A GRAVITY SURVEY OF THE SERPENT MOUND
AREA IN SOUTHERN OHIO

A Thesis
Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by
Jack Cowley Zahn, B.Sc.
The Ohio State University
1965

Approved by

[Signature]
Adviser
Department of Geology
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>LOCATION</td>
<td>3</td>
</tr>
<tr>
<td>GEOLOGY</td>
<td>5</td>
</tr>
<tr>
<td>General Description</td>
<td>5</td>
</tr>
<tr>
<td>Structure</td>
<td>8</td>
</tr>
<tr>
<td>Origin and Age</td>
<td>8</td>
</tr>
<tr>
<td>GRAVITY SURVEY</td>
<td>10</td>
</tr>
<tr>
<td>Introduction</td>
<td>10</td>
</tr>
<tr>
<td>Gravity Method</td>
<td>11</td>
</tr>
<tr>
<td>Instrument</td>
<td>13</td>
</tr>
<tr>
<td>Field Procedure</td>
<td>15</td>
</tr>
<tr>
<td>Elevation Determination</td>
<td>18</td>
</tr>
<tr>
<td>DATA REDUCTION</td>
<td>19</td>
</tr>
<tr>
<td>Drift</td>
<td>19</td>
</tr>
<tr>
<td>Temperature</td>
<td>20</td>
</tr>
<tr>
<td>Elevation, Latitude, and Longitude</td>
<td>21</td>
</tr>
<tr>
<td>Terrain Correction</td>
<td>21</td>
</tr>
<tr>
<td>Density</td>
<td>22</td>
</tr>
<tr>
<td>Errors</td>
<td>23</td>
</tr>
<tr>
<td>INTERPRETATION OF THE BOUGUER ANOMALY MAP</td>
<td>24</td>
</tr>
<tr>
<td>DISCUSSION AND CONCLUSION</td>
<td>27</td>
</tr>
</tbody>
</table>
SUGGESTION FOR FURTHER STUDY ................................. 29
APPENDIX I .......................................................... 30
APPENDIX II .......................................................... 34
BIBLIOGRAPHY ....................................................... 36

LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Map of Ohio</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Schematic Drawing Showing the Spring System of the Worden Gravimeter</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>Regional Bouguer Anomaly Map</td>
<td>25</td>
</tr>
</tbody>
</table>

Plate

<table>
<thead>
<tr>
<th>Plate</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Data for Gravity Survey</td>
<td>in pocket</td>
</tr>
<tr>
<td>II</td>
<td>Free-Air Anomaly Map, Serpent Mound Chaotic Structure Area, Ohio</td>
<td>in pocket</td>
</tr>
<tr>
<td>III</td>
<td>Bouguer Anomaly Map, Serpent Mound Chaotic Structure Area, Ohio</td>
<td>in pocket</td>
</tr>
</tbody>
</table>
A GRAVITY SURVEY OF THE SERPENT MOUND
AREA IN SOUTHERN OHIO

INTRODUCTION

In the Serpent Mound area of southern Ohio, the surface rocks show a structure that has not been explained in a generally acceptable fashion. To obtain more information, a gravity survey was made of the area in the summer of 1962.

The gravity survey of the area was conducted by the author during an eight-week period. Additional gravity work, including linkages to Columbus, Ohio, and the establishment of extra stations required to give the regional variation of gravity anomalies, took three days in 1962 and 1963. Elevations of the gravity stations were determined by topographical surveys conducted by the author with the help of Mr. Sherman Frost and Mr. William Thompson. The gravimeter, a Worden Master Geodetic Model, number 602, and the surveying instruments were provided by the Department of Geology, The Ohio State University.

This survey could not have been conducted without the cooperation of the Ohio Division of Geological Survey and its chief, Mr. Ralph J. Bernhagen, to whom the author extends his gratitude. The Ohio Division of Geological Survey supplied a vehicle with fuel as well as paying a salary to the author.
The author would like to thank Mr. Ralph J. Bernhagen, Chief of the Ohio Division of Geological Survey, and Dr. Howard J. Pincus, Chairman of the Ohio State University Department of Geology, for their guidance in establishing this project.

The writer expresses his gratitude to his adviser, Dr. C. B. B. Bull, of The Ohio State University, for the many hours and unmeasured energy he willingly gave toward the completion of this survey and report.

Valuable advice concerning the geology of the Serpent Mound area was given by Dr. Charles H. Summerston of The Ohio State University. Mr. Ralph W. Betsche, Jr. offered valuable advice concerning the conduct of a gravity survey for which the author is grateful.

The writer acknowledges Mrs. Marilyn Mayhew and Miss Dorothy Amrine who typed the draft and final copies of this thesis.

