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Gravity Modeling of a Patch Reef in Allegan County, Michigan

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GRAVITY MODELING OF A PATCH REEF IN ALLEGAN COUNTY, MICHIGAN

by

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CERTIFICATE OF ORAL EXAMINATION

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The title of the paper is:

"Gravity Modeling of a Reef in Allegan County, Michigan"

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GRAVITY MODELING OF A REEF IN ALLEGAN COUNTY, MICHIGAN

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The study of the Diamond Springs oil field in Allegan County focuses on the use of gravity to delineate individual reef buildups. The Diamond Springs oil field is a small patch reef located in northern Allegan County, Michigan. The reef, which is approximately 1400 feet deep, is located within the Middle Devonian Traverse Limestone and was deposited in an open shelf, carbonate platform and lagoonal environment. The reef covers an area of approximately one square mile and has a vertical relief of 30 to 80 feet. These porous reef materials are commonly buried by muds or evaporites resulting in ideal conditions for the entrapment of hydrocarbons. Using data from cores and well logs available at the Michigan Basin Core Repository at Western Michigan University, the densities of the Diamond Springs patch reef and its surrounding rocks were determined. With this data, a theoretical gravity model was constructed for the reef using a computer modeling program. After these theoretical models were determined on the computer, field work was conducted. The gravity stations were located 200 feet apart, along a paved road and were surveyed in so as to determine their elevation and the location. Gravity models obtained from the reduced field data were then compared with the theoretically determined models.

ACKNOWLEDGEMENTS

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Mei Leng Wong

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INTRODUCTION

A reef is a mound shaped feature that consists of the skeletal remains of corals, algae or similar shallow water organisms. Patch reefs are biohermal buildups formed in shallow waters in close proximity to shallow shelf margins. These porous reef materials are commonly buried by muds or evaporites resulting in ideal conditions for the generation and entrapment of hydrocarbons. Within the Michigan Basin, these reefs are major sources of oil and gas accumulations. Current estimates of total recoverable reserves within Michigan reefs range from 500 to 800 million barrels of oil and 5 to 8 trillion cubic feet of gas. The principal means of exploration for these reefs are geophysical methods.

OBJECTIVES

The objective of this research is to delineate a reef in the subsurface using the geophysical method of gravity which relies on the lateral variation in the densities of the rocks. Data, such as, densities and depths to tops of formation for the Diamond Springs patch reef was collected from driller's logs at the Michigan Basin Core Repository at

Western Michigan University. A cross section of this reef was determined from this data. Based on this cross section, a theoretical gravity model was constructed using the 2D gravity modeling program MAGIX. Field work, utilizing geophysical gravity methods was then conducted across the reef. From the reduced field data, a field gravity model of the reef was simulated. The theoretical and field models were then compared.

STUDY LOCATION

The study area is the Diamond Springs oil field in Allegan County, Michigan (Figure 1). The field is located at the intersection of four townships - Salem (Section 31, T4N, R13W), Overisel (Section 35, T4N, R14W), Monterey (Section 6, T3N, R13W) and Heath (Section 1, T3N, R14W).

The field has an area of approximately one square mile and is limestone in composition. Since its discovery in 1939 to 1986, the Diamond Springs patch reef has produced about one million barrels of oil (Bellinger and others, 1991). The depth of production in this field is relatively shallow at approximately 1300 feet. Several of the wells are still producing today.

The oil in this field has been interpreted as being produced from a patch reef, which is a mound shaped,

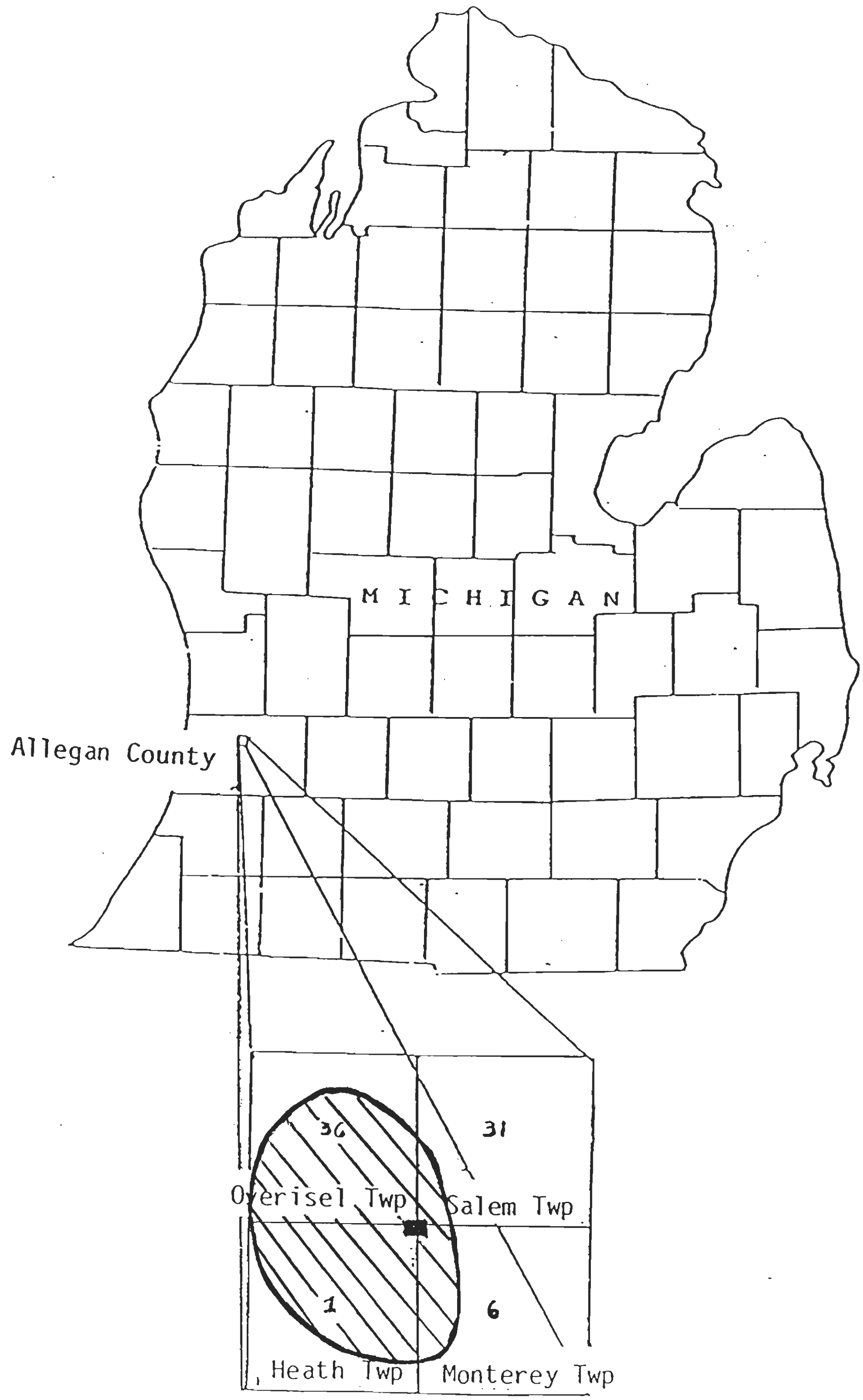


Figure 1: Location map of the Diamond Springs Oil Field (modified from Henderson, 1988)

isolated, carbonate buildup of skeletal material, surrounded on the flanks by fine-grained, white, carbonate sands. The total production of oil from patch reefs in the Traverse Limestone is estimated as being 110 million barrels (Michigan Geological Survey, 1987; Michigan Oil and Gas News, 1988).

GEOLOGICAL HISTORY OF THE STUDY AREA

The Diamond Springs patch reef is in the Middle Devonian Traverse Limestone, which is approximately 400 million years old. The Traverse Limestone formed when a distal muddy sea underwent multiple transgressions and regressions across the Michigan Basin during the Middle Devonian (Gardner, 1974). During this period, a north-south barrier formed on the western side of the Michigan Basin. This barrier created a lagoonal type environment with restricted sea water influx (Henderson, 1988). Reef complexes are commonly encountered on the western edge of this barrier, as patch reefs, or reefs in general, tend to form on hard substrate of a shallow sea, one atop another in defiance to the sorting of waves (Agnich, 1956).

During the Devonian, the Michigan Basin was a sedimentary basin (Caughlin and others, 1976). Today, the Michigan Basin is a large, circular, northward tilting structural depression with 16,000 feet (4800 meters) of Paleozoic marine sedimentary rock overlain by glacial deposits (Catacosinos and others, 1990).

GENERAL GEOLOGY

The subsurface geology of this area can essentially be divided into 3 layers:

A) Layer 1: Glacial outwash and post-glacial alluvium

Layer 1 consists of glacial outwash and debris deposited approximately 14,000 years ago. This layer consists of interbedded sand and gravel layers 10 to 20 feet thick. Incorporated within these layers are occasional clay stringers approximately 5 feet thick (Henderson, 1988). The thickness of the glacial outwash ranges from 60 to at least 142 feet (Figure 2). Surface topography is primarily gentle with occasional rolling hills. The hills within the study area have a relief of approximately 20 feet (Henderson, 1988).

