Using Gravity for Subsurface Imaging at Ship Rock, New Mexico

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ABSTRACT

Ship Rock, a large brecciated formation of igneous rock with radially arranged dikes, is a prominent feature of the Navajo Volcanic Field in northwestern New Mexico. This study uses geophysical gravity surveys and modeling to investigate Ship Rock and test competing hypotheses for its formation. Using LaCoste and Romberg Model G gravimeters, a total of 105 gravity readings were taken at 0.3 km spacing in a 12 km x 11 km study area. After corrections to isolate the effect on gravity anomalies of subsurface density, indicative of subsurface rock type, the Bouguer gravity data show a +16 mGal high and a +7 mGal low in the northwest sector of the study area. Both anomalies are circular and <3 km in diameter. One possible model suggested that the gravity high was produced by a downwards continuation of Ship Rock's diatreme pipe, and the low was produced by a deeply buried magma chamber with hollowed-out components. However, given the context at Ship Rock, it is more likely that the gravity high shows a shallowly buried volcanic plug just east of Ship Rock, and the slight gravity low is a result of Ship Rock itself. This study did not find viable evidence of any magma chamber, and therefore firmly refute the volcanic neck model for Ship Rock, although they cannot reveal specifics of subsurface geometry.

This study is important because subsurface gravity imaging can reveal how Ship Rock formed and could provide a possible model for how other diatreme systems form.

Keywords: Bouguer anomalies, diatremes, geophysical surveys, gravity anomalies, subsurface geology

INTRODUCTION

Ship Rock is a prominent volcanic feature in northwestern New Mexico, and is also called Tse Bit'a'i or "Rock with Wings" by the Navajo (Fig. 1). Radial dikes, the "wings," propagated outward from a magma reservoir and are expressed on the surface flanking the main feature, Ship Rock (Chadwick and Dietrich, 1995). The emplacement history of Ship Rock is debated, although it is featured in many introductory geology textbooks, cited as a prime example of a volcanic neck that was once part of a cinder cone (e.g. Monroe and Wicander, 1995). Many volcanic neck-radial dike systems geometrically resemble Ship Rock.

Recently, however, the volcanic neck interpretation of Ship Rock has been questioned. Instead, some geologists (Delaney, 1987; Semken, 2003) propose that Ship Rock was part of a dike-and-diatreme system. A diatreme is defined as a volcanic vent or pipe drilled vertically through the surrounding rock by the explosive energy of a gas-charged magma (McCallum and Mabarak, 1976) (Fig. 2). Diatremes are typically cylindrical or funnel-shaped with steep sides (Everson and Roggenthen, 1988). As for the radially arranged dikes, Semken (2003) hypothesizes that they formed radiating up and in towards what is now Ship Rock and either preceded or followed the diatreme explosion that created Ship Rock itself.

Because the sequences of events would generate different subsurface geometries, this study aims to answer the questions regarding Ship Rock's formation through geophysical gravity surveys and modeling. Gravity anomalies, as detected on the surface using highly sensitive gravimetry instruments, could indicate the presence and location of subsurface dikes and other igneous features, such as buried volcanic plugs, that formed

Figure 1.
Ship Rock is located in Shiprock, New Mexico on southern Colorado Plateau.
Inset aerial satellite image shows diatreme and associated dikes.
(Aerial photograph from Google Maps)

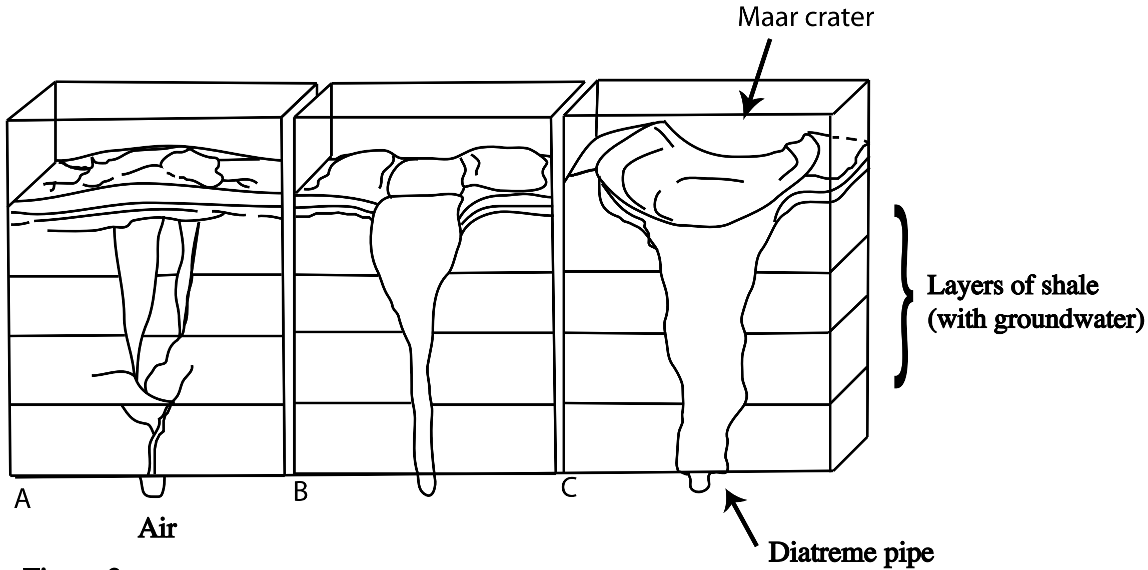

Figure 2.
As a gas-charged magma ascends into a sedimentary environment,
extreme high pressure built up from liquid de-gassing releases
in an explosion, and a diatreme and maar crater develop, as seen in these
cross-section schematic diagrams of how Ship Rock could have developed.
(Adapted from Everson and Roggenthen, 1988)

more slowly as magma was extruded into cracks either opened by an explosive diatreme-forming event, or possibly formed before the explosive event along lines of weakness. A better understanding of the geometry of the explosion chamber and the buried dikes could provide evidence in support of this diatreme model.