Lastly, a very special "thank you" to my wife, Shirley, for enduring, lo these many years.
LOCATION

The Serpent Mound area is located in the southwestern quadrant of Ohio (Fig. 1). It occupies the northern part of Adams County, the southeastern part of Highland County, and the southwestern part of Pike County. The survey area covers a portion of Bratton and Franklin Townships, Adams County; Brush Creek Township, Highland County; and Mifflin Township, Pike County.
Figure 1. Map of Ohio. Shaded area shows extent of Figure 3.
GEOL OGY

General Description

The Serpent Mound structure at the present erosion level is expressed at the surface by a circular feature that is approximately four miles in diameter. The structure is best described as a center hub surrounded by two concentric annuli. The hub is displaced upward stratigraphically, whereas the inner annulus exhibits little stratigraphic displacement. The outer annulus is displaced downward stratigraphically. The topographic relief of the structure is 460 feet.

In the 13 square miles of the survey area, sedimentary Paleozoic rocks are exposed at the surface. In the areas immediately surrounding the Serpent Mound structure only Silurian and Devonian rocks crop out, but within the area of the structure outcrops of Ordovician, Silurian, Devonian, and Mississippian rocks are encountered. The structure lies within the unglaciated portion of Ohio but is only a few miles from the eastern edge of Illinoian glacial deposits.

The structure of the Serpent Mound area was first brought to the attention of the geologic community by W. H. Bucher in 1933 (p. 1055-1064). In this publication, he described the area as the "Serpent Mound Cryptovolcanic structure." This name unfortunately implies
volcanism in an area that shows no direct evidence of volcanism, that is, neither igneous nor metamorphic deposits are present. For this reason the author has chosen to use the name "Serpent Mound chaotic structure area" as being a good representation of the chaotic structure that abounds, without implying mode of generation of the structure.

The outer annulus is topographically the highest portion of the structure. The surface rises to a maximum elevation of 1120 feet and is capped by Mississippian sandstone and siltstone (Bucher, 1933, p. 1060). The inner annulus is the lowest of the three segments of the structure with elevations from 660 feet to 880 feet. The surface rocks are fractured shales, limestones, and dolomites, ranging from Silurian to Devonian in age (Bucher, 1933, p. 1060). The center or hub area is higher than the inner annulus but lower than the outer annulus, and ranges in elevation from 700 to 990 feet above sea level. This area is capped by highly fractured Ordovician and Silurian limestones and shales (Bucher, 1933, p. 1060, 1062). Shatter cones from this hub area have been collected by R. S. Deitz (1960). The structural displacement of the Ordovician beds that are at the same elevation as the Mississippian beds is approximately 800 feet (Schmidt, 1961, p. 292).

Except in the area of the chaotic structure, the Paleozoic strata dip gently to the east and present a normal outcrop pattern, that is, exposed beds strike north-south; older beds are encountered to the west and successively younger beds crop out to the east.
The Upper Ordovician limestones and shales (Cincinnatian Series) are the oldest rocks exposed in the Serpent Mound structure area. The Covington and Richmond Groups are lithologically similar and consist of major thicknesses (990± feet) of interbedded shale and clastic limestones. These rocks crop out west of the edge of the chaotic structure and in the hub area. Normally these beds dip very gently to the east, but within the area of the disturbed structure, the rocks are highly fractured and exhibit random direction and magnitude of dip.

The Silurian strata in southern Ohio are thin bedded limestones overlain by shales and massive dolomites. These rocks crop out around the chaotic structure area and in the inner annulus.

The Devonian rocks of this area consist of a spotty basal sandstone overlain by a thick (260± feet) sequence of black fissile shale (Bucher, 1933, p. 1060). Outside the disturbed area, the Devonian beds crop out to the east. Within the chaotic structure area, the Devonian rocks occupy the outer edge of the inner annulus.

The Lower Mississippian rocks that crop out in the disturbed area are shales, sandstones, and siltstones. The undisturbed area immediately surrounding the Serpent Mound structure is void of Mississippian strata. The nearest outcrops are 1.5 miles to the east. In the area of the chaotic structure, Mississippian rocks cap the outer annulus.

The thickness of the exposed Paleozoic section within the disturbed area is about 950 feet (Bucher, 1933, p. 1060).
Structure

The regional structure of this part of southern Ohio closely follows the general structure of the eastern two-thirds of the state. Gently easterly dipping beds are broken at the surface by a few high angle faults, the dip-slips of which are less than ten feet. Nowhere in the region surrounding the area of the chaotic structure does the dip of the exposed rocks exceed 0.75 degrees.