B) Layer 2: Paleozoic section

Layer 2 contains the Paleozoic stratigraphic section of southwest Michigan (Figure 3) and extends to a depth of about 5000 feet. The

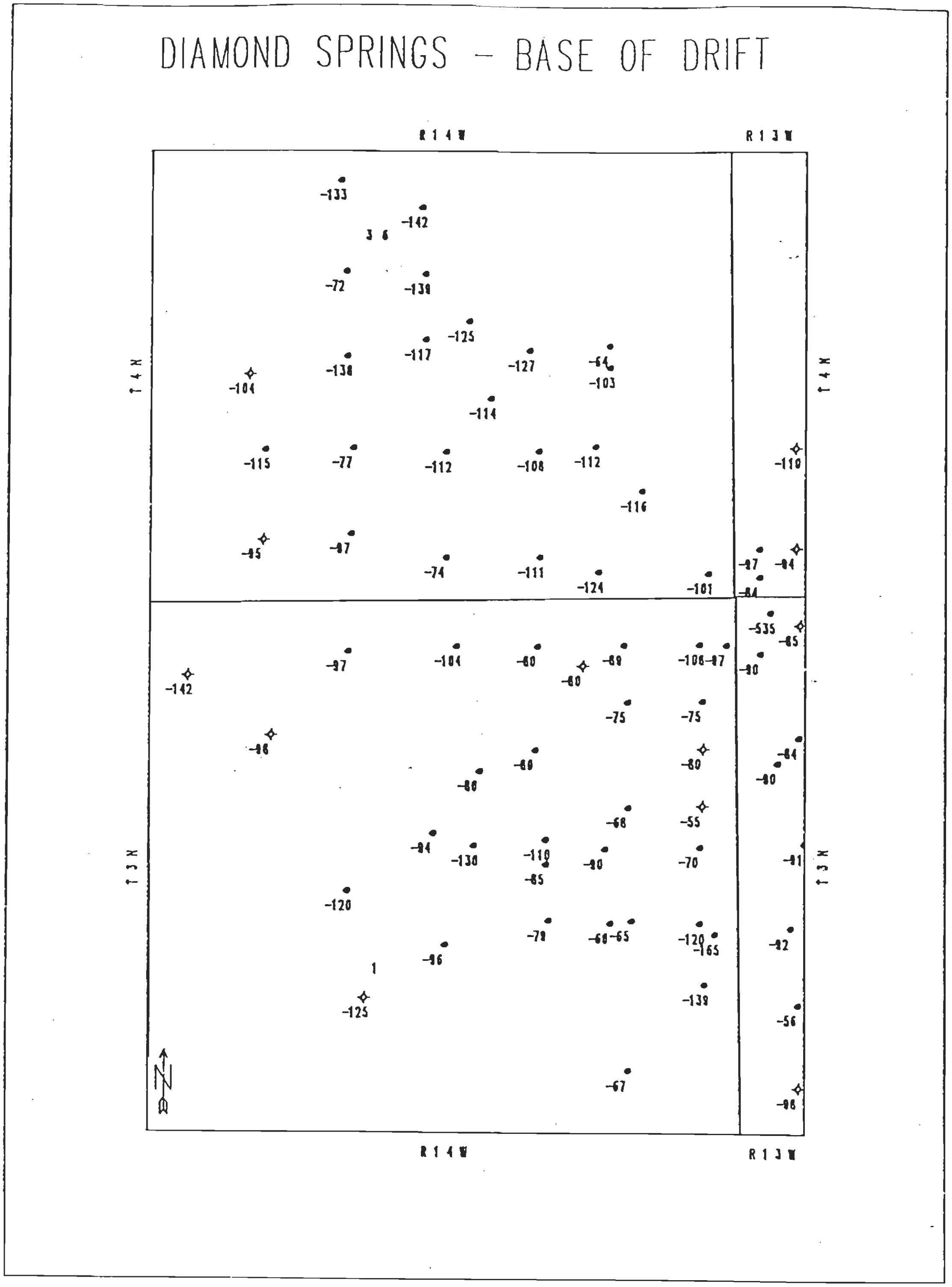
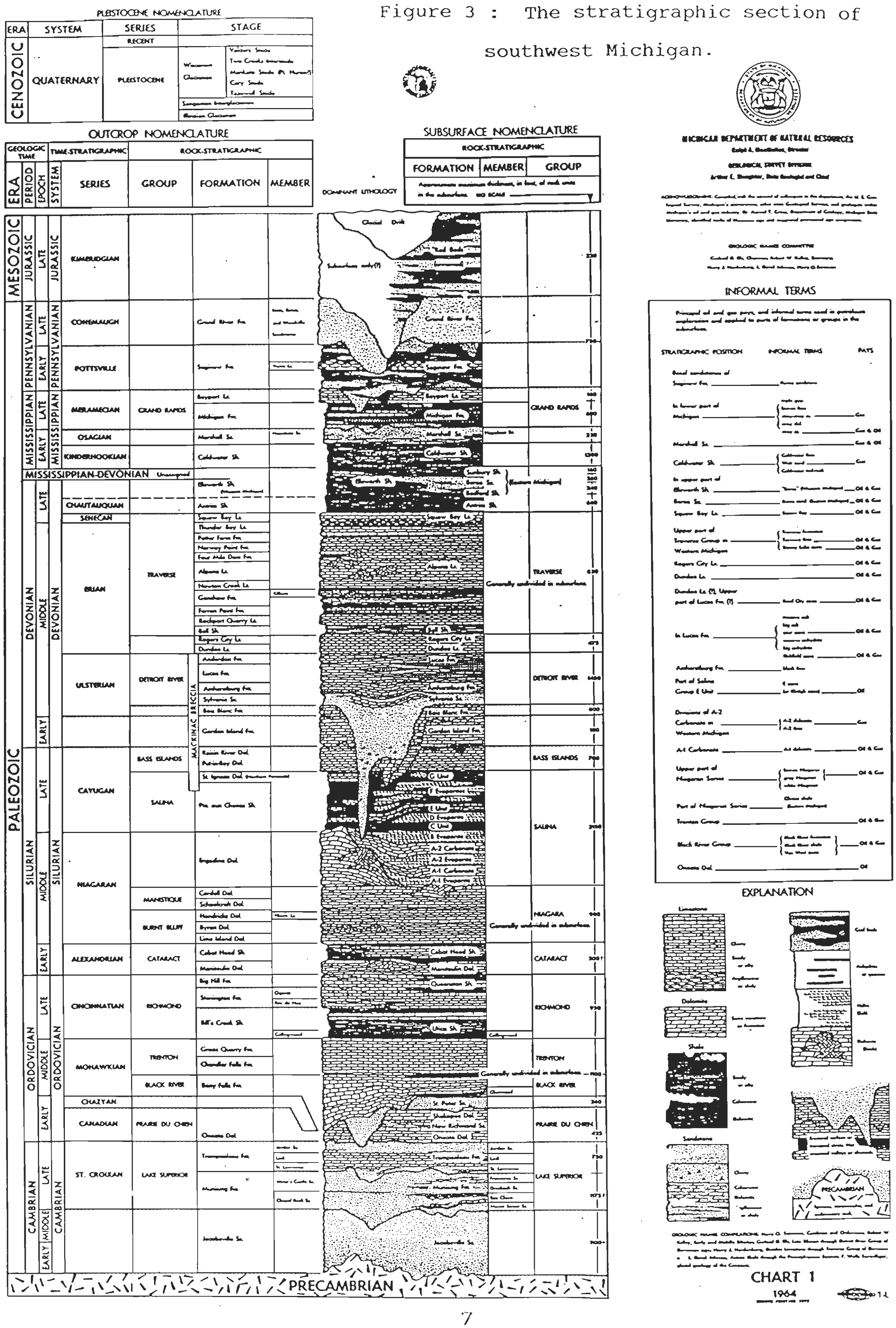


Figure 2: Base map of the Diamond Springs Oil Field, posted with depths to the base of the glacial drift.

Figure 3 : The stratigraphic section of southwest Michigan.



stratigraphic section within the study area is composed primarily of sandstones, limestones and shale. The topmost formation in this area is the Early Mississippian Coldwater Shale and the lowest formation of this Paleozoic section is the Cambrian Jacobsville Sandstone.

At a depth of about 1300 feet is the formation of interest in this research, the Middle Devonian Traverse Limestone. It consists of 80% limestone, 20% dolomite and grades from a brown to a gray limestone (Henderson, 1988). This unit is about 235 feet thick in the study area with the top of it ranging from subsea depths of 1365 to 1482 feet (Figure 4).

