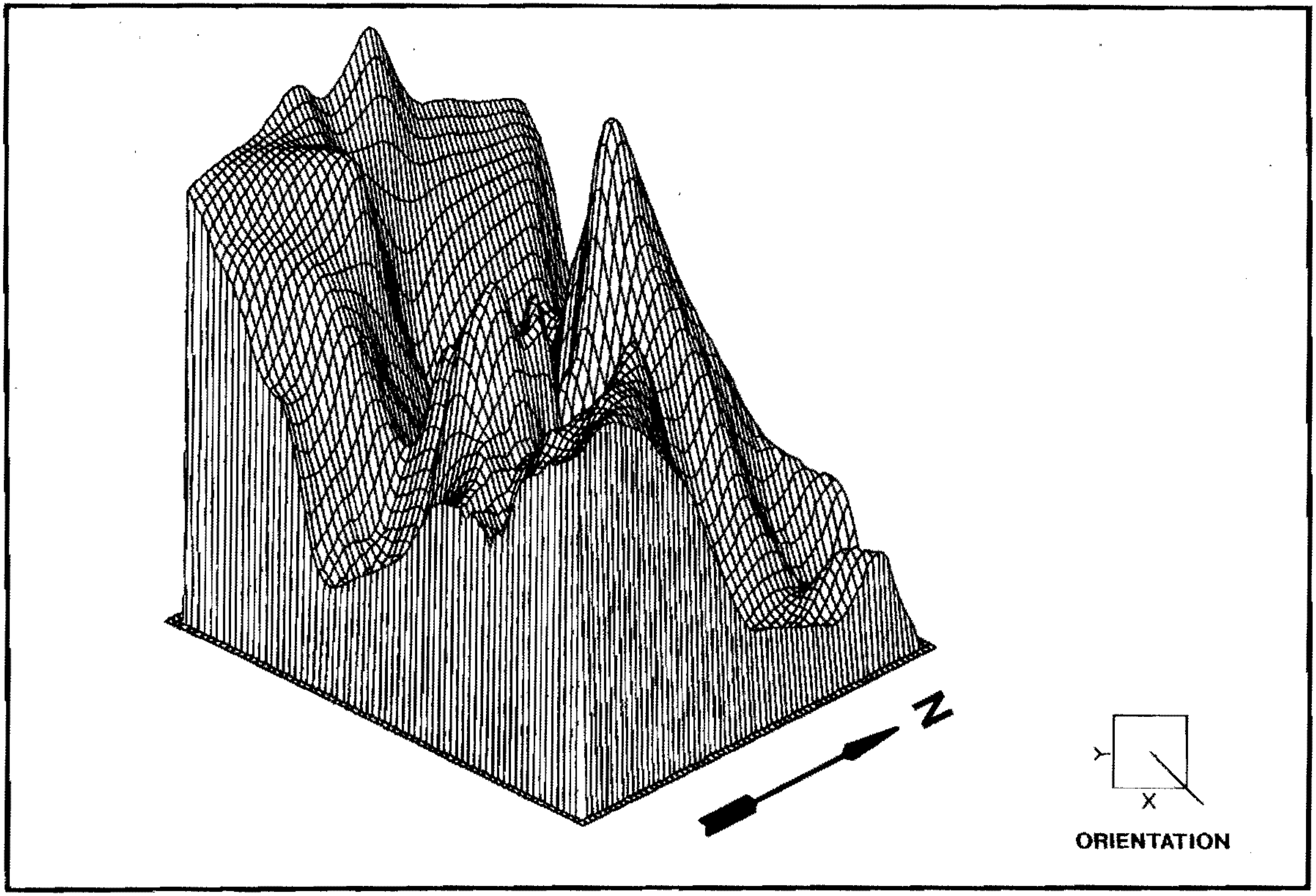

N
Y
X
ORIENTATION

Figure 12. Revised residual Bouguer gravity anomaly map excluding the computer generated data where no field data exists (after Figure 8). Contour interval is 0.05 mgals.

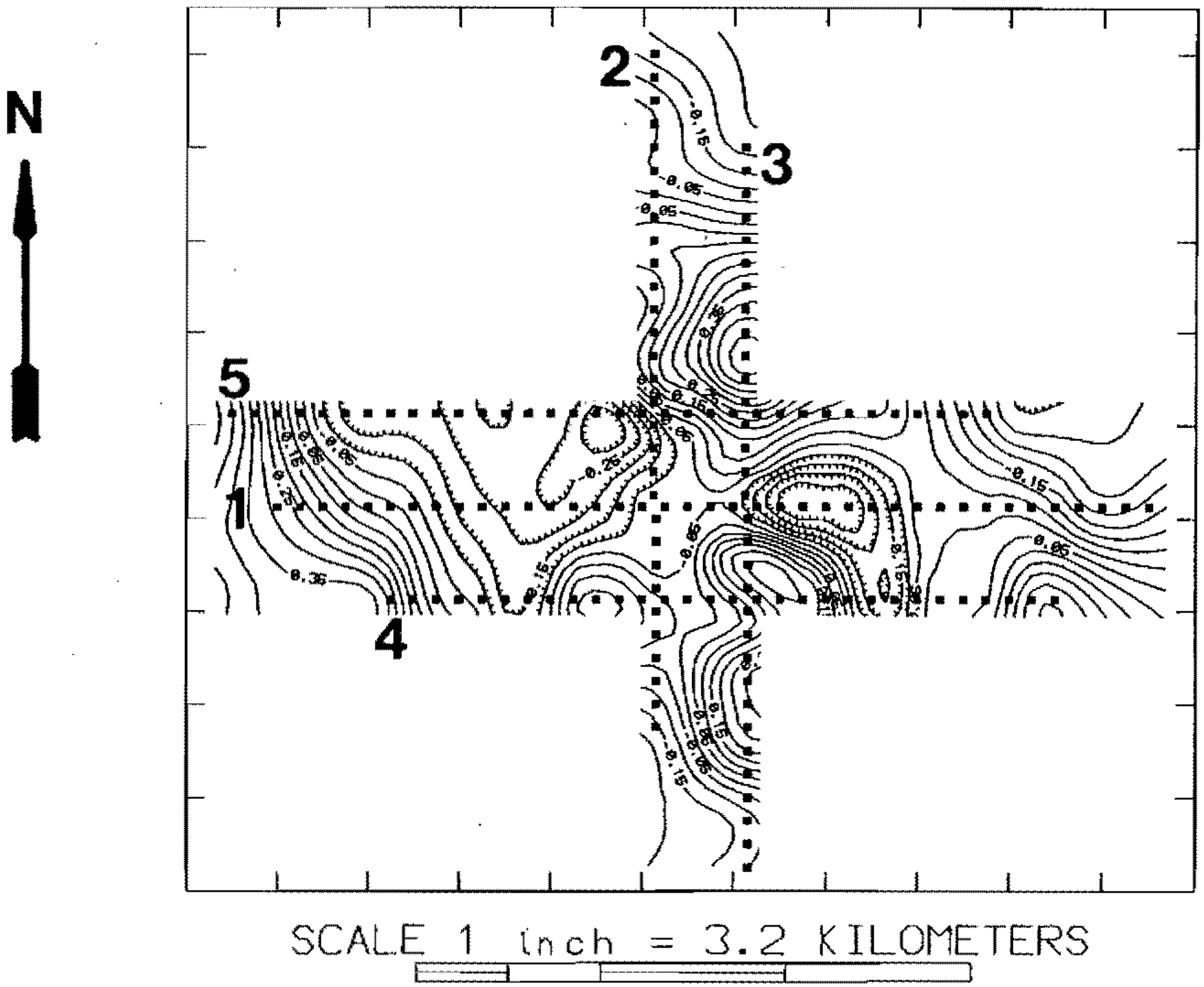
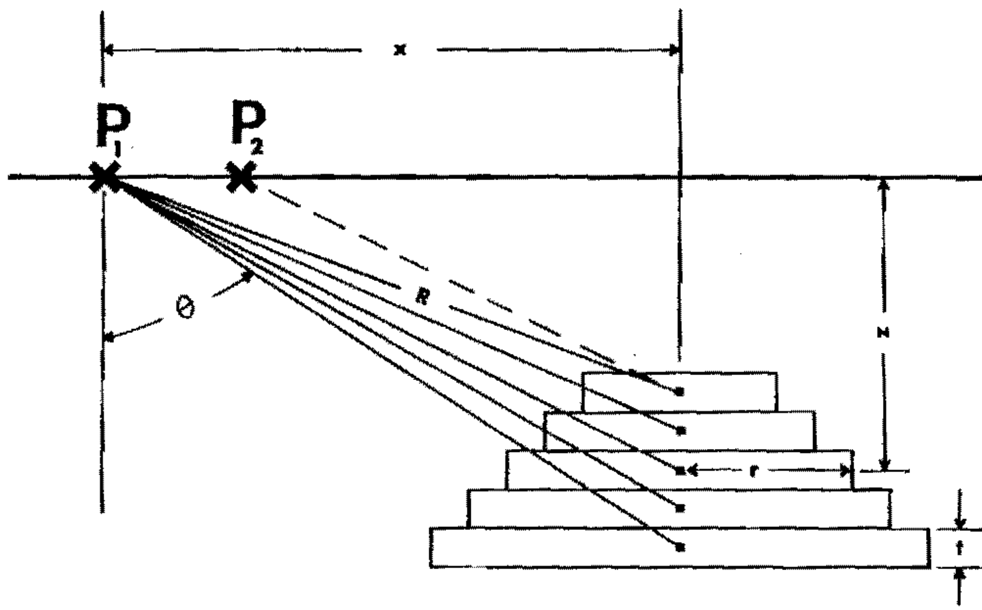