I will investigate the presence of two significant gravity anomalies detected at Ship Rock, will model what subsurface features they may reveal, and will discuss which model of Ship Rock's formation is supported by the gravity data.

LOCATION, GEOLOGIC HISTORY AND SETTING

In the Cretaceous, a great continental seaway covered the southern Colorado Plateau and deposited sandstone, mudstone and shale, including the prominent 200 m thick Mancos Shale layer at Ship Rock (Delaney and Pollard, 1981). In the early Tertiary, roughly 60 million years ago, subduction of the Farallon plate to the west fueled the Laramide orogeny. Between the Oligocene and Miocene, part of the Farallon detached and the Laramide orogeny ended, relaxing E-W compression and building the area into alternating uplifts and basins bounded by north- to northeast-trending monoclines, possibly related to reverse faulting at depth (Charles and Laughlin, 1992). Volcanism erupted onto the Colorado Plateau and continued throughout the mid-Tertiary, often characterized by explosive volcanism (Fig. 3). This episode led to the emplacement of several types of volcanic features: kimberlite pipes, composed of volatile-rich potassic ultrabasic rocks; diatremes, breccia- filled pipes formed by gaseous explosions; and, by more passive volcanism, potassic and ultrapotassic flows; sills; and dikes (Charles and Laughlin, 1992) (Fig. 4). Ship Rock is one of over 80 of these volcanic centers in the

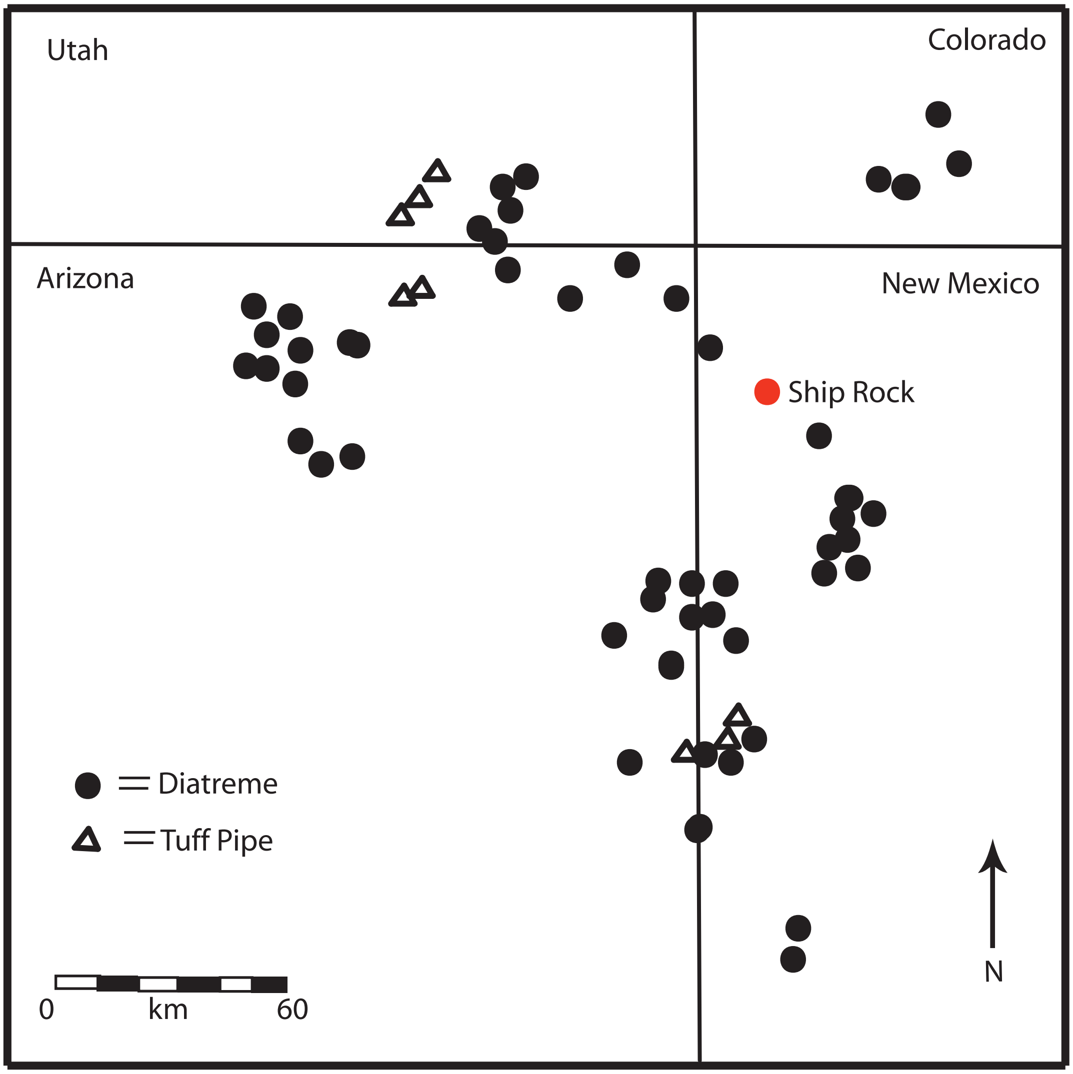

Figure 3.
Ship Rock is one of over 80 volcanic centers in the Navajo Volcanic Field and many more on the Colorado Plateau. Major volcanic features of the Plateau are shown above. (Adapted from Semken, 2003)