C) Layer 3: Basement complex

The underlying basement complex, which is at a depth of approximately 5000 feet, consists of granites and gneiss from the PreCambrian Eastern granite-rhyolite province (Bickford and others, 1986).

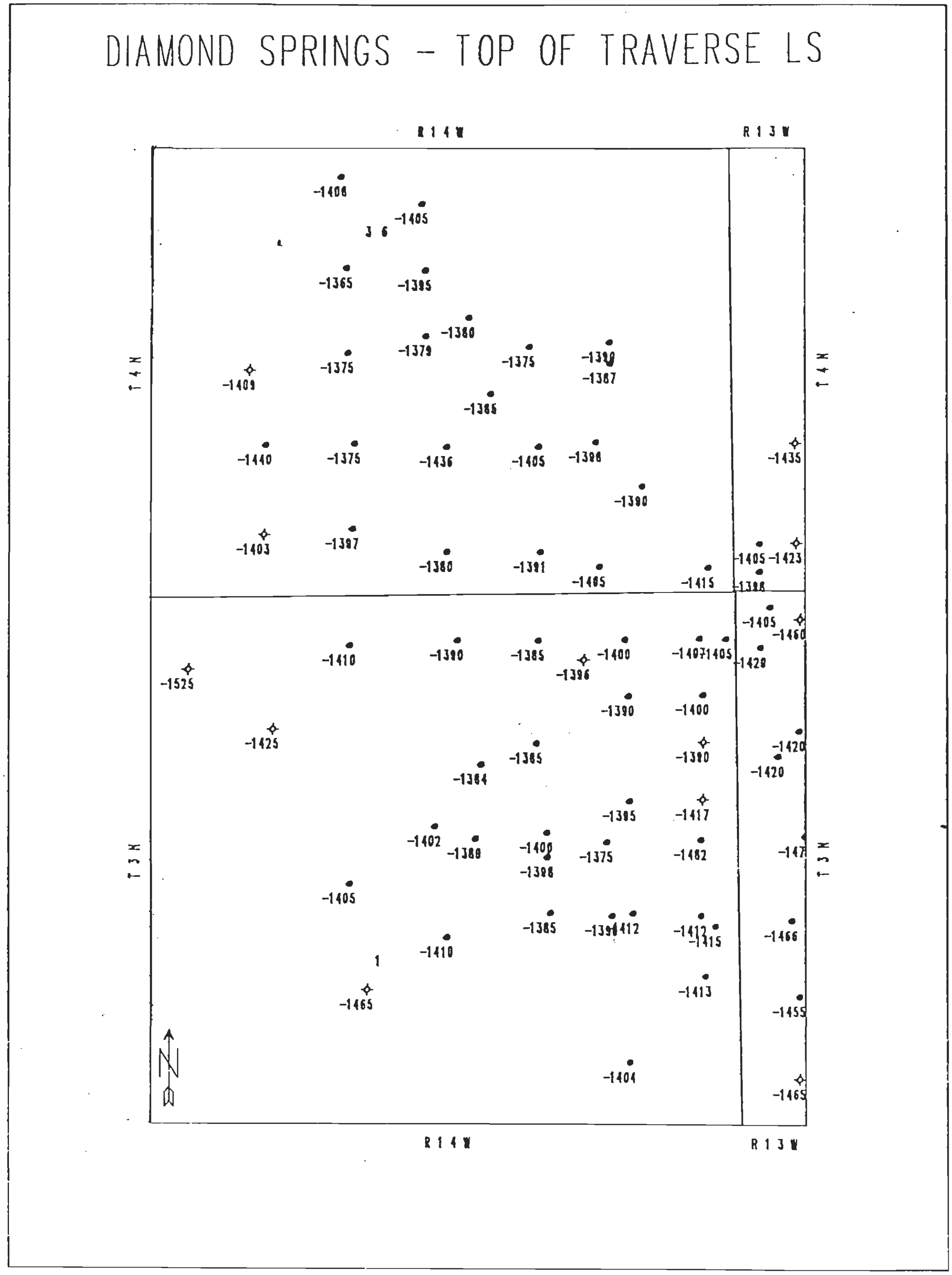


Figure 4: Base map of the Diamond Springs Oil Field, posted with depths to the top of the Traverse Limestone.

METHODOLOGY

THEORETICAL DATA ACQUISITION AND PROCEDURE

Depths to the base of the glacial drift and to the top of the Traverse Limestone within the study area, were obtained from drillers reports and well logs. Figure 4 shows the posting of wells in the Diamond Springs oil field where depths into the subsurface were recorded. The wells on this map indicates the extent of the Diamond Springs field.

The depths for wells in the cross-section A-A′ (Figure 5) were entered into the TERRASTATION computer program and an east-west stratigraphic cross section of the Diamond Springs oil field was constructed (Figure 6). Wells used in cross-section A-A′ are listed in Appendix I. Structure contour maps of the top of the Traverse Limestone (Figure 7) and the base of the drift (Figure 8) were also made.

The purpose of this part of my research was to ascertain if the Diamond Springs patch reef would appear as a mound shaped feature at the top of the Traverse Limestone because a reef creates a positive topographic expression on the sea floor even after it is buried at great depth. It was also to determine if this mound shaped effect would show up at the base of the glacial drift due to the draping effect of beds overlying the reef from differential

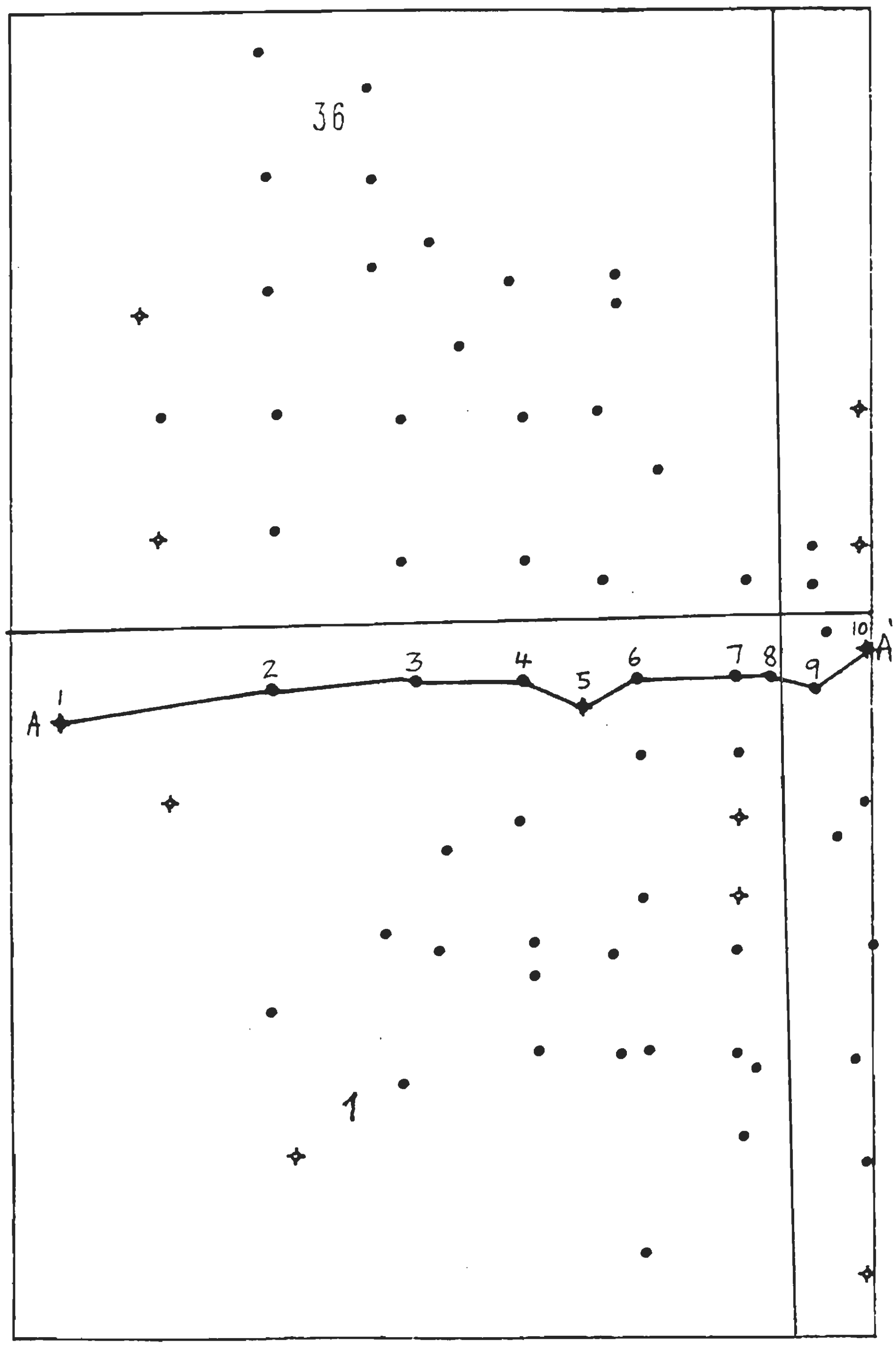


Figure 5: Base map of the Diamond Springs oil field indicating the wells which were chosen to make the east-west stratigraphic cross section A-A' (Appendix I).