The structure within the disturbed area has been described above and by Bucher (1933, p. 1061-1064). The center portion of the Serpent Mound structure consists of Ordovician and Silurian rocks that have been raised well above their normal stratigraphic position. The inner ring consists of Silurian and Devonian rocks that lie very close to their normal stratigraphic position. The outer ring consists of fractured Devonian and Mississippian rocks that lie well below their normal stratigraphic position.

Origin and Age

Two major hypotheses have been presented for the origin of the forces responsible for creating the area of chaotic structure. The first is by Bucher, who attributes the disturbing forces to "Cryptovolcanism". Bucher (1933, p. 1055) states that cryptovolcanic structures such as the one at Serpent Mound, Adams County, Ohio, "...are thought to be the result of a sudden liberation of pent-up volcanic gases, which had accumulated near the surface, the explosion having been too weak to produce a shallow explosion crater..." The
second hypothesis is championed by Dietz (1960). He states that the origin of the forces that produced the Serpent Mound structure was the impact of a meteorite. He uses the term "Astrobleme" in describing the area of disturbed rocks and states that forces associated with high velocity waves or impacts are required to form the shatter cones found within the chaotic structure.

Little is known about the absolute age of this structure. Bucher (1933, p. 1063) states that it must be younger than Lower Mississippian because rocks of that age are the youngest beds to be disturbed within the structure.
GRAVITY SURVEY

Introduction

It appeared that further information on the origin of the structure might be obtained from a gravity survey of the area. If the structure is a result of cryptovolcanism, disturbances can be expected to extend into the basement. These could be associated with changes in density compared with the surrounding undisturbed areas, which would give values of gravity under the structure different from those in the surrounding areas.

On the other hand, if the structure is an astrobleme, the disturbance could be relatively shallow, perhaps not extending below sea level. Lower density brecciated rocks might be expected under the impact area, which could be detected by the areal study of gravity.

Previous gravity surveys (Heiskanen and Uotila, 1959) of this part of Ohio have been on a reconnaissance scale, with approximately one station every 20 square miles. This is sufficient to give a regional picture of gravity variations, but is insufficient for the detailed investigation of a small structure.
Gravity Method

The value of the acceleration due to gravity, 'g', at a point on the earth is controlled by a number of factors. These are:

(1) The latitude. (The earth is approximately an ellipsoid. The rotation and the polar flattening give a variation of the value of 'g' at sea level from about 983 gals at the poles to 978 gals at the equator. The variation of 'g' with latitude is normally represented by the international gravity formula (I.G.F.) (Dobrin, 1960, p. 234).

(2) The elevation. (The distance of the point from the center of mass of the earth controls the gravitational attraction by the Newtonian expression \( F = \frac{G m_1 m_2}{r^2} \). To permit comparison between gravity values, these are "reduced" to sea level. This allowance for the elevation alone is called the Free-Air correction. Free-Air correction = 0.09406 mgal X elevation (ft.).)

(3) The material between the point of observation and sea level. (In "reducing" the values of station gravity to sea level, allowance can be made for the gravitational attraction of the slab of material between the station and sea level. This allowance is called the Bouguer correction, and involves the density of the material above sea level. Bouguer correction = 0.01276 mgal X material density X elevation (ft.). When applied with the Free-Air correction, the process is called the Bouguer reduction.)

(4) The gravitational attraction of material at points surrounding the station. (The Bouguer reduction allows for the attraction of a slab of material, of thickness equal to the station altitude, and
extending to infinity horizontally. Departures of the real topography from this condition produce the topographic or terrain correction.)

(5) Abnormalities in the density of the subsurface layers. The usual procedure is to take values of station gravity, and apply either the Free-Air correction or the Free-Air and Bouguer (and terrain) corrections. The difference between the corrected values and the "normal" calculated values for the latitude (given by the I.G.F.) are referred to as the anomalies, being the Free-Air anomalies and the Bouguer anomalies, depending on the type of reduction.)

The anomalies are thus obtained by the following equations:

(1) \( \gamma + 0.09406 \ h - \gamma_t = \text{Free-Air anomaly,} \)

(11) \( \gamma + 0.09406 \ h - 0.01276 \ h \ (\text{terrain correction}) - \gamma_t = \text{Bouguer anomaly,} \)

where \( \gamma \) = observed gravity at each gravity station, \( h \) = elevation in feet, \( \sigma \) = density in g cm\(^{-3}\), and \( \gamma_t \) = calculated or theoretical gravity.

Methods of interpretation of the Bouguer anomaly maps depend on the extent of the geologic knowledge of the area. The interpretations are seldom unambiguous - the same "shape" of anomaly can be produced by a small, deeply buried mass of high density contrast or a shallower, larger one of lower density contrast from the surrounding rock (Nettleton, 1940, p. 119).