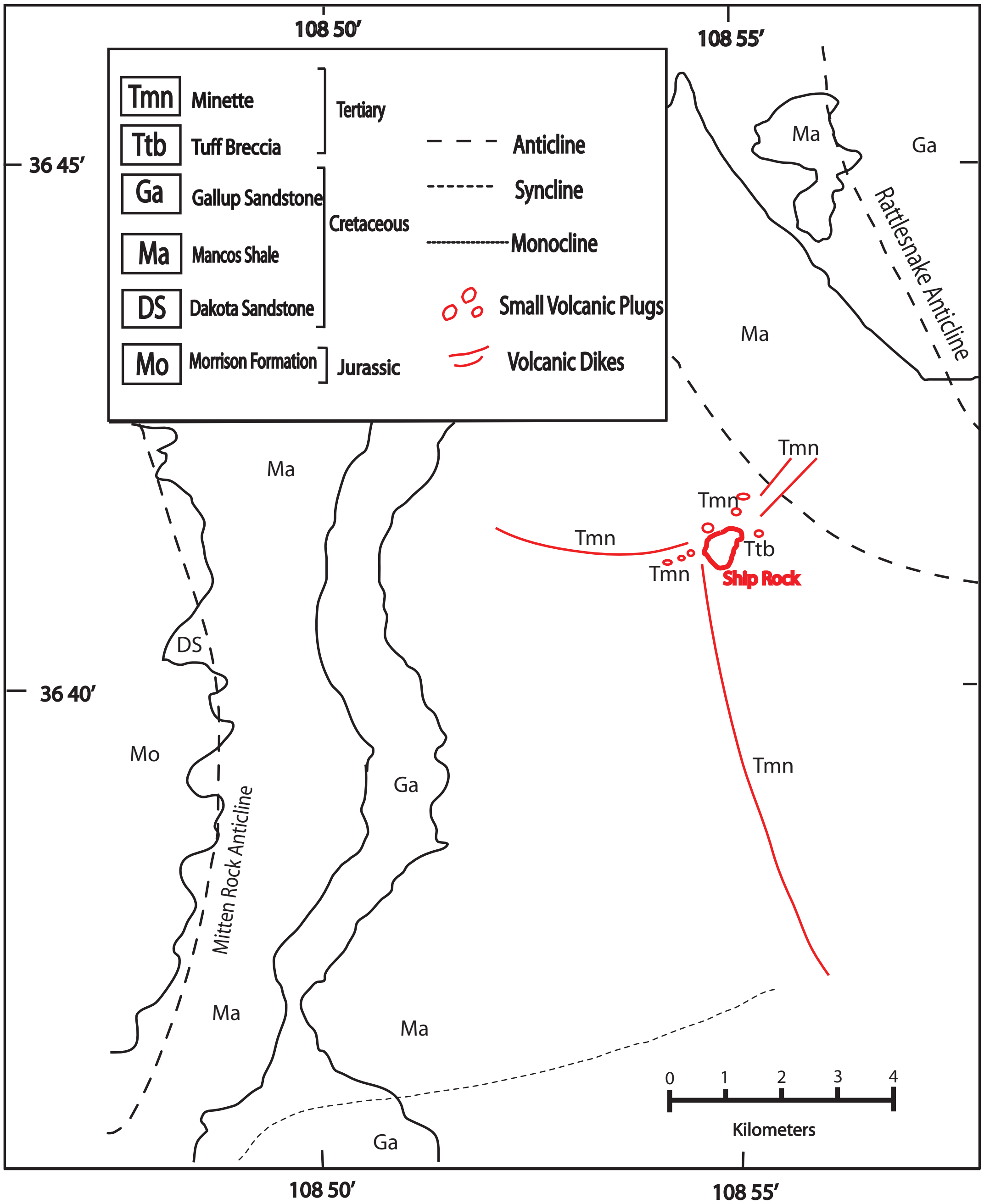

Figure 4.
Geologic map of the Ship Rock area, showing sedimentary formations, volcanic features and regional structures.
(Adapted from Delaney and Pollard, 1981)

Navajo Volcanic Field (Semken, 2003).

In some of Ship Rock's breccia, angular fragments of minette are housed in a tuff matrix, implying that effusive minette features (dikes) were emplaced prior to the explosive (diatreme). However, there are also dikes of solid minette locally cutting the Ship Rock diatreme; the relationship between these two rock types does not definitively indicate the temporal relationship of their emplacement in the study area (Delaney and Pollard, 1981).

COMPETING MODELS FOR EMPLACEMENT

Volcanic Neck Model

If Ship Rock were emplaced as a volcanic neck, as it is often labeled, the material of the main feature would be the same fine-grained material of the dikes, as both would have formed non-explosively. The feature as seen today, according to this model, is the solidified neck of an enormous volcano, whose cinder-cone exterior has entirely eroded away. Gravity anomalies could reveal buried dikes, arranged in a very regular, radial pattern, even underground, and the entire system would rest atop an extremely large magma chamber that would have held all the magma fueling the active volcanic system.