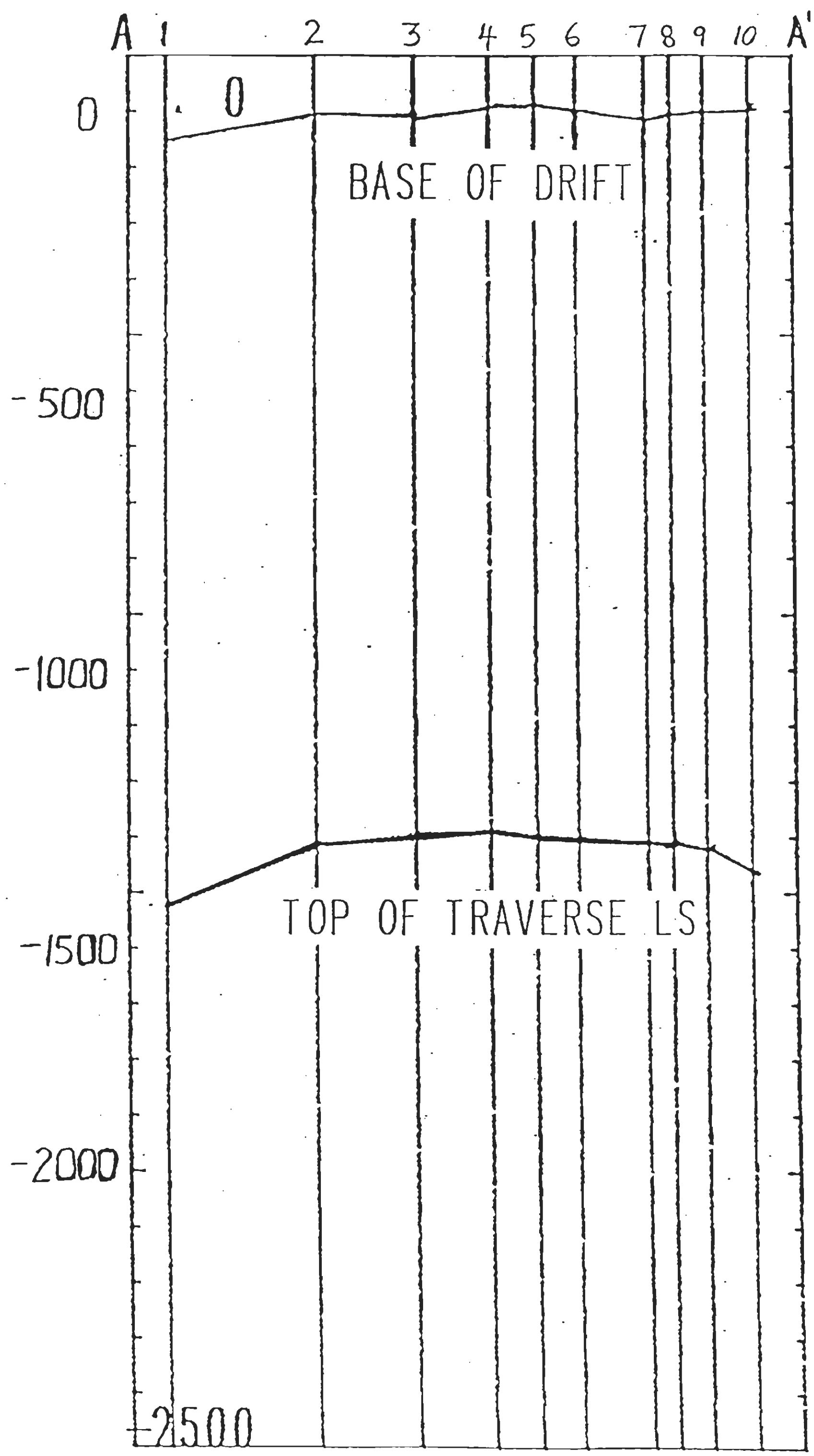


Figure 6: The east-west stratigraphic cross-section A-A' of the Diamond Springs oil field.

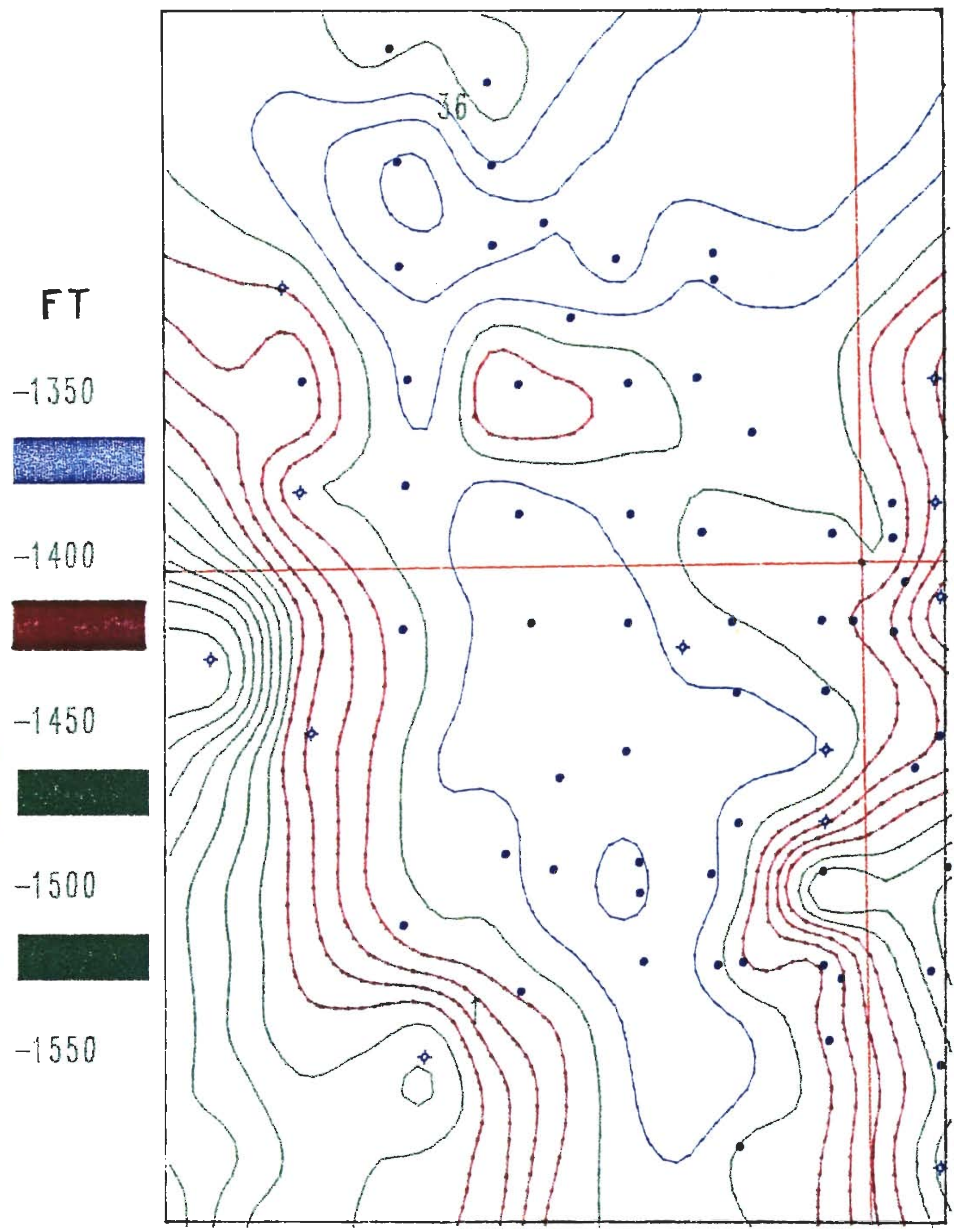


Figure 7: Structure contour map of the top of the Traverse Limestone.