N
1
2
3
4
5
0.05
0.15
0.25
0.35
SCALE 1 inch = 3.2 KILOMETERS

Figure 13. Generalized geometry of stacked discs used in the computer program to model the residual signals as reef structures.



x
P1
P2
R
θ
z
r
t

permitted arrangements which simulated the assumed pinnacle geometry suggested by Ehrets and Kissling (1987). A general expression for the gravity signal (g_z) at point P is given by:

$$g_z = G * \rho * \frac{\cos(\theta)}{R^2} * V$$

where G = the universal gravity constant
ρ = density contrast
θ = angle between vertical and center of disc
R = distance from P to center of disc
$V = \pi * r^2 * t$ (volume of each disc)

therefore,

$$g_z = G * \rho * \frac{\pi * r^2 * t}{R^2} * \cos(\theta)$$

$$g_z = G * \rho * \frac{\pi * r^2 * t}{R^2} * \frac{z}{R}$$

and finally,

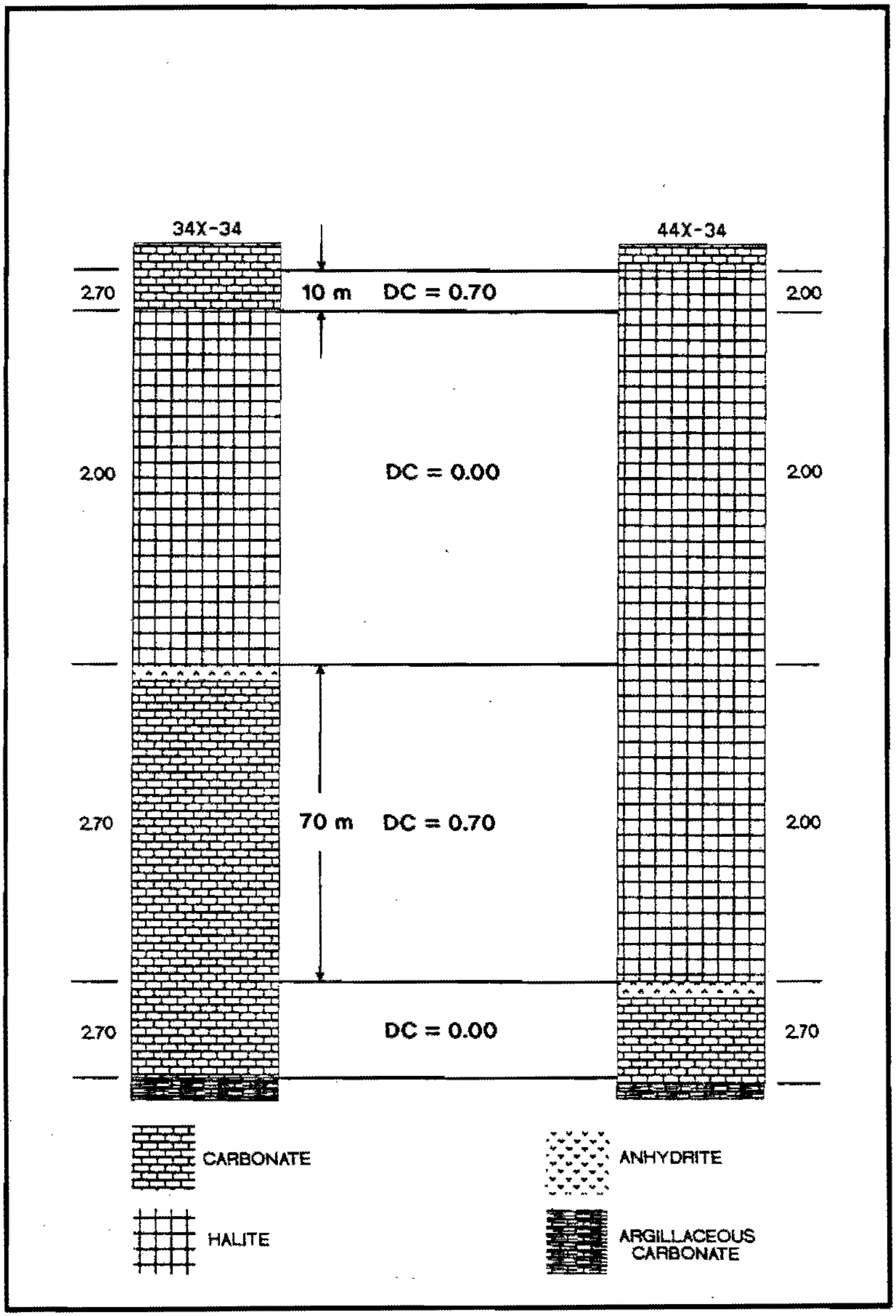
$$g_z = G * \rho * \pi * \frac{r^2 * t * z}{(x^2 + z^2)^{3/2}} .$$