However, from the horizontal extent of the anomalies, some information on the depth of the anomalous mass can be gained. A deep body cannot produce a steep gradient of anomaly. For anomalous masses
of simple geometrical form the half-width of the gravity anomaly is related to the depth of the anomalous mass.

The survey was undertaken to see (1) if the Serpent Mound chaotic structure was related to the area Bouguer anomalies, and (2) whether these could be related to shallow or deep mass anomalies.

Instrument

The instrument used in this survey was a Worden Master Geodetic Model Gravimeter, number 602. At the time of the survey, the instrument was new, having been purchased in May, 1962. A gravimeter of this type can be represented as a horizontal bar, length L, free to rotate about a horizontal axis at one end of the bar. A mass M at the end of the bar is acted on by the local gravity field, which produces a torque of MgL about the axis (Fig. 2). This torque is balanced against the tension in an adjustable spring attached vertically to the bar.

The difference in the tensions required to keep the bar horizontal at two places is directly proportional to the difference in the values of gravity at the two places. Once the constant of proportionality has been established, the instrument can be used to measure differences in gravity, but to obtain absolute values, the survey with the gravimeter must include one point at which the value of gravity is already known. In this survey, the constant of proportionality given by the manufacturer has been used. During the survey one other station was occupied at which 'g' was already known. The disparity between the previously accepted value and the one now calculated is
Figure 2. Schematic drawing showing the spring system of the Worden Gravimeter.
so small that no error can be detected in the maker's calibration.
A more detailed check of the sensitivity was made by C. Bull in
December, 1962, with gravity linkages between the primary stations
at Christchurch, New Zealand and McMurdo Station, Antarctica.
Errors in the maker's calibration are less than 0.2 per cent.

In the Worden meter, the entire working system and springs are
made of quartz, and include temperature compensating devices. The
elastic properties and the dimensions of the quartz system vary
slowly with time, producing the phenomenon of "drift". Thus, the
indicated tension required to balance the horizontal beam varies
with time.

Field Procedure

Before the detailed survey was begun, a network of ten base
stations was established. These were at convenient points distributed
through the area. (See map, Plate II.) The detailed survey of the
area, involving 125 gravity stations, was based on these ten base
stations.

Five rounds (each taking about two hours) were made of the base
stations and the meter was read at each station. To increase the
accuracy of these station values, the drift rate curve was corrected
for the tidal effect.

A one-quarter mile grid was superimposed upon a map of the chaotic
structure area. Originally it was intended to make a gravity station
at each point on the grid, but this was not practicable due to the
poor access and very rough topography in some areas. Of approximately 200 gravity points on the one-quarter mile grid within the 4 mile diameter structure, two-thirds or 131 points were eventually occupied.

After the detailed survey had been completed, a linkage was made between the gravity station at The Ohio State University, and one of the base stations. Later (in October, 1963) some additional gravity stations were established, most of them outside the Serpent Mound chaotic structure area, to obtain a better picture of the regional gravity anomalies. These were based on the original ten base stations.

All of the gravity values in this report are based on a value of 980.09447 gals\(^1\) observed gravity at the Ohio State 40\(^\circ\) N latitude stone. The value of 'g' here was determined by Heiskanen and Uotila (1959) with gravimetric linkages to the primary U.S.A. gravity bases. Errors in the absolute value of 'g' assumed for this station will not effect the form of the Bouguer anomaly map, which arises entirely from differences in gravity values between neighboring points.

A linkage from The Ohio State University base station to Base Station 7 in Serpent Mound State Park was made in the following way.

A series of three readings (over a period of five minutes) was made at The Ohio State University base. The instrument was taken (by car) to Circleville, where a series of readings was made. This was repeated at Chillicothe, after which the instrument was returned to Circleville for a further set of readings, and then to Columbus. The complete loop took two hours. One more loop was made.

\(^1\)1 gal = 1 cm/sec\(^2\). 1 milligal, written 1 mgal, = 0.001 cm/sec\(^2\).
On the following day, the author established a similar loop from Chillicothe to Serpent Mound State Park, Ohio, where Base Station 7 for this survey is located. As in the other loop, an intermediate station was established southwest of Bainbridge, Ohio. Again, the complete route was travelled twice, each trip taking two hours.

In calculating the accuracy of this linkage, the first step was to determine the linearity of the drift. After correcting the observed differences in gravimeter readings between the various stations, for changes in the tidal component of gravity, the departures of the drift from linearity were negligible. The maximum error in the complete linkage is estimated to be 0.05 mgal.