Diatreme Model

According to this diatreme model of interpretation, the feature was emplaced when groundwater in the shale was heated to extremely high temperatures under confining pressure by upwelling magma in upward-migrating dikes (Semken, 2001; Sheridan and Wohletz, 1983; Wolhetz and Heiken, 1992). A series of phreatomagmatic explosions ensued, creating a shallow maar crater at the surface. As the groundwater reservoir was depleted, the explosions migrated downwards, building up a pipe of minette tuff breccia, specifically identified as a potassic mica lamprophyre (Semken, 2003), with some collapsed sedimentary wall rock and pyroclastics. According to the diatreme model, Ship Rock would not have been formed by magma from a large subterranean chamber, as would a large volcanic neck; gravity data would be expected to show only a small magma chamber underneath the Rock, at a depth much greater than that of the dikes.

The diatreme, formed as an underground explosion chamber, has been exhumed since formation. Because Ship Rock is composed of almost all minette tuff-breccia, and not a large amount of slumped-in wallrock, it is thought by those who support the diatreme model that the above-surface feature is at mid-diatreme, and therefore at least 550 m of material originally above the present feature has been eroded (Semken, 2001).

Scientists have developed competing hypotheses to explain the non-volcanic neck model for Ship Rock. One school explains the coexistence of the phreatomagmatic feature (diatreme) and effusive features (the associated dikes and plugs) by hypothesizing that the effusive features formed later, when magma resurgence built up dikes and plugs not related to the initial explosion. If the violent explosion during which Ship Rock was formed opened up great tension fractures, these could have immediately filled with magma from a large magma chamber conduit, and solidified to form the dikes (Vokes, 1942).

Another view is that these dikes preceded the formation of Ship Rock diatreme, with one main dike, likely the largest South Dike, fed the diatreme. The dike-fed diatreme model postulates that a small but highly active magma chamber sent pressurized molten material through cracks and weaknesses in the surrounding rocks. The material in these cracks cooled and formed the dikes. Perhaps they were all trending towards a singular weak point or area in the Mancos shale that offered the least confining pressure, and in this area, when the dikes built up sufficient pressure by heating moisture in the shale, the explosion occurred and the diatreme was formed.

GRAVITY

These possibilities (volcanic neck or diatreme; dike-fed diatreme or diatreme pre-dating dikes) can be tested by using gravity anomalies, as detected on the surface, indicative of subsurface rock density differences, to model images of subsurface geometry. Imaging can show the subsurface bodies' shapes and locations in the volcanic field, and the root contacts of dikes and diatreme or magma chamber at depth. Subsurface gravity anomalies caused by dense volcanic rock in less dense Mancos shale (country rock) can be detected by sensitive instruments at the surface, using geophysical surveying methods, including the gravimeters used in this study. Testing with gravity is the method of this study because of its capabilities for accurate subsurface imaging. This technique is especially important at Ship Rock, where surveys involving more invasive methods like drilling or coring would be both uneconomical and highly disrespectful and inappropriate on these lands sacred to and owned by the Navajo Nation.

QUESTIONS AND PLANS OF STUDY

Several questions can be addressed by analyzing gravity anomalies:

(1) Using the technology available for this study, are significant gravity anomalies detected?

(2) Do gravity anomalies show evidence for subsurface dikes, plugs, or sills of dense, volcanic material buried in the less-dense country rock?

(3) Can the data be modeled to understand and constrain the subsurface dike geometry and depth of their emplacement, and provide support for any one model of Ship Rock's formation?

(4) Do gravity data indicate the presence of a buried magma chamber underneath Ship Rock?

All of these questions are important because answering them could reveal how Ship Rock formed and how its dikes propagated, either as a volcanic neck or as a diatreme, and, if it formed as a diatreme, the sequence of events of its features' formations. In the latter case, Ship Rock could provide a possible model for how other diatreme systems form.

METHODS

Two LaCoste and Romberg Model G gravimeters were used in this study (Fig. 5). Both operated using leveling and aliod system, one electronic and one non-electronic. Each gravimeter houses a mass suspended on a spring. After the device is precisely leveled on the ground, and the mass is given at least ten seconds to stabilize, the spring's

Figure 5.
Two LaCoste and Romberg Model G Gravimeters were used for gravity data collection. The box containing the highly sensitive spring and extension-reading device must be set on a completely level plate before a reading is taken.
(Photo: Yospin, 2006)

extension is measured and interpreted as indicative of the gravity field strength in that location.

Gravity readings were taken at .3 km (300 m) spacing in a 12 km E-W x 11 km N-S area along several roads around Ship Rock, creating a network of approximately E-W and N-S striking gravity profiles. The data collection lines were selected to construct a loose grid around the Ship Rock diatreme and its associated dikes, with a total of 105 readings taken along 8 sampling lines. Gravity was read in milligals, and recorded from two separate gravimeters. One measured in milligals, while the other measured in dial-spins. All readings taken on the latter gravimeter had to be multiplied by a conversion constant of 1.0264 dials to milligals so that all readings could be compared.

Horizontal position was taken at each measurement site using Trimble roving GPS units (Fig. 6). GPS error sources include interference from the ionosphere and troposphere, inaccuracy in satellite clocks and receiver noise (Bank, 2006). With these inaccuracies, a regular GPS reading gives location with a roughly 9 m horizontal error. Most of these errors can be corrected with differential processing, reducing error to roughly 1.3 m. For even greater accuracy, the carrier phase is used, reducing error to 10 – 20 cm, post-processing. Horizontal position was recorded in Universal Transverse Mercator Zone 12, which contains the area of study.