The summation of each disc's gravity signal contribution at a given point P was the total gravity signal at that point. As the disc or point changed, all distances and dimensions were recalculated within the program to account for the new spatial relationship. The three-dimensional computer program also has the capability to generate a total gravity measurement at each point due to several individual stacks (buildups), each with unique dimensions and positions.

The bulk density wireline logs from each borehole (Shell Golden #34X-34 and Shell Golden #44X-34) were used to obtain the density contrast between the Prairie Formation halite and the Winnipegosis Formation carbonate buildup (Figure 14). The average bulk density of the halite in Shell Golden #44X-34 was 2.05 gm/cm^3 while in Shell Golden #34X-34 it was 1.95 gm/cm^3. The combined average value of 2.00 gm/cm^3 was therefore used as the density of the halite for the model. The average bulk density of the carbonate buildup in both Shell Golden #44X-34 and Shell Golden #34X-34 was about 2.70 gm/cm^3. Therefore, the density contrast (DC) between the halite and the carbonate buildup was determined to be 0.70 gm/cm^3 (Figure 14).

Because the base of the Dawson Bay is lower over the reef (Shell Golden #34X-34) than off-reef (Shell Golden #44X-34), a lateral density contrast 10 m thick exists that will contribute to the overall gravity signal observed at the surface (Figure 14). A similar value of 0.70 gm/cm^3 was used for the density contrast between the Dawson Bay carbonates and the Prairie halite.

Figure 14. Determination of density contrast (DC) between the carbonate material of the Winnipegosis and Dawson Bay and the Prairie evaporites. Densities are based on average bulk density logs given for each hole. Density units are gm/cm^3.


34X-34
44X-34
2.70
10 m
DC = 0.70
2.00
2.00
DC = 0.00
2.00
2.70
70 m
DC = 0.70
2.00
2.70
DC = 0.00
2.70
CARBONATE
ANHYDRITE
HALITE
ARGILLACEOUS CARBONATE

INTERPRETATION

Based on data from only two boreholes, the Shell Golden reef was interpreted as a pinnacle reef (Fischer and Burke, 1987). However, in other Winnipegosis reef studies where more data exist, such as increased core control and/or seismic information (i.e. Martindale and MacDonald, 1989), more refined interpretations have been made. These studies indicate a variety of carbonate buildup morphologies exist including elongate buildups (Martindale and MacDonald, 1989).

The residual Bouguer gravity anomaly map (Figures 10 and 12) reveals two anomalies. One is centered along Line 3 about 1.2 km north of Line 5. The anomaly appears circular with a maximum amplitude of about 0.5 mgals., however, the actual geometry is not known because data do not exist to the east. The other anomaly appears more elongate and is located along Line 3 beginning at Line 1 and extending south-southeastward for about 4 kilometers. A maximum amplitude of about 0.3 mgals occurs in two places within this anomaly.

Shell Golden #34X-34, the borehole that penetrates reef material, is located between the two anomalies described previously. This indicates that Shell Golden #34X-34 is on the flank and not on the apex of the reef.

By assuming the Shell Golden reef to be a string of interconnected carbonate buildups and not a single buildup, a modelled gravity signal similar to the observed anomaly was obtained. The elongate anomaly (Figures 10 and 12) was modelled using two stacks of discs (reefs #1 and #2) with only a slight variation in dimensions and geometry (Table 1). Modelling this anomaly as an elongate buildup corresponds to the findings of Gendzwill (1978) and Martindale and MacDonald (1989) in the Williston Basin.

Table 1. Geometry of reef models. Diameters, depths, and thicknesses in meters, density contrasts in gms/cm^3. X and Y coordinates in .25 mile increments.

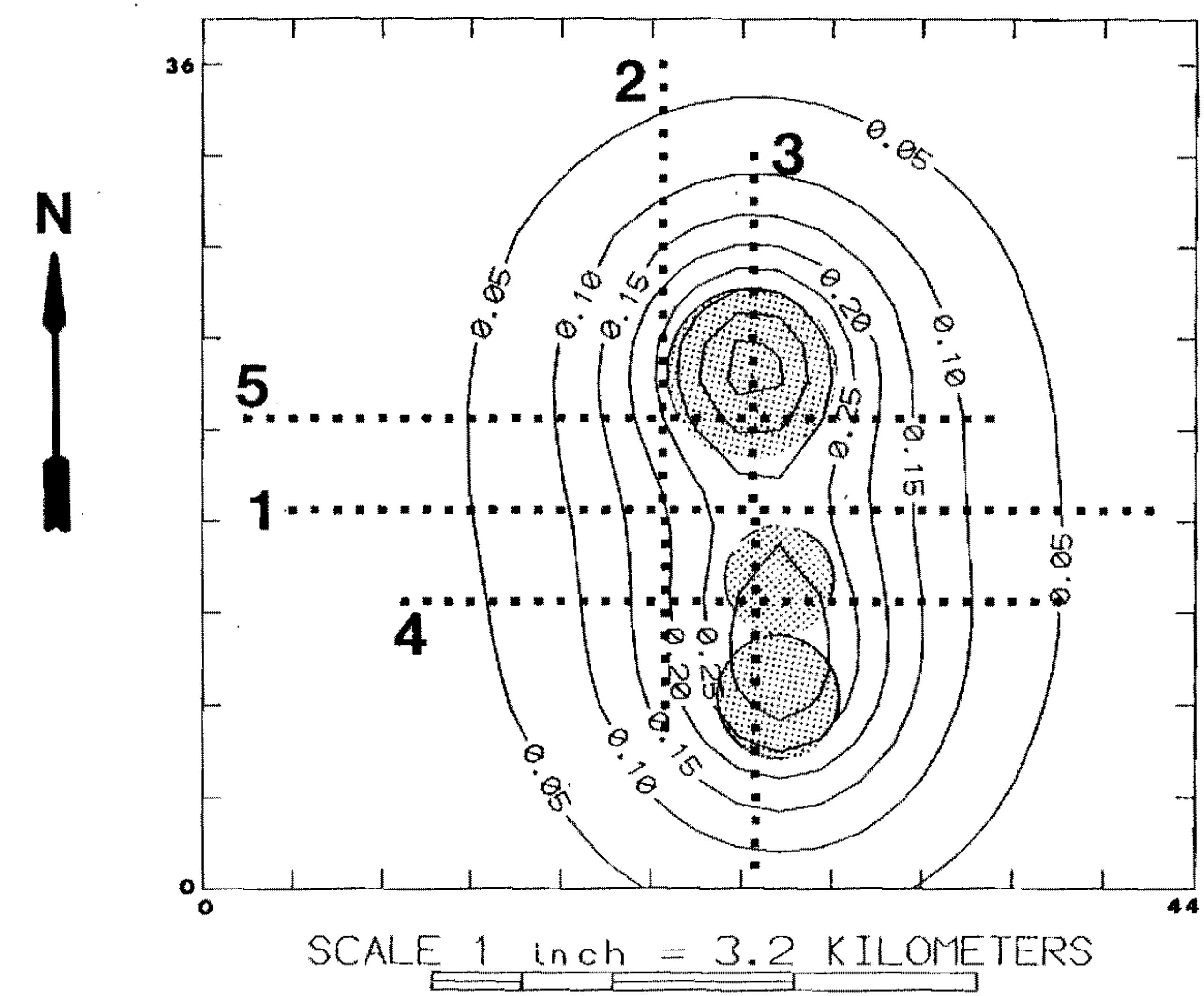
Reef #	X	Y	Bottom Dia.	Top Dia.	Depth to Top	Density Contrast	Thickness
1	25.75	13.50	855	760	2510	0.7	90
2	25.75	8.50	1160	1035	2510	0.7	90
3	24.50	23.00	1525	1220	2495	0.7	105