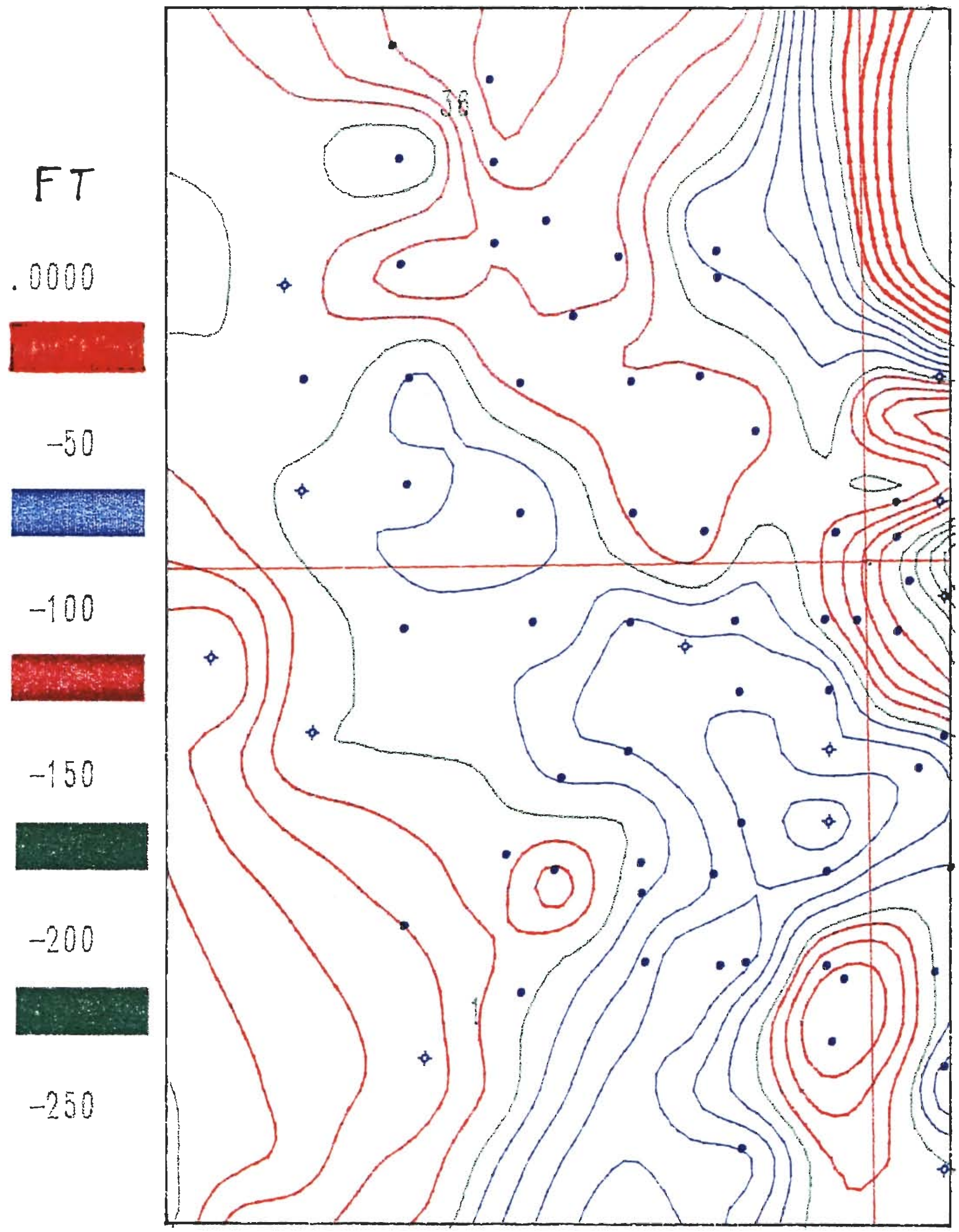


Figure 8: Structure contour map of the base of the glacial drift.

compaction (Gretener, 1970). This draping effect causes a thinning of beds on the reef and a thickening of beds off the reef (Ferris, 1962).

Depths to the base of the glacial drift in the study area had to be obtained so that the irregularities of this eroded and glaciated boundary could be accounted for during the gravity modeling of the subsurface (Pohly, 1968). Gravity readings are affected by changes in density between the unconsolidated drift material and the more dense Paleozoic bedrock. Irregularities at the base of the drift can thus cause minor gravity maximums or minimums to appear on the observed Bouguer anomaly of a gravity survey (Pohly, 1956).

The stratigraphic cross-section A-A′ indicates the mound-shaped presence of a reef in the subsurface Traverse Limestone (Figure 6). The structure contour map of the top of the Traverse Limestone (Figure 7) confirms the presence of this feature (the patch reef) in the subsurface because there is a shallow north-south trend in the middle of the map which gets progressively deeper toward the east-west flanks. Although it is not seen very clearly on the stratigraphic cross-section, the mound-shaped feature of the reef also shows up at the base of the glacial drift. This can be seen more clearly from the structure contour map of the base of the drift (Figure 8) where again we see a shallow north-south trend in the middle of the map getting progressively deeper towards the east-west flanks.

FIELD DATA ACQUISITION AND PROCEDURE

A detailed gravity survey was conducted on roads that ran across the Diamond Springs oil field (Figure in Appendix II). The road intersection of the four townships in the Diamond Springs oil field was established as a base station (DSBS). Fifty two stations, spaced 200 feet apart, were established a mile to the east and a mile to the west of this point. The 200 feet distance was measured by tape and the stations were marked by paint. Along the east side of the base station, the stations were marked by stakes with survey ribbons as paint was not an effective marker on dirt road.

Elevation of each of these stations was then measured relative to the elevation of the base station. Base station elevation was read off of the topographic map of the area as 645 feet. Elevation readings were established using a transit. Elevation of a gravity station affects the accuracy of the gravity readings obtained. Therefore, determination of the elevation of each station is essential in obtaining accurate gravity readings (Brown, 1949).

Gravity readings were taken at each of these station using a Lacoste-Romberg Gravimeter. The time at which these readings were taken was also recorded. The gravity reading at the base station was repeated every hour so that the drift of the instrument could be taken into account when reducing the field data.

DATA REDUCTION

The gravity values obtained by surveying differ from place to place because of the variances in the shape of the earth and the distribution of mass within the earth. These gravity values need to be corrected for variances in latitude, tidal variations, terrain, elevation (free-air) and Bouguer corrections. The observed (field) data is thus reduced (corrected) to obtain a value called the Bouguer anomaly.

The collected gravity data consists of station number, time, elevation and gravimeter dial reading. The GRAVPAC computer program was used to reduce this data. Station numbers, elevation, date, time and gravimeter dial readings were entered into this program. The program computed drift corrections, free-air corrections and Bouguer anomaly values for a density of 2.67 g/cm^3 (Appendix II).

MODELING

Models are used to explain the subsurface features which cause the patterns of gravity anomaly obtained from a survey. In two dimensional modeling (Talwani and others, 1959), the subsurface is divided into several different bodies which by themselves are homogenous. These different bodies are pieced together to reconstruct the subsurface. Because gravity is a function of the lateral variation in the densities of rocks, each modeled body is assigned an average density that simulates its condition in the subsurface (Pohly, 1954). The gravity anomaly produced by this reconstruction is then compared with the anomaly that is obtained from the gravity survey. A good fit or similarity for both these anomalies would indicate a reasonably good reconstruction of the subsurface (Pohly, 1953).

The subsurface features of the study area were modeled in this study using the 2D gravity modeling program MAGIX. A theoretical model of the subsurface was constructed based on the east-west stratigraphic cross-section to obtain a theoretical Bouguer anomaly. Then, based on the field Bouguer anomaly, the subsurface is modeled.

In the modeling process, five bodies were constructed in the subsurface (Figure 9). Densities for each of these bodies were obtained from well logs at the Michigan Basin