Total Station surveying equipment was used at each gravity station site to obtain vertical position data within 10 cm of the elevation at every site (Fig. 7). The raw data in this study consist of gravity readings in milligals with the time each reading was taken, as

Figure 6.
GPS data collection was done using roving units to gather carrier-phase data at each measurement site. Data was corrected to the differential for 10 - 20 cm horizontal position accuracy.
In photo: Carolyn Tewksbury, Smith College
(Photo: Yospin, 2006)

Figure 7.
Total Station elevation readings, were taken at every gravity site using a Leica sighting instrument, providing 10 cm vertical position accuracy. (Photo: Yospin, 2006)

well as the GPS-provided and total station-revised northing and easting values of its precise location, and vertical position data from total station measurements.

I will use published densities of the various rock types present in the Ship Rock area to construct and interpret models in examination of this factor's effect on observed gravity anomalies from the 1981 Ship Rock study by Delaney and Pollard.

Minette ≈ 3.0 g/cm^3
Tuff breccia ≈ 2.04 – 2.27 g/cm^3
Shale ≈ 1.8 g/cm^3 at surface, ≈ 2 g/cm^3 at depth

THEORY OF GRAVITY CORRECTION

Gravity's effect varies significantly in space from the standard 9.8m/s^2, due to several factors. Gravity variation can be measured as an anomaly; as with any sort of anomaly, a gravity anomaly signals that something is out of the ordinary. This deviation can be caused by any number of variables, including rock density, the factor of interest to this study. To isolate the effect of rock density on a gravity reading, which this study must do to constrain data for subsurface imaging, each unrelated variable must be extracted out of the data. To account for these unrelated factors, a value must be either added to or subtracted from the gravity reading as taken in the field.

Drift Correction

In this gravity survey, loops back to base stations were completed approximately every hour to re-measure gravity and account for abundant sources of drift. Readings do vary slightly with time, due to internal machine spring fatigue, temperature variation, and most significantly, variation with the tidal cycle. Within the time space of about an hour, this drift is assumed to be roughly linear. A drift curve is constructed from the data and every reading is corrected to this curve.

Latitude correction

The latitude at which a gravity reading is taken must be accounted for, as gravity is affected by the amount of material between a body and the massive core of the earth. Because the shape of the earth is an oblate spheroid, not a sphere, gravity varies depending on latitude. The closer one is to the poles of the earth, the stronger the gravity field. This phenomenon is also related to the effect of strong centrifugal force at the equator. The difference in gravity field reading moving from the equator to a pole is 5 gal (Bank, 2007), a significant difference for a study such as this one.

The latitude correction was calculated using published values for the region's height above the ellipsoid base level, as determined by the base station elevation, according to differentially corrected GPS.

Free-air correction

The free air correction amount is 0.3086 mGal per meter above sea level, and adjusts data to fit the assumption that there is only "free air" between sea level and the station being measured. This correction is positive, because increased distance from earth's center serves to decrease gravity readings. Given the magnitude of gravity readings taken, this is quite a large correction; hence, accuracy in elevation data (from GPS) is particularly significant for the study.

Simple Bouguer Correction

The Bouguer correction accounts for elevation and rock density between the measurement station and a reference level – the "Bouguer slab." The Bouguer slab is a simplified model of the earth's surface used in gravity surveys, based on the assumption that the world's topography can be represented by a flat plate of uniform density with a thickness equal to the height of a gravity station above a known reference level. This correction removes the effect of the slab's gravitational pull, when the slab is assigned a known density. The Bouguer gravity effect is calculated as

$$\mathbf{Field = 2\pi\rho Gh}$$

where $\boldsymbol{\rho}$ is the density of the surface rock, approximately 2.67g/cm^3, **G** is the universal gravitational constant, and **h** is plate thickness. This correction is negative, to adjust for the positive effect of slab thickness.

Regional Gravity Trend Correction

In a given region, gravity often increases or decreases on a continuous gradient, because of large-scale regional structures. In order to correctly interpret local gravity anomalies, the slope of this gradient's line must be corrected to horizontal, and anomalies must be analyzed in terms of their deviation from this corrected gradient.

Terrain Correction

Terrain corrections adjust for deviations of actual topography from an imaginary plane, running parallel to sea level, at the elevation of a gravity station. Terrain corrections are always positive. Curvature correction is another part of terrain correction, accounting for the spherical cap shape of the Bouguer slab, as draped over the Earth's surface. The Hayford-Bowie system of compartment curvature adjustment corrects for these terrain effects out to a radius of 167 km (LaFehr, 1991), which is adequate for the relatively non-rugged terrain surveyed in this project.

For this study, complete terrain corrections would be done using terrain correction software and the total station data we gathered to provide a high-accuracy Digital Elevation Map (DEM) for the small region. However, such a program was not available for my use in this study, and it should be noted that in this almost-flat landscape, terrain corrections may not be the most crucial adjustment made to data. Ship Rock itself, however, does potentially exert a large terrain-effect on gravity anomalies, and this effect was roughly corrected for, as will be addressed later in the "Interpreting the Model" section of this paper.

RESULTS

A high gravity anomaly in this case would reflect that the detection instrument was situated above high-density material. Solid minette (as in the dikes) is the densest material this study will likely encounter; minette tuff breccia, the material of the diatreme and likely of its feeder pipe, is less dense than pure minette; and the Mancos shale country rock is far less dense than either igneous material. Because of the density difference anticipated between dike-material and diatreme-material, it is possible that though the volume of the diatreme pipe is likely much greater than any dike's volume, the gradient of an anomaly caused by tuff-breccia will be less steep than an anomaly from a minette dike. Other factors such as depth of burial will complicate this.