The total thickness of laterally contrasting material is 80 m, 70 m of which is from the reef buildup (Figure 14). The 70 m thickness indicated is only the minimum possible thickness of the reef because it is unlikely that a single borehole penetrates the reef at its apex and provides the maximum thickness. The 10 m thickness of laterally contrasting lithology created by probable salt solution of the Prairie Formation and subsequent subsidence of the Dawson Bay has been interpreted over other buildups in the Williston Basin (Gendzwill, 1978) and may apply to the Shell Golden reef. Whether or not the Dawson Bay has subsided over the entire area occupied by the reef is not known and cannot be determined using gravity methods.

The model anomaly (Figure 15) and the residual anomaly (Figures 10 and 12) are similar. Overall, the model is generally elongated, trending north-south along Line 3 with a maximum signal of about 0.3 mgals. The circular residual anomaly to the north was modelled using reef model #3 (Table 1) and all signals contributed from reef models #1 and #2. Although the residual anomaly has a maximum gravity signal of about 0.5 mgals, reef model #3 generated a maximum gravity signal of only about 0.4 mgals. If additional reef buildups existed to the east beyond the existing gravity data, they would contribute to the gravity signal and increase the maximum gravity signal obtained in the model of Table 1.

The residual Bouguer gravity anomaly map (Figures 10 and 12) indicates that the two anomalies modelled appear to be separated by a linear eastwest gravity low feature. This gravity low feature begins east of the intersection of Lines 1 and 3 and continues westward along Line 1 to the low indicated west of Line 2. This separation is interpreted to be due to the influence of an undetermined geologic feature that generates a negative anomaly along this Line. The algebraic sum of the higher density carbonate signals and the lower density undetermined geologic feature signals would be less than the positive signal of the reef complex, hence masking the positive signal of the reef. This would explain the absence of a positive residual anomaly where the Shell Golden carbonate buildup is identified by the two drill holes (Figure 4). The extent of the reef buildup therefore would continue along Line 3 for about 8 km in a north-south direction

Figure 15. Contour map of combined computer generated gravity data. Three hypothetical carbonate buildups were modelled with reef #1 and reef #2 side by side to generate an elongate anomaly. Reef #3 was isolated to generate the circular anomaly. Table 1 lists the specific geometry of each reef model. Contour interval is 0.05 mgals.


N
36
0
0
44
1
2
3
4
5
0.05
0.10
0.15
0.20
0.25
SCALE 1 inch = 3.2 KILOMETERS

(Figure 15). The trend of the elongate buildup indicates that it developed parallel to the adjacent margin of the Elk Point basin.

Proprietary seismic data on the Shell Golden reef were not available for use in this study. Consequently, the analysis presented in this study relies on gravity data and stratigraphic data from two well logs. Ideally, a combination of geophysical methods, such as gravity and seismology, would provide a better constrained model.

CONCLUSIONS

The Shell Golden reef is known to exist because of interpretations of wireline logs and cores from two boreholes located about 280 m apart. Because data from two boreholes is insufficient to accurately determine the dimensions of a carbonate reef or buildup, gravity techniques were used to indicate the actual dimensions of the Shell Golden reef.

The residual Bouguer gravity anomaly map generated over the Shell Golden reef indicates an elongate north-south trending carbonate buildup about 8 km long and 850 to 1500 m wide. Gravity modelling indicates relief between the base and the top of the buildup ranged between 90 and 105 m. This elongate interpretation of the Shell Golden reef conflicts with the present interpretation that shows the reef as a pinnacle.

The occurrence of elongate carbonate buildups have been documented elsewhere in the Winnipegosis Formation. Drill core and seismic information were the primary data used in these other studies. However, seismic data over the Shell Golden reef was not found in the literature. The use of detailed gravity analysis, however, could complement and/or reduce the amount of seismic data needed. Gravity data could also increase the horizontal coverage over known carbonate buildups.

RECOMMENDATIONS

Gravity data should be reduced and interpreted in the field at appropriate stages of the data collection process. This would aid in determining if additional features are present as well as ascertaining their directional trends. Consequently, gravity stations can be added and additional survey lines strategically located for optimum data collection.

Survey line spacing less than 1.6 kilometer should be attempted where possible or economically feasible. If the station spacing along the profiles is 0.4 kilometer, then the survey line spacing should also be 0.4 kilometer. This generates a uniform grid pattern and eliminates the possibility of holes or gaps in the data set.

Survey equipment should consist of a level instead of a theodolite. Although creating more setups, the level is a more accurate instrument and would reduce the amount of error in determining the elevation of the gravity stations. The use of the Global Positioning Satellite (GPS) for locating the gravity stations should also be considered when determining the methods to be used for other detailed gravity surveys.