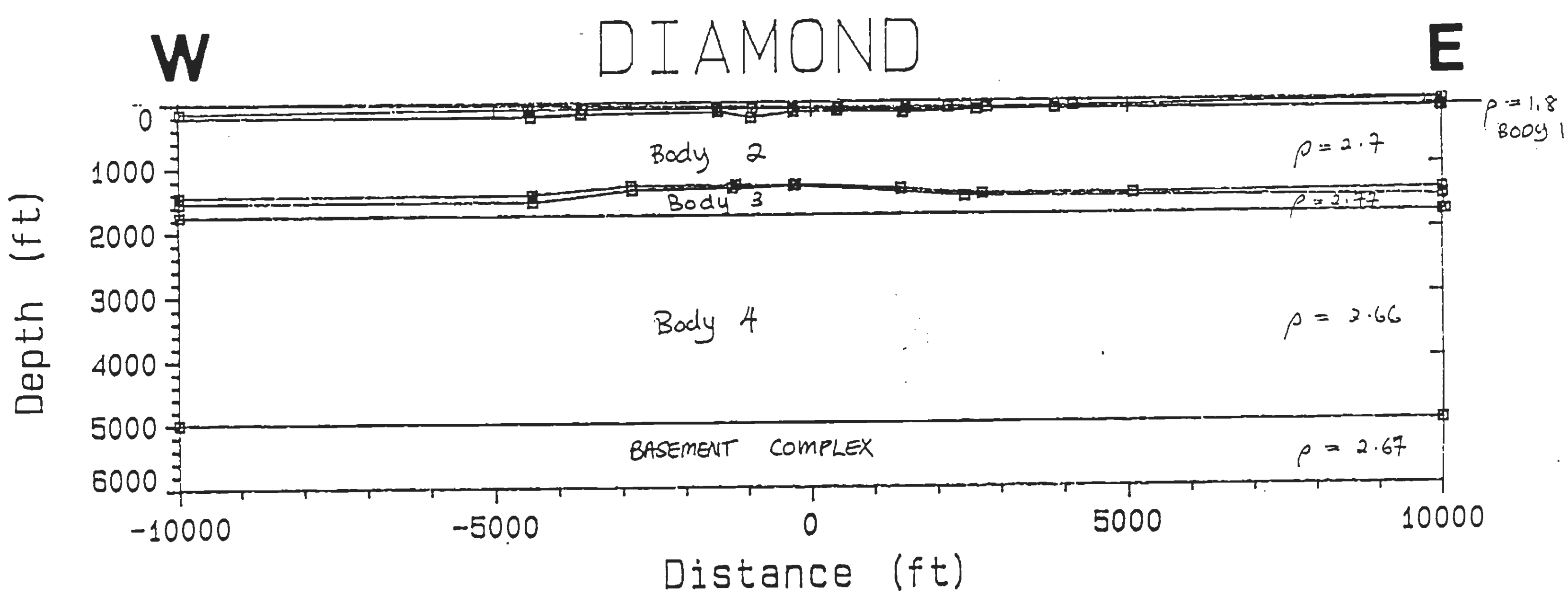


Figure 9: Bodies constructed in the gravity modeling of the study area, together with respective densities.

Core Repository at Western Michigan University. Density contrasts for these bodies were chosen relative to the density of the basement complex which is approximately 2.67 g/cm^3.

The description of the five bodies which were constructed to simulate the subsurface is as below :

A) <u>Body #1 - Glacial drift</u>

This body was given a density of 1.8 g/cm^3 (density contrast of - 0.87). The average depth was 100 feet.

B) <u>Body #2 - Upper Paleozoic</u>

A density of 2.7 g/cm^3 was given to this body (density contrast of 0.03). This body extends from approximately 100 to 1400 feet into subsurface.

C) <u>Body #3 - The Traverse Limestone (Reef)</u>

The Traverse Limestone and patch reef was given a density of 2.77 g/cm^3 (density contrast of 0.1). This body is approximately 250 feet thick and therefore extends from 1400 to 1650 feet into the subsurface.

D) <u>Body #4 - Lower Paleozoic</u>

This body was given a density of 2.66 g/cm^3 (density contrast of -0.01). It extends from approximately

1650 feet to 5280 feet below the subsurface.

E) Body #5 - Basement complex

Beneath the Lower Paleozoic is the basement complex with an assumed density of 2.67 g/cm^3 (density contrast of 0.0).

THEORETICAL MODEL

Based on the east-west stratigraphic cross section a theoretical model of the subsurface was constructed using the 2D gravity modeling program MAGIX. The five bodies listed above were modeled with their individual density and density contrasts. A theoretical Bouguer anomaly based on the stratigraphic cross-section was then obtained. It is plotted with milligals on the y-axis and distances from the base station on the x-axis (Figure 10).

FIELD MODEL

Using the 2D gravity modeling program MAGIX program again, the subsurface geology of the study area was simulated. However, this time, the construction of the models was based on field data. The observed Bouguer

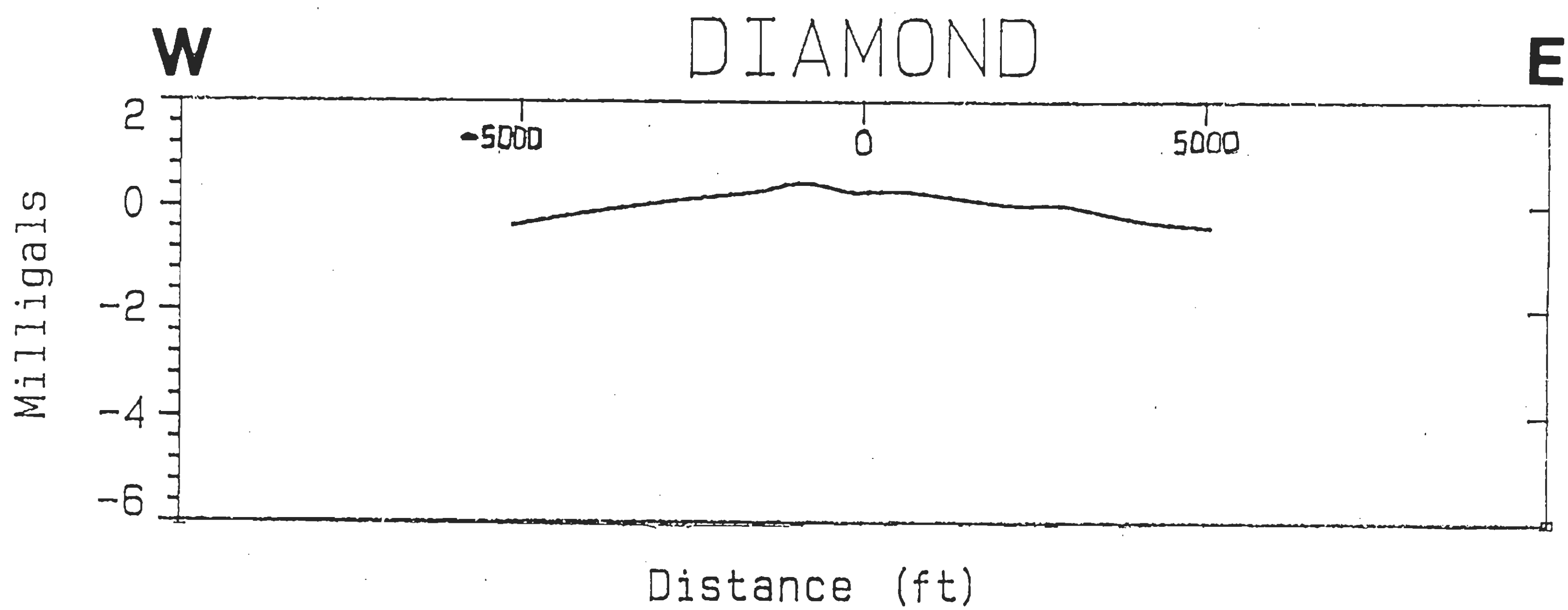


Figure 10: The Bouguer anomaly of the theoretical data based on the east-west stratigraphic cross-section.

anomaly values for each station, which were obtained from the data reduction program GRAVPAC, were entered into the program. Bouguer values for a density of 2.67 g/cm^3 were used. A field Bouguer anomaly was then generated by MAGIX with milligals on the y-axis and distances from the base station on the x-axis (Figure 11). The observed data did not form a smooth curve as was expected. There were several minor irregularities on this curve and therefore a best fit line was drawn (Nettleton, 1972).

REGIONAL GRAVITY

The Bouguer anomaly is a sum of the attractions of local sources and broader or more distant regional sources. Nowhere can we measure an anomaly from one source that is not distorted by overlapping anomalies from other sources (Robinson and Coruh, 1988). Regional gravity is the gravity field produced by large scale variations ignoring anomalies of smaller sizes. It is often the field produced by density variations within or below the basement complex. The observed data needs to be separated into its low frequency (the regional) and high frequency (the residual) components as seen in Figure 12. Thus, residualizing, which is the process of separating an anomaly into its components, attempts to predict regional effects and find local