A contour map, constructed using the computer program Surfer, shows simple Bouguer gravity data as gathered in the field (Fig. 8). A consistent gravity value trend can be observed, with values decreasing on a line striking NW-SE. The removal of this regional gravity gradient is a correction supported by a statewide regional gravity gradient in New Mexico, trending in the same direction (Fig. 9). The regionally corrected data are deflected around two main features: the paired steep high and slight low in the northwest sector of the study area (Fig. 10).

The roughly circular +16 mGal high extends about 2 km E-W and 2.5 km N-S. Just east of this, a slight gravity low of +7mGal has a 1 km E-W, 2.5 km N-S extent. The +16 mGal high is steepest to the northwest of the anomaly's center, and gravity values decrease away from the anomaly on all other sides at a fairly steady rate, with the exception of the location of the +7 mGal low. These are the two most prominent anomaly features of the gravity data, and given the distribution of stations around them, the anomalies are well-constrained and credible. Figure 11 shows the corrected and contoured Bouguer gravity data superimposed onto a DEM of the Ship Rock area. As seen on this map, the gravity high falls west of Ship Rock and the slight gravity low is located at Ship Rock itself. A three-dimensional representation of this data, as viewed from three points of perspective, shows how this high and low relate to gravity value trends over the study area (Fig. 12).

SUBSURFACE MODELING OF GRAVITY FEATURES

The gravity high and low are the most significant anomalies detected in this study, so modeling was done for these buried bodies along the line of Northing position that cut

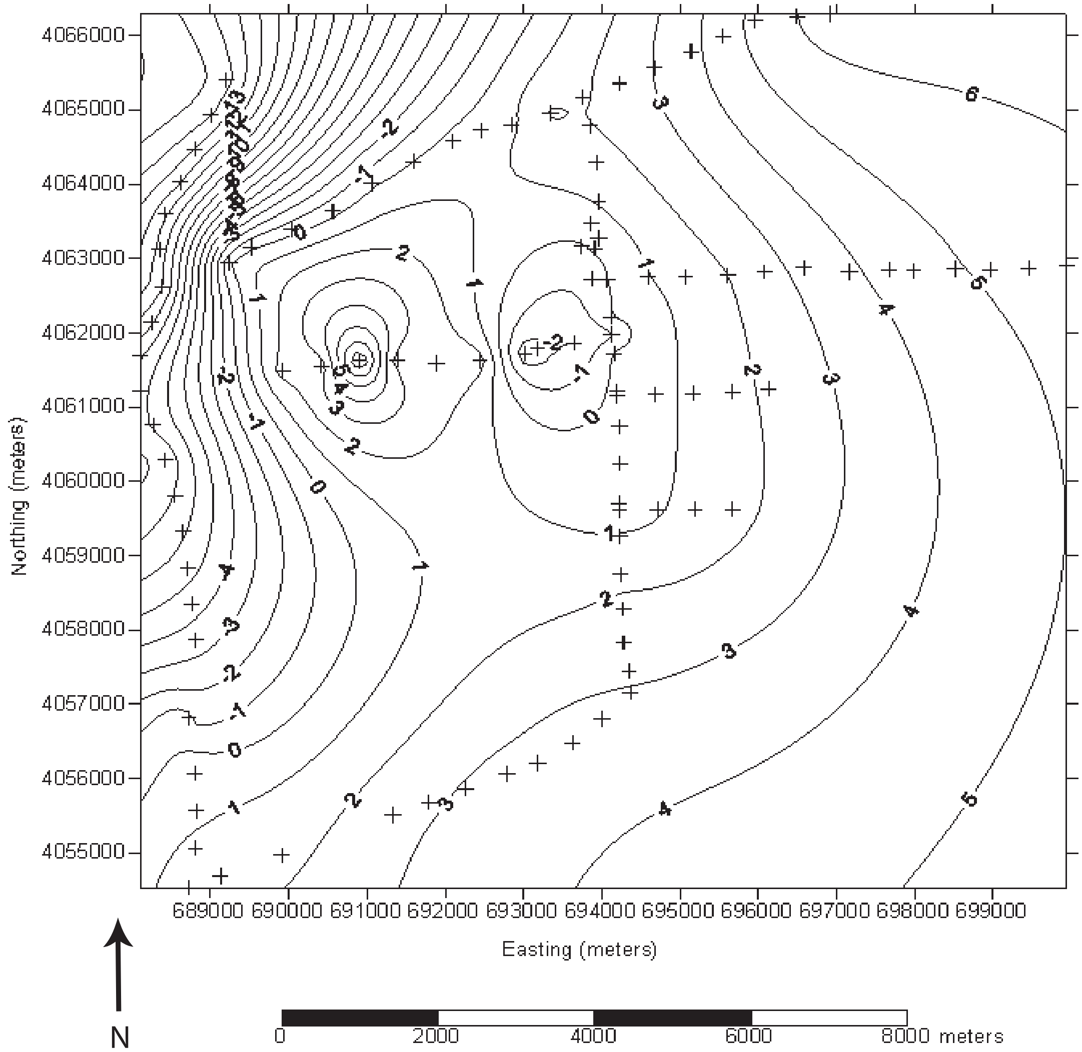

Figure 8.
Contoured Bouguer gravity data, before extraction of the regional gravity gradient, shows a steep decreasing trend from NW to SE. Gravity measurement stations are indicated by post marks.