APPENDICES

APPENDIX A

Field Data and Corrections

GOLDEN REEF: LINE 1 (E-W)

STATION	ELEVATION	OBSERVED GRAVITY	METER CORRECTION	DRIFT CORRECTION	FREE-AIR CORRECTION	BOUGUER CORRECTION	LATITUDE CORRECTION	N/S DEVIATION	N/S CORRECTION	OFFSET CORRECTION	BOUGUER ANOMALY
1	1912.0	4269.803	118.444	-0.043	179.839	-61.039	0.000	-78	-0.0191	0.650	4507.634
2	1911.9	4269.837	118.445	-0.041	179.836	-61.038	0.000	-68	-0.0167	0.650	4507.672
3	1916.1	4269.431	118.434	-0.040	180.228	-61.172	0.000	0	0.0000	0.650	4507.532
4	1912.3	4269.560	118.438	-0.038	179.871	-61.050	0.000	100	0.0245	0.650	4507.455
5	1913.2	4269.422	118.434	-0.036	179.956	-61.079	0.000	100	0.0245	0.650	4507.371
6	1909.7	4269.671	118.441	-0.028	179.626	-60.967	0.000	80	0.0196	0.650	4507.413
7	1903.6	4270.068	118.452	-0.024	179.053	-60.772	0.000	80	0.0196	0.650	4507.446
8	1896.3	4270.333	118.459	-0.018	178.366	-60.539	0.000	75	0.0184	0.650	4507.269
9	1903.5	4269.811	118.445	-0.012	179.043	-60.769	0.000	-74	-0.0182	0.650	4507.149
10	1893.5	4270.458	118.463	-0.007	178.103	-60.450	0.000	-90	-0.0221	0.650	4507.194
11	1899.3	4270.056	118.451	-0.001	178.648	-60.635	0.000	103	0.0253	0.650	4507.195
12	1897.6	4270.069	118.452	0.005	178.488	-60.581	0.000	122	0.0299	0.650	4507.113
13	1898.0	4270.021	118.450	0.011	178.526	-60.594	0.000	-89	-0.0218	0.650	4507.043
14	1887.8	4270.594	118.466	-0.009	177.567	-60.268	0.000	-68	-0.0167	0.650	4506.983
15	1885.3	4270.955	118.476	-0.021	177.331	-60.188	0.000	-97	-0.0238	0.650	4507.179
16	1882.7	4271.075	118.480	-0.029	177.087	-60.105	0.000	-105	-0.0258	0.650	4507.131
17	1878.9	4271.308	118.486	-0.039	176.729	-59.984	0.000	-75	-0.0184	0.650	4507.132
18	1886.6	4271.196	118.483	-0.046	177.454	-60.230	0.000	0	0.0000	0.650	4507.507
19	1885.3	4270.679	118.469	-0.056	177.328	-60.187	0.000	-50	-0.0123	0.650	4506.870
20	1888.5	4270.680	118.469	-0.064	177.634	-60.291	0.000	80	0.0196	0.650	4507.098
21	1887.2	4270.549	118.465	-0.075	177.513	-60.250	0.000	0	0.0000	0.650	4506.852
22	1873.8	4271.058	118.479	-0.215	176.250	-59.821	0.000	0	0.0000	0.650	4506.400
23	1864.2	4271.575	118.493	-0.094	175.347	-59.515	0.000	53	0.0130	0.650	4506.470
24	1860.8	4272.172	118.510	-0.104	175.027	-59.406	0.000	-66	-0.0162	0.650	4506.833
25	1856.5	4272.155	118.510	-0.111	174.621	-59.268	0.000	-66	-0.0162	0.650	4506.539
26	1853.7	4272.353	118.515	-0.039	174.363	-59.181	0.000	144	0.0353	0.650	4506.697
27	1846.7	4272.456	118.518	-0.034	173.698	-58.955	0.000	120	0.0295	0.650	4506.362
28	1845.9	4273.141	118.537	-0.030	173.628	-58.931	0.000	138	0.0339	0.650	4507.029
29	1841.9	4272.917	118.531	0.085	173.252	-58.804	0.000	130	0.0319	0.650	4506.663
30	1841.2	4273.257	118.540	-0.023	173.187	-58.782	0.000	-100	-0.0245	0.650	4506.805
31	1837.7	4273.366	118.543	-0.019	172.857	-58.670	0.000	-100	-0.0245	0.650	4506.703
32	1832.8	4273.560	118.549	-0.015	172.390	-58.511	0.000	-90	-0.0221	0.650	4506.601
33	1830.0	4273.608	118.550	-0.011	172.133	-58.424	0.000	80	0.0196	0.650	4506.525
34	1829.8	4273.786	118.555	-0.003	172.113	-58.417	0.000	-70	-0.0172	0.650	4506.666
35	1824.9	4273.746	118.554	-0.088	171.652	-58.261	0.000	50	0.0123	0.650	4506.265
36	1824.8	4273.712	118.553	-0.062	171.637	-58.255	0.000	-60	-0.0147	0.650	4506.220
37	1823.9	4273.549	118.548	-0.039	171.559	-58.229	0.000	-60	-0.0147	0.650	4506.023
38	1823.9	4273.511	118.547	-0.018	171.559	-58.229	0.000	-73	-0.0179	0.650	4506.002
39	1831.9	4273.047	118.534	0.004	172.309	-58.483	0.000	-80	-0.0196	0.650	4506.041

GOLDEN REEF: LINE 2 (N-S)