The procedure for conducting the gravity survey was as follows. The gravimeter was taken to a base station, set upon a tripod, and levelled. The tension in one of the internal springs was altered by moving an accurate screw, until the reading beam was centered. The gravimeter was read by recording the extent of the spring's stretching (tension) from the screw dial. Three readings were taken, the time and the internal temperature of the gravimeter were recorded for calculating the drift rate and because the meter calibration varies slightly with temperature. Then gravity stations were occupied and the above recording sequence was followed. The position of the station was marked on a map and the ground position was marked with paint and flagging. Other stations were occupied within the general area of the same base station. Before leaving the area, the base station was reoccupied and the recording sequence repeated. This
placed all stations on loops which were tied to the base station network. The average time of a loop of stations was 3 hours and 50 minutes. At the close of each day the level bubbles of the gravimeter were checked and adjusted if necessary.

Elevation Determination

After the completion of the gravity survey, a survey was conducted from bench marks using an alidade, plane table, and stadia rod to determine elevations of gravity stations. Many points of known elevation were occupied during the survey, giving good checks on survey elevation accuracy. The estimated maximum elevation error in this survey is ±2 feet.
DATA REDUCTION

The reduction of the data falls logically into two parts. The first part is the processing of the direct readings of spring tension of the gravimeter, so that differences between gravity values at the stations may be determined. Hence, by starting the survey at a point where 'g' is known already, values of gravity at the various stations may be obtained.

The second part is the application of corrections to the values of station gravity, so that they may be compared with each other, and the values used in inferring changes in geological structure beneath the surface.

The first part involves corrections for the "drift" of the instrument (discussed above) and variations of the calibration coefficient with temperature. In order to determine the drift rate satisfactorily, it is desirable to apply tidal corrections to the recorded values of spring tension at some stations, to allow for the varying gravitational attraction of the sun and moon.

Drift

Rate of drift of the gravimeter was determined graphically for the traverse loops from the gravity station in Columbus, Ohio, the loops establishing the base station network, and each of the gravity station loops originating from the base stations. For the loop from
Columbus and the loop establishing the base stations, a tidal correction was made and then the results of drift were reduced from dial units to milligals, and the differences in observed gravity recorded for these traverses. This tidal correction was obtained by using the Tidal Gravity Correction for 1962 printed as Supplement No. 1, Volume IX, Geophysical Prospecting, Dec. 1961. From the information in this publication, the tidal correction for stations in the Serpent Mound area was calculated for every hour on the days of the linkages.

The maximum value of the tidal correction is about 0.15 mgals and the variation in the correction over a period of the few hours involved in a loop of gravity stations based on one of the base stations, is only 0.02 mgals. The detailed calculations of drift rate, for the base stations, using tidal corrections, showed that the instrument was extremely stable; the drift rate never exceeded 0.05 mgal for the whole day. The absence of tidal corrections can introduce errors into the values of station gravity of only 0.02 mgals, which is insignificant compared with errors in the corrections to the values of station gravity, arising from errors in elevation and assumed density.

Temperature

As mentioned above, the elastic properties of the spring system vary only slightly with the instrument temperature. For converting differences in dial reading into differences in gravity at different temperatures, the coefficients were taken from the information supplied by Texas Instruments, the makers of the gravimeter.
Elevation, Latitude, and Longitude

The reduction of the values of station gravity requires a knowledge of the elevation and latitude of the station, the elevation of surrounding areas (for terrain corrections), and the density of the material below the station. In addition, longitudes of stations are required for plotting.

Differences in elevation between the gravity stations were determined by standard stadia methods. By reference to the bench marks, absolute values of elevation were obtained. Latitudes and longitudes of stations and elevations of surrounding areas were determined from the 1:24000 topographic sheet published by the U. S. Geological Survey. Coordinates were determined directly from the maps. Latitude corrections were determined from the Table of Values of Theoretical Gravity on the International Ellipsoid (Nettleton, 1940, p. 139).

Terrain Correction

For calculations, all gravity stations are assumed to lie upon a featureless plane, the elevations of which is the same as the station's. The effect of terrain on gravity measurements can be generalized by stating that a valley near a gravity station represents a mass deficiency and therefore a lower value of gravity is observed than would be if the topography were flat. Similarly, the effect of a hill near the station would represent a mass surplus above the assumed level plane and again observed gravity would be less, due to the upward attraction of the hill.
The terrain correction for the survey was obtained by using tables due to Hammer (Dobrin, 1960, p. 222).

An overlay incorporating Zones C through M (55 feet to 71,999 feet radius) was used in conjunction with the U.S. Geological Survey topographic maps. Terrain corrections for this survey ranged from 0.00 mgal to 0.73 mgal.