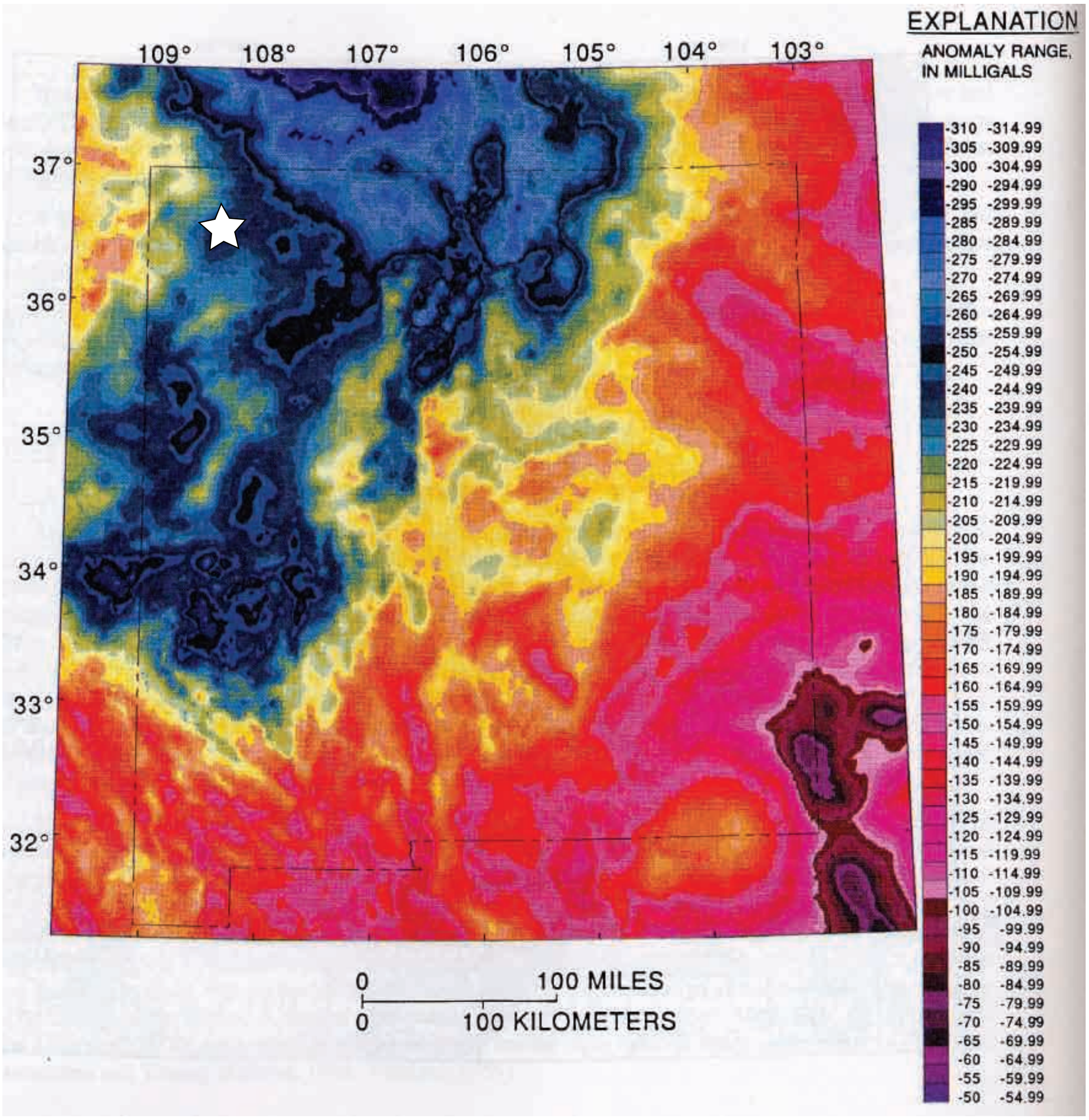

Figure 9.
The Bouguer gravity anomaly map for the state of New Mexico shows a decreasing large-scale regional gravity gradient trending NW to SE. This gradient trend is echoed in the trend for data in this Ship Rock study, located at white star on the above map, and was corrected out of the Bouguer gravity data.
(Adadpted from Heywood, 1992)