STATION	ELEVATION	OBSERVED GRAVITY	METER CORRECTION	DRIFT CORRECTION	FREE-AIR CORRECTION	BOUGUER CORRECTION	LATITUDE CORRECTION	N/S DEVIATION	N/S CORRECTION	OFFSET CORRECTION	BOUGUER ANOMALY
40	1853.1	4279.071	118.701	-0.101	174.303	-59.160	-6.174	0.000	0.0000	0.569	4507.208
41	1851.0	4279.033	118.700	-0.100	174.105	-59.093	-5.849	0.000	0.0000	0.569	4507.365
42	1859.7	4278.291	118.680	-0.099	174.923	-59.371	-5.524	0.000	0.0000	0.569	4507.469
43	1864.6	4277.742	118.665	-0.097	175.384	-59.527	-5.199	0.000	0.0000	0.569	4507.535
44	1863.5	4277.515	118.658	-0.096	175.281	-59.492	-4.874	0.000	0.0000	0.569	4507.560
45	1864.9	4277.036	118.645	-0.095	175.413	-59.537	-4.549	0.000	0.0000	0.569	4507.481
46	1868.9	4276.571	118.632	-0.092	175.789	-59.665	-4.224	0.000	0.0000	0.569	4507.579
47	1873.6	4276.139	118.620	-0.091	176.231	-59.815	-3.900	0.000	0.0000	0.569	4507.753
48	1879.2	4275.509	118.603	-0.023	176.758	-59.993	-3.575	0.000	0.0000	0.569	4507.847
49	1880.0	4275.100	118.591	0.001	176.833	-60.019	-3.250	0.000	0.0000	0.569	4507.825
50	1878.5	4274.559	118.576	0.018	176.692	-59.971	-2.925	0.000	0.0000	0.569	4507.518
51	1891.6	4273.593	118.549	0.056	177.924	-60.389	-2.600	0.000	0.0000	0.569	4507.702
52	1885.2	4273.607	118.550	0.098	177.322	-60.185	-2.275	0.000	0.0000	0.569	4507.686
53	1881.2	4273.702	118.552	0.100	176.946	-60.057	-1.950	0.000	0.0000	0.569	4507.862
54	1882.5	4273.320	118.542	0.102	177.068	-60.099	-1.625	0.000	0.0000	0.569	4507.877
55	1886.2	4272.694	118.525	0.104	177.416	-60.217	-1.300	0.000	0.0000	0.569	4507.791
56	1887.8	4271.812	118.500	0.106	177.567	-60.268	-0.975	0.000	0.0000	0.569	4507.311
57	1887.0	4271.425	118.489	0.113	177.491	-60.242	-0.650	0.000	0.0000	0.569	4507.195
58	1877.5	4271.852	118.501	0.117	176.598	-59.939	-0.325	0.000	0.0000	0.569	4507.372
59	1883.6	4270.938	118.476	0.119	177.171	-60.134	0.000	0.000	0.0000	0.569	4507.139
60	1879.9	4271.046	118.479	-0.007	176.823	-60.016	0.000	0.000	0.0000	0.876	4507.202
61	1877.8	4270.754	118.471	-0.027	176.626	-59.949	0.325	0.000	0.0000	0.876	4507.076
62	1884.1	4270.143	118.454	-0.337	177.218	-60.150	0.650	0.000	0.0000	0.876	4506.854
63	1884.9	4269.866	118.446	-0.347	177.294	-60.175	0.975	0.000	0.0000	0.876	4506.935
64	1893.5	4268.949	118.421	-0.360	178.103	-60.450	1.300	0.000	0.0000	0.876	4506.839
65	1895.4	4268.511	118.408	-0.369	178.281	-60.511	1.625	0.000	0.0000	0.876	4506.822
66	1895.1	4267.997	118.394	-0.383	178.253	-60.501	1.950	0.000	0.0000	0.876	4506.587
67	1887.3	4267.918	118.392	-0.397	177.519	-60.252	2.275	0.000	0.0000	0.876	4506.331
68	1886.6	4267.634	118.384	-0.405	177.454	-60.230	2.600	0.000	0.0000	0.876	4506.313
69	1886.8	4267.060	118.368	-0.416	177.472	-60.236	2.925	0.000	0.0000	0.876	4506.050

GOLDEN REEF: LINE 3 (N-S)

STATION	ELEVATION	OBSERVED GRAVITY	METER CORRECTION	DRIFT CORRECTION	FREE-AIR CORRECTION	BOUGUER CORRECTION	LATITUDE CORRECTION	N/S DEVIATION	N/S CORRECTION	OFFSET CORRECTION	BOUGUER ANOMALY
70	1852.5	4278.421	118.683	-0.257	174.246	-59.141	-4.874	0.000	0.000	0.556	4507.634
71	1854.6	4278.123	118.675	-0.256	174.444	-59.208	-4.549	0.000	0.000	0.556	4507.784
72	1862.1	4277.369	118.654	-0.255	175.149	-59.448	-4.224	0.000	0.000	0.556	4507.802
73	1864.5	4276.816	118.639	-0.088	175.375	-59.524	-3.900	0.000	0.000	0.556	4507.875
74	1857.9	4276.999	118.644	-0.073	174.754	-59.313	-3.575	0.000	0.000	0.556	4507.993
75	1860.4	4276.706	118.636	-0.059	174.989	-59.393	-3.250	0.000	0.000	0.556	4508.186
76	1859.9	4276.311	118.625	-0.046	174.942	-59.377	-2.925	0.000	0.000	0.556	4508.086
77	1859.1	4276.241	118.623	-0.037	174.867	-59.352	-2.600	0.000	0.000	0.556	4508.298
78	1862.7	4275.649	118.607	-0.016	175.206	-59.467	-2.275	0.000	0.000	0.556	4508.260
79	1862.6	4275.329	118.598	-0.001	175.196	-59.464	-1.950	0.000	0.000	0.556	4508.265
80	1865.4	4274.932	118.587	-0.049	175.460	-59.553	-1.625	0.000	0.000	0.556	4508.308
81	1870.9	4274.173	118.566	-0.067	175.977	-59.728	-1.300	0.000	0.000	0.556	4508.177
82	1864.9	4273.797	118.555	-0.089	175.413	-59.537	-0.975	0.000	0.000	0.556	4507.720
83	1865.8	4273.301	118.541	-0.119	175.497	-59.566	-0.650	0.000	0.000	0.556	4507.561
84	1872.3	4272.404	118.516	-0.155	176.109	-59.773	-0.325	0.000	0.000	0.556	4507.332
85	1878.9	4271.892	118.502	-0.193	176.729	-59.984	0.000	0.000	0.000	0.556	4507.503
86	1883.8	4270.679	118.469	-0.052	177.190	-60.140	0.000	0.000	0.000	1.042	4507.187
87	1884.3	4270.597	118.466	-0.173	177.237	-60.156	0.325	0.000	0.000	1.042	4507.338
88	1872.9	4270.934	118.476	-0.193	176.165	-59.792	0.650	0.000	0.000	1.042	4507.281
89	1874.0	4270.411	118.461	-0.203	176.268	-59.827	0.975	0.000	0.000	1.042	4507.126
90	1871.8	4269.680	118.441	-0.227	176.062	-59.757	1.300	0.000	0.000	1.042	4506.540
91	1876.6	4269.011	118.422	-0.244	176.513	-59.910	1.625	0.000	0.000	1.042	4506.458
92	1890.7	4268.096	118.397	-0.258	177.839	-60.361	1.950	0.000	0.000	1.042	4506.704
93	1890.1	4267.722	118.387	-0.273	177.783	-60.341	2.275	0.000	0.000	1.042	4506.593
94	1892.0	4267.060	118.368	-0.289	177.962	-60.402	2.600	0.000	0.000	1.042	4506.340
95	1891.4	4266.574	118.355	-0.286	177.905	-60.383	2.925	0.000	0.000	1.042	4506.131
96	1889.7	4266.401	118.350	-0.282	177.745	-60.329	3.250	0.000	0.000	1.042	4506.177
97	1885.4	4265.731	118.331	-0.278	177.341	-60.191	3.575	0.000	0.000	1.042	4505.550
98	1891.4	4264.678	118.302	-0.275	177.905	-60.383	3.900	0.000	0.000	1.042	4505.169
99	1883.6	4264.842	118.307	-0.271	177.171	-60.134	4.224	0.000	0.000	1.042	4505.181
100	1876.7	4264.436	118.295	-0.268	176.522	-59.914	4.549	0.000	0.000	1.042	4504.663
101	1878.0	4264.149	118.287	-0.264	176.645	-59.955	4.874	0.000	0.000	1.042	4504.778