Density

In trying to determine a realistic density to use with the Bouguer correction for this gravity data, the author considered many factors. First among these was the many published densities of sedimentary rocks that are available. Values from the "Handbook of Physical Constants" (Birch, 1942) and Dobrin (1960, p. 250) and elsewhere, were scanned. However, the most complete data information was obtained from "Porosity and Bulk Density of Sedimentary Rocks" (Manger, 1963). Data compiled by Batsche (1963) was also reviewed.

The next phase was the examination of the stratigraphic column in the report area, and the determination of the percentage of the different lithologies in the vertical section above sea level. This vertical column contains approximately 45 per cent dolomite, 25 per cent limestone, and 30 per cent shale. The mean density was calculated from the following representative bulk density values: dolomite, 2.5 g cm\(^{-3}\); limestone, 2.6 g cm\(^{-3}\); shale, 2.4 g cm\(^{-3}\). These values multiplied by the above percentages gave a mean of 2.495 g cm\(^{-3}\). A value of 2.5 g cm\(^{-3}\) was chosen.
Errors

The following are estimated maximum errors that may be found in the Bouguer anomaly of this survey.

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Mean mgal</th>
<th>Max. mgal</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Columbus value</td>
<td>not known but believed small</td>
<td></td>
</tr>
<tr>
<td>*Columbus to base station tie</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>**base station loop</td>
<td>0.033</td>
<td>0.06</td>
</tr>
<tr>
<td>**station drift</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>**tidal effect</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>density</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>density difference between adjacent sta.</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>elevation</td>
<td>&lt; 0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>terrain correction</td>
<td>&lt; 0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>latitude</td>
<td>&lt; 0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*These errors would affect absolute gravity but not relative gravity, and hence would not affect the form of the gravity anomaly maps.

**Regarding the estimated mean error as r.m.s. errors, the r.m.s. error of the values of station gravity is 0.16 mgal.

The uncertainties in the density give possible errors in the Bouguer anomalies that are so large that they completely outweigh the other possible errors.
INTERPRETATION OF THE BOUGUER ANOMALY MAP

The Bouguer anomaly map (Plate III) shows little relationship to the surface structure of the area. There are no closed isogals (contour lines of equal gravity) around the structure that might be expected if either cryptovolcanism or meteorite impact were causitive factors. Instead, the Bouguer maps show an elongate anomaly trending northwest-southeast and having a relief of over 28 mgal (Fig. 3).

The problem of explaining the very steep gradient (28 mgal in 15 miles) of the Bouguer anomaly (Plate III) was approached by assuming that the disturbing mass was a buried horizontal cylinder, with an assumed density of 3.0 g cm\(^{-3}\) (McCormick, 1961, p. 4). Half-width of this anomaly is 44 kilo-feet, which is the depth to the center of the assumed cylinder. Using the formula \(R = 0.28 \frac{Zc}{\sigma} g \max\), where \(Zc\) is depth to the center of the cylinder in kilo-feet, \(g \max\) is the maximum anomaly in mgals, \(\sigma\) is the density contrast in g cm\(^{-3}\), \(R\) is the radius of the cylinder in kilo-feet and the values are:

\[
\begin{align*}
Zc &= 44.0 \text{ kilo-feet} \\
g \max &= 28 \text{ milligals} \\
\sigma &= 0.5 \text{ g cm}^{-3}
\end{align*}
\]

then \(R = 13.9 \text{ kilo-feet}\). Depth to the top of the assumed horizontal cylinder is \(Zt = Zc - R\). \(Zt = 30.1 \text{ kilo-feet}\), or 5.7 miles.

The surface of the basement in the region is thought to be approximately 3000 feet below sea level (Summerson, 1962, Plate I).
Figure 3. Regional Bouguer anomaly map. Iso-gal interval = 5 mgal.
Scale 1:250,000.
This depth, 5.7 miles, is much too deep to cause a surface expression such as the chaotic structure area.

Because the gradient of anomaly across the area is so large (and could be due to very deep mass anomalies), small anomalies could be hidden. Attempts to remove the regional gradient were made in two ways.

In an analytical method (Griffin, 1949), the average Bouguer anomaly values of a ring of stations were subtracted from the Bouguer anomaly value of a central station. The resultant values were mapped and the final figure bore no resemblance to the surface structure.

The graphical method was equally unsuccessful. Along several northeast-southwest lines through the area, the best fit linear gradient was determined. The mean value was taken, and from it a grid was constructed of the "expected" anomaly at each point. As above, the finished map did not reflect the surface structure.

The most important point to be derived from the above calculations is that the cause of the Bouguer anomaly lies well below the surface of the basement rocks. Thus, the conclusion may be drawn that the Bouguer anomalies in this area bear no direct relation to the chaotic structure area.