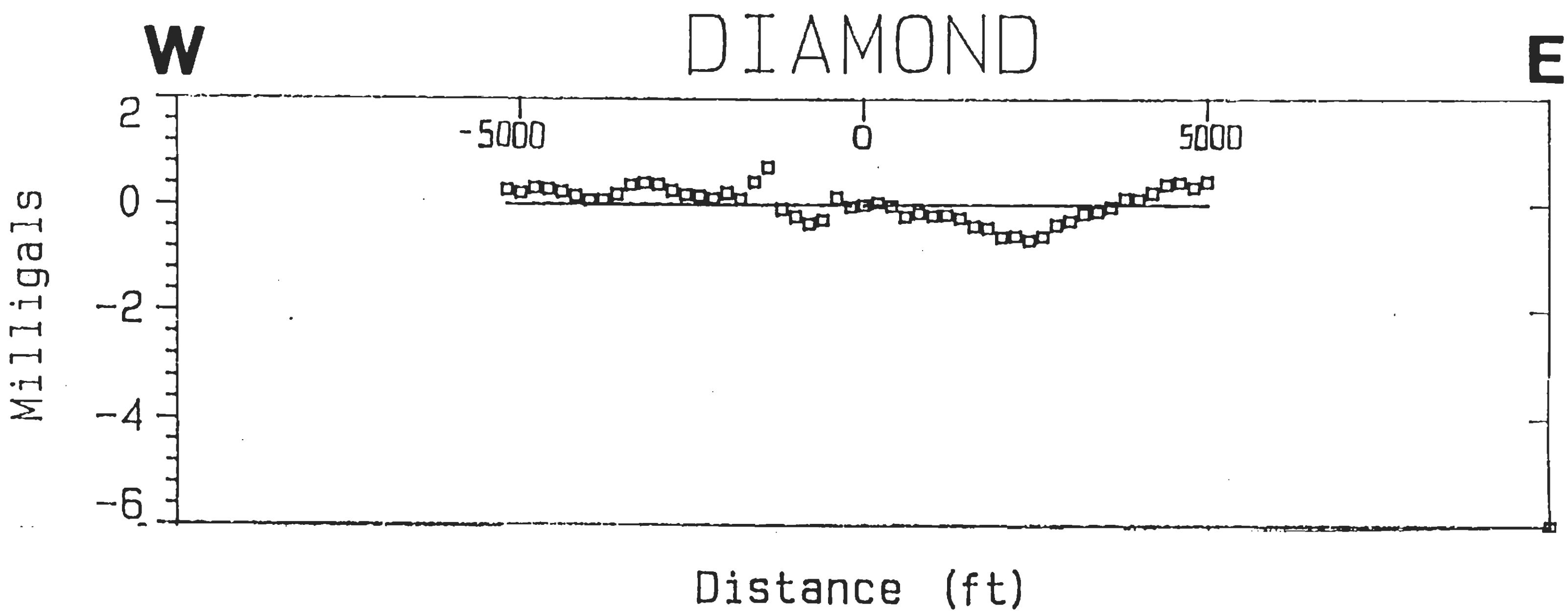


Figure 11: The field Bouguer anomaly of the observed data.

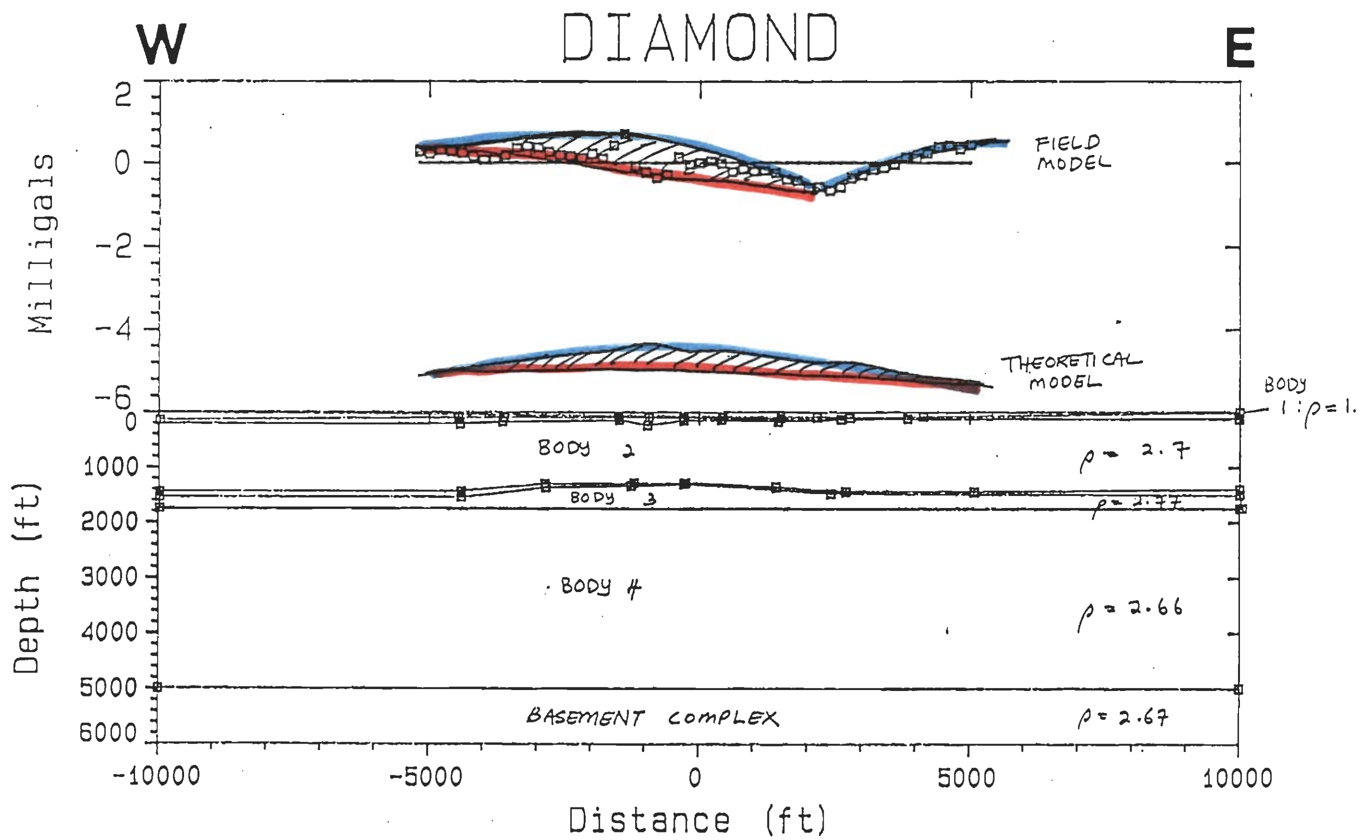


Figure 12: Subtraction of regional effects (red) from the observed data (blue) to delineate the reef (residual anomaly) which is the shaded area.

anomalies by subtracting the regional effects. The residual is then the difference between the observed data and the regional.

INTERPRETATION

Gravity anomalies are largely due to the integrated effect of several vertically extending density contrasts caused by differential compaction over a reef and its erosional remnants (Ferris, 1964, 1968; Haye, 1967). Thus the origin of gravity anomalies over a reef is formed by differential compaction at depths shallower than the reef body itself (Gretener, 1970). Reefs most typically show recognizable gravity anomalies which may be a (a) simple high, (b) high with a negative rim around it ("sombrero-like"), (c) low with a positive tendency in the center, or (d) simple low (Haye, 1966, 1967). When the gravity anomaly is of the "sombrero" type, the width of the anomaly is proportional to the width of the reef, irrespective of the reef depth (Haye, 1967). The Bouguer anomaly over a reef is typically small, in the range of 0.2 to 0.5 milligals as seen in Figure 13 (Ferris, 1964, 1972a, 1972b). However, there is no direct evident relation between a reef mass specification (depth, height, extent, density) and the gravity anomaly specification (type, intensity, extent)