GOLDEN REEF: LINE 4 (E-W)

STATION	ELEVATION	OBSERVED GRAVITY	METER CORRECTION	DRIFT CORRECTION	FREE-AIR CORRECTION	BOUGUER CORRECTION	LATITUDE CORRECTION	N/S DEVIATION	N/S CORRECTION	OFFSET CORRECTION	BOUGUER ANOMALY
102	1916.0	4268.760	118.415	-0.293	180.219	-61.168	0.000	0.0	0.000	1.950	4507.882
103	1921.2	4268.129	118.398	-0.289	180.708	-61.334	0.000	0.0	0.000	1.950	4507.561
104	1909.4	4268.303	118.403	-0.285	179.598	-60.958	0.000	0.0	0.000	1.950	4507.011
105	1909.2	4268.768	118.416	-0.279	179.579	-60.951	0.000	0.0	0.000	1.950	4507.483
106	1913.2	4268.324	118.403	-0.273	179.956	-61.079	0.000	-20.0	-0.005	1.950	4507.275
107	1912.8	4268.086	118.397	-0.267	179.918	-61.066	0.000	0.0	0.000	1.950	4507.017
108	1897.8	4268.684	118.413	-0.263	178.507	-60.587	0.000	0.0	0.000	1.950	4506.704
109	1904.8	4268.867	118.418	-0.255	179.166	-60.811	0.000	0.0	0.000	1.950	4507.335
110	1892.6	4269.332	118.431	-0.194	178.018	-60.421	0.000	-30.0	-0.007	1.950	4507.108
111	1888.6	4269.885	118.447	-0.203	177.642	-60.294	0.000	0.0	0.000	1.950	4507.427
112	1889.2	4269.487	118.436	-0.216	177.698	-60.313	0.000	10.0	0.002	1.950	4507.045
113	1886.6	4269.650	118.440	-0.225	177.454	-60.230	0.000	20.0	0.005	1.950	4507.044
114	1890.9	4269.344	118.432	-0.234	177.858	-60.367	0.000	0.0	0.000	1.950	4506.982
115	1888.6	4269.317	118.431	-0.245	177.642	-60.294	0.000	0.0	0.000	1.950	4506.801
116	1882.8	4269.528	118.437	-0.257	177.096	-60.108	0.000	-27.0	-0.007	1.950	4506.639
117	1882.6	4269.629	118.440	-0.266	177.077	-60.102	0.000	0.0	0.000	1.950	4506.728
118	1876.4	4269.966	118.449	-0.263	176.494	-59.904	0.000	-78.0	-0.019	1.950	4506.673
119	1879.4	4269.872	118.446	-0.255	176.776	-60.000	0.000	-80.0	-0.020	1.950	4506.770
120	1874.9	4270.331	118.459	-0.252	176.353	-59.856	0.000	-62.0	-0.015	1.950	4506.970
121	1864.5	4270.682	118.469	-0.294	175.375	-59.524	0.000	-72.0	-0.018	1.950	4506.639
122	1864.8	4270.577	118.466	-0.284	175.403	-59.534	0.000	-65.0	-0.016	1.950	4506.562
123	1856.0	4270.133	118.453	-0.277	174.575	-59.253	0.000	-75.0	-0.018	1.950	4505.564
124	1857.0	4270.699	118.469	-0.271	174.669	-59.285	0.000	-62.0	-0.015	1.950	4506.217
125	1847.8	4270.847	118.473	-0.265	173.804	-58.991	0.000	0.0	0.000	1.950	4505.818
126	1844.8	4271.657	118.496	-0.256	173.522	-58.895	0.000	90.0	0.022	1.950	4506.495
127	1843.5	4271.334	118.487	-0.435	173.400	-58.854	0.000	90.0	0.022	1.950	4505.904
128	1843.4	4271.047	118.479	-0.420	173.390	-58.851	0.000	90.0	0.022	1.950	4505.617
129	1846.0	4271.313	118.486	-0.406	173.635	-58.934	0.000	90.0	0.022	1.950	4506.066
130	1838.0	4271.818	118.500	-0.396	172.882	-58.678	0.000	55.0	0.013	1.950	4506.090
131	1839.5	4271.589	118.494	-0.380	173.023	-58.726	0.000	0.0	0.000	1.950	4505.950

GOLDEN REEF: LINE 5 (E-W)

STATION	ELEVATION	OBSERVED GRAVITY	METER CORRECTION	DRIFT CORRECTION	FREE-AIR CORRECTION	BOUGUER CORRECTION	LATITUDE CORRECTION	N/S DEVIATION	N/S CORRECTION	OFFSET CORRECTION	BOUGUER ANOMALY
132	1902.5	4271.839	118.501	-0.344	178.949	-60.737	0.000	50	0.0123	-0.647	4507.572
133	1903.9	4271.533	118.492	-0.356	179.081	-60.782	0.000	61	0.0150	-0.647	4507.336
134	1905.9	4271.417	118.489	-0.371	179.269	-60.846	0.000	60	0.0147	-0.647	4507.326
135	1899.9	4271.597	118.494	-0.363	178.705	-60.654	0.000	-50	-0.0123	-0.647	4507.119
136	1897.3	4271.600	118.494	-0.351	178.460	-60.571	0.000	-82	-0.0201	-0.647	4506.965
137	1894.8	4271.781	118.499	-0.335	178.225	-60.491	0.000	-51	-0.0125	-0.647	4507.019
138	1890.9	4272.034	118.506	-0.321	177.858	-60.367	0.000	-65	-0.0160	-0.647	4507.047
139	1892.3	4271.821	118.500	-0.308	177.990	-60.412	0.000	70	0.0172	-0.647	4506.961
140	1894.4	4272.083	118.508	-0.387	178.187	-60.479	0.000	45	0.0110	-0.647	4507.276
141	1891.1	4272.018	118.506	-0.287	177.877	-60.373	0.000	-50	-0.0123	-0.647	4507.080
142	1886.3	4272.291	118.513	-0.273	177.425	-60.220	0.000	60	0.0147	-0.647	4507.104
143	1878.8	4272.742	118.526	-0.259	176.720	-59.981	0.000	100	0.0245	-0.647	4507.125
144	1884.3	4272.377	118.516	-0.247	177.237	-60.156	0.000	65	0.0160	-0.647	4507.095
145	1878.3	4272.809	118.528	-0.234	176.673	-59.965	0.000	60	0.0147	-0.647	4507.178
146	1882.6	4272.596	118.522	-0.210	177.077	-60.102	0.000	53	0.0130	-0.647	4507.249
147	1883.0	4272.502	118.519	-0.207	177.115	-60.115	0.000	50	0.0123	-0.647	4507.179
148	1872.4	4273.195	118.538	-0.204	176.118	-59.776	0.000	0	0.0000	-0.647	4507.223
149	1863.1	4273.090	118.536	-0.201	175.243	-59.479	0.000	78	0.0191	-0.647	4506.560
150	1861.1	4274.176	118.566	-0.198	175.055	-59.416	0.000	84	0.0206	-0.647	4507.557
151	1861.6	4274.183	118.566	-0.351	175.102	-59.432	0.000	80	0.0196	-0.647	4507.441
152	1860.3	4274.255	118.568	-0.350	174.980	-59.390	0.000	92	0.0226	-0.647	4507.438
153	1863.4	4274.078	118.563	-0.348	175.271	-59.489	0.000	58	0.0142	-0.647	4507.442
154	1851.4	4274.936	118.587	-0.347	174.143	-59.106	0.000	72	0.0177	-0.647	4507.583
155	1845.9	4275.292	118.597	-0.346	173.625	-58.930	0.000	75	0.0184	-0.647	4507.609
156	1844.7	4275.290	118.597	-0.345	173.513	-58.892	0.000	65	0.0160	-0.647	4507.531
157	1841.3	4275.500	118.602	-0.343	173.193	-58.784	0.000	75	0.0184	-0.647	4507.539
158	1838.0	4275.723	118.609	-0.342	172.882	-58.678	0.000	86	0.0211	-0.647	4507.568
159	1837.1	4275.687	118.608	-0.341	172.798	-58.649	0.000	75	0.0184	-0.647	4507.473
160	1837.6	4275.660	118.607	-0.339	172.845	-58.665	0.000	-75	-0.0184	-0.647	4507.442
161	1841.8	4275.468	118.601	-0.179	173.240	-58.799	0.000	-65	-0.0160	-0.647	4507.667
162	1834.0	4275.582	118.605	-0.183	172.506	-58.550	0.000	-83	-0.0204	-0.647	4507.291
163	1832.2	4275.505	118.603	-0.186	172.337	-58.493	0.000	67	0.0164	-0.647	4507.134
164	1836.5	4275.550	118.604	-0.190	172.741	-58.630	0.000	70	0.0172	-0.647	4507.444
165	1832.6	4275.256	118.596	-0.193	172.374	-58.506	0.000	70	0.0172	-0.647	4506.897