The author believes that further refinements, such as constructing basement models to better approximate the observed anomaly, are pointless exercises, because nothing is known of the lithology of the basement.
DISCUSSION AND CONCLUSION

The results of the gravity survey indicate that the Bouguer anomaly of the Serpent Mound chaotic structure area and the structure itself have no apparent relationship. As stated above, the mass causing this anomaly seems too far below the surface of the basement to be able to produce a ground surface feature as has been described. The greatest drawback in attempting to relate the gravity data with the surficial structure is the lack of geologic control at depth. This large basement-produced anomaly could possibly mask any surface- or near surface-produced anomaly.

If this structure were cryptovolcanic in origin, one might expect a gravity anomaly that would reflect a local rise in the basement surface. If the structure were the product of meteorite impact, a gravity anomaly reflecting the lower density of the brecciated material present might be expected (Innes, 1961, p. 2225-2239).

A Bouguer anomaly that directly relates to the surface form of the Serpent Mound structure might be expected if one of the following two conditions were present:

1) If the structure were the result of meteorite impact, there might be sufficient broken rock present to cause a density deficiency, and therefore, a Bouguer anomaly algebraically smaller than in the surrounding areas.
11) If the structure were the result of cryptovolcanism, there might be sufficient relief on the surface of the basement (in the form of a stock with its density nearly equal to that of the basement and a relatively higher density than that of the surrounding sedimentary section) to produce a local density excess, and therefore, an increase in the Bouguer anomaly compared with the surrounding areas.

Since there is no Bouguer anomaly related in form to the surface expression of the chaotic structure, the following explanations for its absence may be examined.

1) In the case of the broken rock,
   a) Most of the broken rock may have been removed by erosion.
   b) There is little or no density contrast between the broken and the less disturbed strata.

2) In the instance of the basement relief:
   There is little or no density contrast between the upper basement rock and the lower sedimentary section.

3) In the instance of the broken rock and the relief on the basement:
   The deep basement anomaly may be large enough to mask any anomaly caused by either of the above.

One or more of the above explanations could cause a lack of relationship between the structural surface form of the area and the existing Bouguer anomaly. The author believes that 1) a) and 3) are definite contributors to the problem of lack of relationship.

Thus, no direct evidence in support of either theory is provided by this survey.
SUGGESTIONS FOR FURTHER STUDY

The best way to determine the geologic character of the chaotic structure is to core the rocks to a depth below the top of the basement. A program of three or four holes placed in line across the structure with some holes outside the structure would be needed.

The large expense of the above suggestion indicates the need for a more practical approach. A seismic survey should be conducted around and across the chaotic structure. Both reflection and refraction surveys should be conducted to establish the depth to the top of the basement and give some insight into the character of the basement section. The cost of such a survey would be a fraction of the expense incurred in coring. Again, the survey should traverse the area from undisturbed beds into the chaotic structure.
Sample Station Data Reduction

All gravity stations of this survey were tied to loops that, in turn, were tied to the gravity station at the 40° North Latitude stone on The Ohio State University campus. The observed gravity at the station on campus is 980094.47 milligals. Since it is not possible to determine absolute gravity by reading the gravimeter, but only possible to measure gravity differences between stations, a point of known relative gravity was needed. The campus gravity station is tied to the Don Scott Airport gravity station which in turn is tied to the Washington, D.C. Commerce Building base station via Hopkins Airport, Cleveland, Ohio (Heiskanen and Uotila, 1956, p. 7).

The difference between the observed gravity at Columbus and the observed gravity at base station 7 of this survey is 67.08 milligals with the base station the lesser of the two. This information was determined from the rate of drift graphs.

\[
\text{observed gravity at Columbus} = 980094.47 \text{ milligals} \\
- 67.08 \text{ milligals} \\
\text{observed gravity at base station 7} = 980027.39 \text{ milligals}
\]

The other base stations of the survey were tied to base station 7. An example of this would be base station 4 which was found, from the rate drift graphs, to have an observed gravity value 11.33 milligals greater than base station 7.

\[
\text{observed gravity at base station 7} = 980027.39 \text{ milligals} \\
+ 11.33 \text{ milligals} \\
\text{observed gravity at base station 4} = 980038.72 \text{ milligals}
\]
The gravity stations were tied to one of the ten base stations. An example would be gravity station 100. From the rate of drift graphs, it is calculated that gravity station 100 has an observed gravity value of 9.64 milligals less than base station 4.

\[
\text{observed gravity at base station 4} = 980038.72 \text{ milligals} \\
\quad \quad - 9.64 \text{ milligals}
\]

\[
\text{observed gravity at gravity station 100} = 980029.08 \text{ milligals}
\]

The elevation of gravity station 100 was surveyed at 844 feet above mean sea level. The latitude of this station was determined to be 39°02.6'. The theoretical gravity for this latitude was calculated to be 980095.78 milligals.