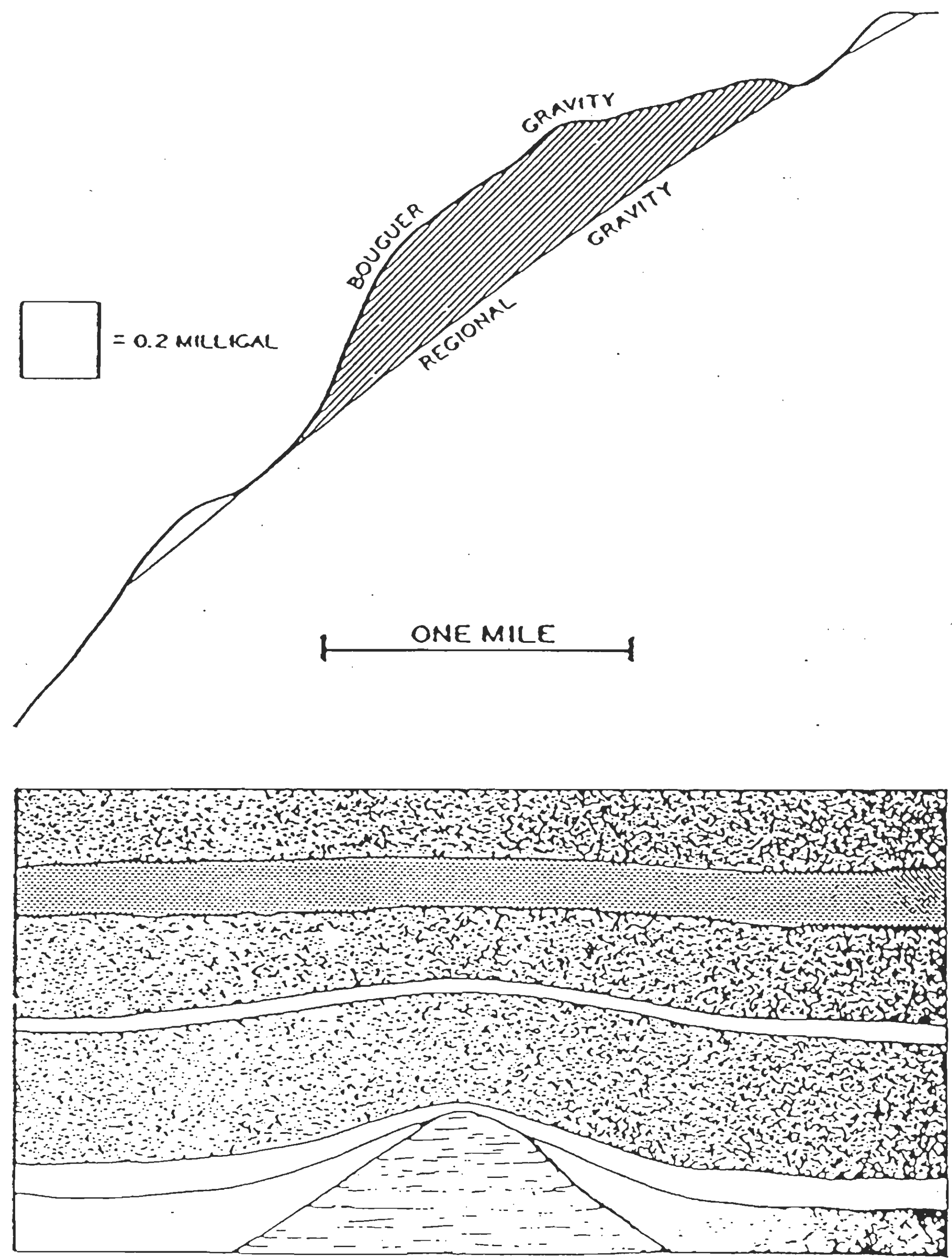


Figure 13: Representative profile of the Bouguer gravity anomaly associated with a sub-surface reef (modified from Ferris, 1972b)

(Haye, 1967).

Residual anomalies were obtained for both the theoretical and field models after removal of the regional. The residual anomalies were small (size), positive and showed the typical "sombrero-like" anomaly which is commonly associated with reefs (Figure 12). The residual anomalies, therefore, suggest the presence of a reef in the subsurface.

Minor anomalies (irregularities) were observed in the Bouguer anomaly of the observed data. In modeling the subsurface based on this field Bouguer anomaly, I found that the model was not all that different from the theoretical model. By modeling the uneven topography at the base of the drift, the irregularities on the field Bouguer anomaly seem to be accounted for. Thus, these irregularities are possibly attributed to variations in lithology, depth and thickness of the glacial drift.

A gravity high appears on the east side of the observed Bouguer anomaly (Figure 11). This could turn out to be an exciting find due to the possibility that there might be another reef adjacent to the Diamond Springs patch reef.

CONCLUSION

Detailed gravity surveys suggest the presence of a patch reef in the subsurface. Cross sections obtained from well logs also show a correlation in that they indicate the presence of a reef. Minor irregularities in the Bouguer anomaly of the observed data are possibly caused by variations in the glacial drift. I suggest that further detailed gravity surveys be done in order to investigate the possibility of a reef adjacent to the Diamond Springs patch reef.

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APPENDIX I

APPENDIX I

WELL NAME	SURFACE ELEVATION (FEET)	SUBSURFACE DEPTH (FEET) GLACIAL DRIFT	SUBSURFACE DEPTH (FEET) TOP OF TRAVERSE
1. G&D PAUL #1	672	-142	-1525
2. J.H. SCHOLTEN #6	654	- 97	-1410
3. J.H. SCHOLTEN #3	661	-104	-1390
4. J.H. SCHOLTEN #1	646	- 80	-1385
5. WAYNE C-J SCHOLTEN #2	654	- 80	-1396
6. J.H. SCHOLTEN #5	665	- 89	-1400
7. J.H. SCHOLTEN #2	663	-108	-1407
8. P.B.WESSELING #2	656	- 97	-1405
9. P.B.WESSELING #5	653	- 90	-1420
10. JOHN DeYOUNG #1	661	- 85	-1460

APPENDIX II

APPENDIX II

Survey: DIAMOND SPRINGS OIL FIELD, ALLEGAN COUNTY, MICHIGAN

Time-keeping: Local Standard Time, Zone: 5 West

Coordinates: Feet N-S & E-W of:

North 42 degrees, 40.8375 minutes

West 85 degrees, 53.885 minutes

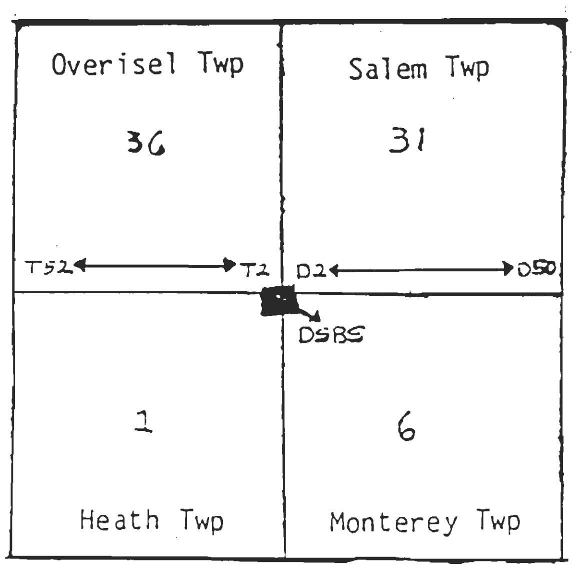
Elevation in feet.

Gravity Meter: LaCoste & Romberg meter G7

Meter factor: 0.99397 mGal/unit

Base Stations:

Station	Absolute Gravity (mGal)
DSBS	980360.00



Obs no.	Station no.	Elevation (feet)	Latitude (°N)	Longitude (°W)	Bouguer anomaly (mGal)
1	DSBS	645.00	42.6806	85.8981	-10.712
2	D-2	642.79	42.6806	85.8988	-10.668
3	D-4	645.87	42.6806	85.8996	-10.726
4	D-6	658.60	42.6806	85.9003	-10.929
5	D-8	663.19	42.6806	85.9011	-10.863
6	D-10	662.89	42.6806	85.9018	-10.905
7	D-12	661.06	42.6806	85.9025	-10.894
8	D-14	664.89	42.6806	85.9033	-10.952
9	D-16	668.53	42.6806	85.9040	-11.105
10	D-18	668.05	42.6806	85.9048	-11.137
11	D-20	667.15	42.6806	85.9055	-11.307
12	D-22	665.96	42.6806	85.9063	-11.289
13	D-24	663.30	42.6806	85.9070	-11.249
14	D-26	662.04	42.6806	85.9078	-11.174
15	D-28	661.62	42.6806	85.9085	-10.953
16	D-30	660.09	42.6806	85.9093	-10.883
17	D-32	658.69	42.6806	85.9100	-10.738
18	D-34	658.78	42.6806	85.9108	-10.707
19	D-36	658.90	42.6806	85.9115	-10.621
20	D-38	659.46	42.6806	85.9122	-10.461
21	D-40	661.48	42.6806	85.9130	-10.475
22	D-42	663.40	42.6806	85.9137	-10.351
23	D-44	664.68	42.6806	85.9145	-10.197
24	D-46	665.00	42.6806	85.9152	-10.165

Obs no.	Station no.	Elevation (feet)	Latitude (°N)	Longitude (°W)	Bouguer anomaly (mGal)
25	D-48	665.67	42.6806	85.9160	-10.257
26	D-50	665.41	42.6806	85.9167	-10.147
27	T-2	648.06	42.6806	85.8973	-10.739
28	T-4	649.27	42.6806	85.8966	-10.569
29	T-6	654.90	42.6806	85.958	-10.991
30	T-8	653.51	42.6806	85.8951	-11.061
31	T-10	650.93	42.6806	85.8943	-10.922
32	T-12	652.06	42.6806	85.8936	-10.855
33	T-14	648.04	42.6806	85.8929	-10.141
34	T-16	641.04	42.6806	85.8921	-10.423
35	T-18	637.09	42.6806	85.8914	-10.739
36	T-20	642.14	42.6806	85.8906	-10.669
37	T-22	643.67	42.6806	85.8899	-10.730
38	T-24	645.70	42.6806	85.8891	-10.687
39	T-26	645.73	42.6806	85.8884	-10.664
40	T-28	642.13	42.6806	85.8876	-10.585
41	T-30	639.31	42.6806	85.8869	-10.469
42	T-32	638.20	42.6806	85.8861	-10.449
43	T-34	638.69	42.6806	85.8854	-10.487
44	T-36	638.39	42.6806	85.8847	-10.668
45	T-38	649.71	42.6806	85.8839	-10.764
46	T-40	655.24	42.6806	85.8832	-10.772
47	T-42	649.99	42.6806	85.8824	-10.686
48	T-44	643.18	42.6806	85.8817	-10.611

Obs no.	Station no.	Elevation (feet)	Latitude (°N)	Longitude (°W)	Bouguer anomaly (mGal)
49	T-46	642.35	42.6806	85.8809	-10.561
50	T-48	641.72	42.6806	85.8802	-10.541
51	T-50	640.59	42.6806	85.8794	-10.634
52	T-52	640.94	42.6806	85.8787	-10.564