APPENDIX B

Computer Program Listing

```
10 DIM X(10), Y(10), RAD1(10), RAD2(10), DT(10), DRAD(25, 10), TGXY(50, 50), RHO(10), T(10)
20 KEY OFF
30 CLS
40 WIDTH "LPT1:", 132
50 REM N = 0
60 CLS : REM N = N + 1
61 OPEN "A:REEF.DAT" FOR INPUT AS #1
62 DO UNTIL EOF(1)
     INPUT #1, N, X(N), Y(N), RAD1(N), RAD2(N), DT(N), RHO(N), T(N)
     LPRINT USING "#####.#  "; N; X(N); Y(N); RAD1(N); RAD2(N); DT(N); RHO(N); T(N)
63 LOOP
64 CLOSE #1: GOTO 200
70 LOCATE 10, 10: PRINT ; "Enter the X and Y coordinate of reef  . (X,Y):"
80 LOCATE 10, 46: PRINT N
90 LOCATE 10, 56: INPUT ; " ", X(N), Y(N)
100 LOCATE 11, 10: PRINT "Enter the following dimensions: "
110 LOCATE 13, 13: INPUT ; "Enter the bottom disc radius: ", RAD1(N)
120 LOCATE 14, 13: INPUT ; "Enter the top disc radius: ", RAD2(N)
130 LOCATE 15, 13: INPUT ; "Enter the depth to the top of the stack: ", DT(N)
140 LOCATE 16, 13: INPUT ; "Enter the density contrast of the stack, (g/cm^3): ", RHO(N)
150 IF N > 1 GOTO 180
160 LOCATE 17, 13: INPUT ; "Enter the thickness of the stack: ", T
170 LOCATE 18, 13: INPUT ; "Enter the size of the square grid: ", GS
180 LOCATE 20, 13: INPUT ; "Do you want another stack? ", ANS1$
190 IF ANS1$ = "Y" OR ANS1$ = "y" THEN 60
200 M = 5280: PI = 3.1415926#: G = 2.029225E-03: ND = 25: SS = 1320: L = N: GS = 11
210 INC = GS * M / SS
220 FOR N = 0 TO 10
230     DRAD(0, N) = RAD2(N + 1)
240     IF N = L - 1 THEN 250 ELSE 241
241 NEXT N
250 N = L
260 FOR J = 0 TO N
270 IF J = N GOTO 320
280     FOR I = 1 TO ND - 1
290     DRAD(I, J) = DRAD(I - 1, J) + (RAD1(J + 1) - RAD2(J + 1)) / (ND - 1)
300     NEXT I
310 NEXT J
320 H = T(N) / ND
330 FOR J = 0 TO INC
340 REM LPRINT : REM LPRINT
350     FOR I = 0 TO INC
360     TG = 0
370             FOR N = 1 TO 10
380             TGRAV = 0
390             IF X(N) = 0 AND Y(N) = 0 THEN 480
400                     FOR K = 0 TO ND - 1
410                     Z = DT(N) + H / 2 + H * K
420                     KJ = G * RHO(N) * PI
430 GRAV = KJ * DRAD(K, N - 1) ^ 2 * H * Z / ((ABS(X(N) - SS * I)) ^ 2 + (ABS(Y(N) - SS * J)) ^
        2 + Z ^ 2) ^ 1.5
440                     TGRAV = TGRAV + GRAV
450                     NEXT K
460             TG = TG + TGRAV
```

```
470              NEXT N
480      TGXY(I, J) = TG
490 REM     LPRINT CHR$(27); CHR$(15);
500 REM     LPRINT USING "+.###"; TGXY(I, J);
501 REM     PRINT I
510      NEXT I
511 PRINT J
520 NEXT J
530 REM LPRINT CHR$(12);
540 REM LPRINT CHR$(18);
550 CLS
551 LOCATE 10, 10: INPUT ; "Do you want to save this data to disk for SURFII? (Y/N) ", ANS3$
552 IF ANS3$ = "Y" OR ANS3$ = "y" THEN 590 ELSE 560
560 CLS : LOCATE 10, 10: INPUT ; "Do you want to create another model? ", ANS2$
570 IF ANS2$ = "Y" OR ANS2$ = "y" THEN 20 ELSE END
580 REM LPRINT CHR$(27); CHR$(15);
590 LOCATE 12, 10: INPUT ; "Enter the file name for this data. ", C$: C$ = C$ + ".out"
591 OPEN C$ FOR OUTPUT AS #1
600 FOR J = 0 TO INC
605 Y = INC - J
610      FOR I = 0 TO INC
615      X = 0 + I
620      PRINT #1, USING "##.## ##.## #.###"; X; Y; TGXY(I, J):
630      NEXT I
640 NEXT J
650 CLOSE #1: GOTO 560
660 END
```

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