Terrain corrections were calculated in two parts. Hammer zones C through H were read directly. For gravity station 100, the following corrections were noted.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Correction (milligals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.006</td>
</tr>
<tr>
<td>D</td>
<td>0.037</td>
</tr>
<tr>
<td>E</td>
<td>0.028</td>
</tr>
<tr>
<td>F</td>
<td>0.015</td>
</tr>
<tr>
<td>G</td>
<td>0.011</td>
</tr>
<tr>
<td>H</td>
<td>0.001</td>
</tr>
</tbody>
</table>

\[
0.098 \text{ milligals}
\]

Zones I through M were calculated from an overlay and graph. In the case of gravity station 100, the terrain correction for these five outer zones was found to be zero milligals.

The total terrain correction for station 100 was calculated to be 0.098 milligals at a density of 2.00 g cm\(^{-3}\). Converted to a density of 2.50 g cm\(^{-3}\), this correction becomes 0.12 milligals.
The Free-Air correction for gravity station 100 was derived from the formula:

Free-Air correction = 0.09406 milligals/feet of elevation

0.09406 x 844 = 79.39 milligals.

The Bouguer correction for this sample station was calculated from the formula:

Bouguer correction = 0.01276 \( \sigma \) milligals/feet of elevation, where \( \sigma \) = rock density, which in this survey is 2.5 g cm\(^{-3}\).

0.01276 x 2.5 x 844 = 26.92 milligals.

The Free-Air anomaly for gravity station 100 was derived from the formula:

Free-Air anomaly = observed gravity + Free-Air correction - theoretical gravity.

\[
\begin{align*}
980029.08 \text{ milligals} \\
+ & \hspace{1em} 79.39 \\
- & \hspace{1em} 980095.78 \\
\hline
\text{Free-Air anomaly} & = + \hspace{1em} 12.69 \text{ milligals}
\end{align*}
\]

The Bouguer anomaly for this station was calculated from the following formula:

Bouguer anomaly = observed gravity + Free-Air correction - Bouguer correction + terrain correction - theoretical gravity.

\[
\begin{align*}
980029.08 \text{ milligals} \\
+ & \hspace{1em} 79.39 \\
- & \hspace{1em} 26.92 \\
+ & \hspace{1em} 0.12 \\
- & \hspace{1em} 980095.78 \\
\hline
\text{Bouguer anomaly} & = - \hspace{1em} 14.11 \text{ milligals}
\end{align*}
\]
APPENDIX II
Permitting Procedure

Before the actual gravity survey was conducted, a week was spent in obtaining the right of trespass from the land owners in the survey area. Time must be set aside for this procedure which should be completed before a survey is begun. It is a good rule to permit all the land in the study area that might be crossed, even though this possibility may be slight.

In the survey area, a list was kept of property cleared for trespass, date of clearance, name of the person giving clearance, and the name of the property owner if different from the person providing clearance. The results of this type of permitting procedure was most satisfactory. Forty-six of the forty-seven land owners contacted in the survey area granted permission to trespass on their property. Usually permission was granted after the purpose and procedure of the survey was outlined. The owners were told that they would again be contacted at the time the survey crossed their land. In most cases, the land owners stated that this last courtesy was not necessary.

The whole object of this procedure is to get the land owners on your side, the side of scientific research. It must be remembered at all times that neither the Ohio Division of Geological Survey nor individuals doing geological investigations in Ohio have the right to trespass on private property without permission of the owner (Bernhagen, 1963). In disregarding the above, the geologist is courting trouble; not only for himself, but for all succeeding scientific surveys that might follow him into the geographical area of his investigation.
BIBLIOGRAPHY


Batsche, R. W., Jr., 1963, Field Study and Geological Interpretation of a Gravity Anomaly Located in the Fayette County, Ohio, Area; unpublished Master's thesis, Ohio State University.


<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude (N)</th>
<th>Longitude (W)</th>
<th>Elevation (feet)</th>
<th>Observed Theoretical</th>
<th>Free Air</th>
<th>Free Air Terma</th>
<th>Supers</th>
<th>Supers</th>
<th>Supers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degrees</td>
<td>Minutes</td>
<td>Degrees</td>
<td>Feet</td>
<td>Meters</td>
<td>Meters</td>
<td>corr.</td>
<td>corr.</td>
<td>corr.</td>
</tr>
<tr>
<td>81</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>30° 0' 15&quot;</td>
<td>00''</td>
<td>738.53</td>
<td>145.06</td>
<td>145.06</td>
<td>145.06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Stations 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, and 99 were not calculated because of the lack of elevation control due to failure to obtain the right of trespass from the land owners or errors in the attitude survey.*