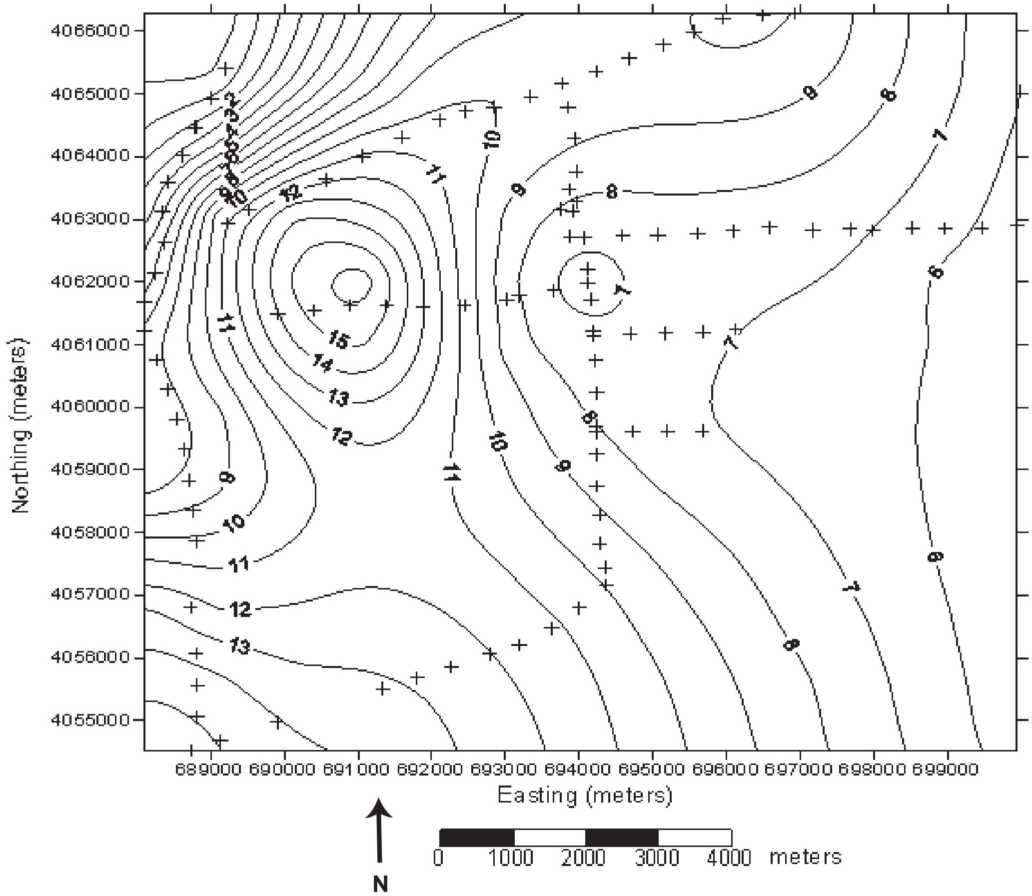

Figure 10.
Regionally corrected Bouguer gravity data values are deflected around two main anomalies, a high and slight low. Gravity measurement sites are represented by post marks.

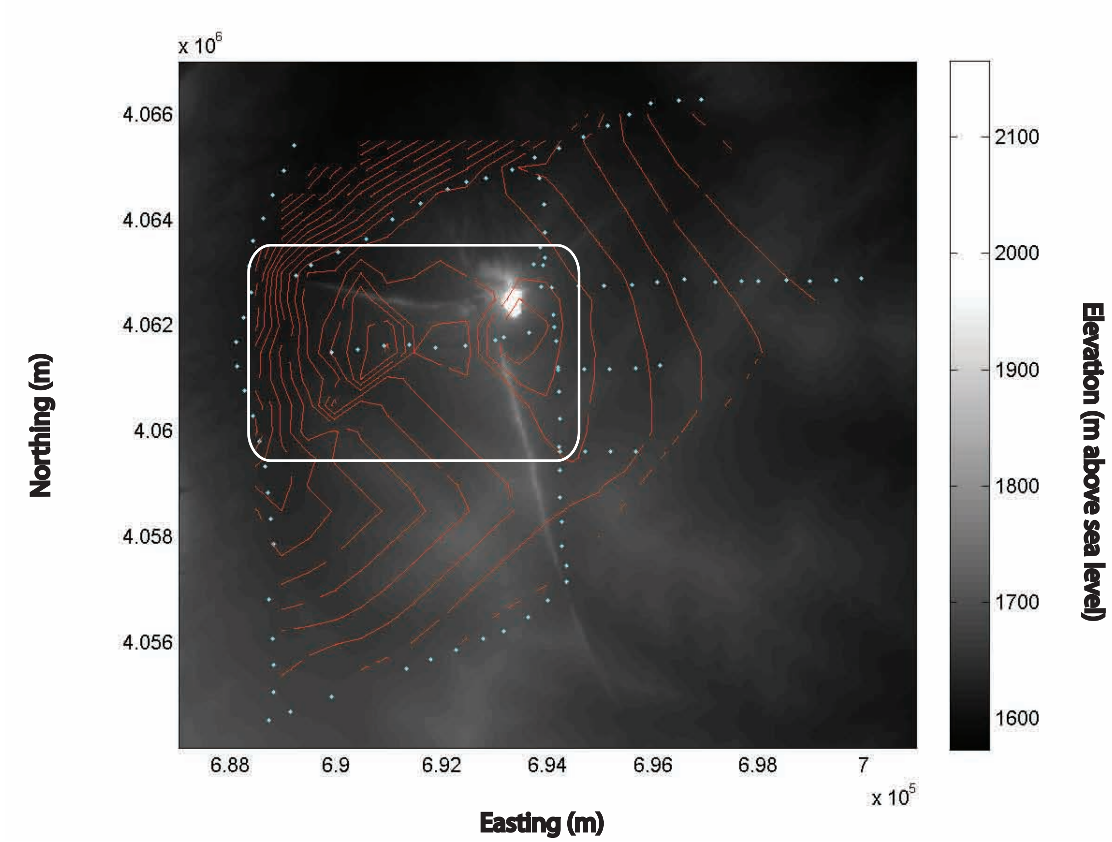

Figure 11.
Regionally corrected Bouguer gravity value contours, in red, are laid over a Digital Elevation Map (DEM) of Ship Rock (the white area with radiating dikes), with gravity measurement sites in blue. The bounded area contains the paired set of gravity anomalies modelled for in this study. The anomaly to the west of Ship Rock is the gravity high, and the gravity low is shown to be at Ship Rock itself.
(Adapted from Bank, 2007)

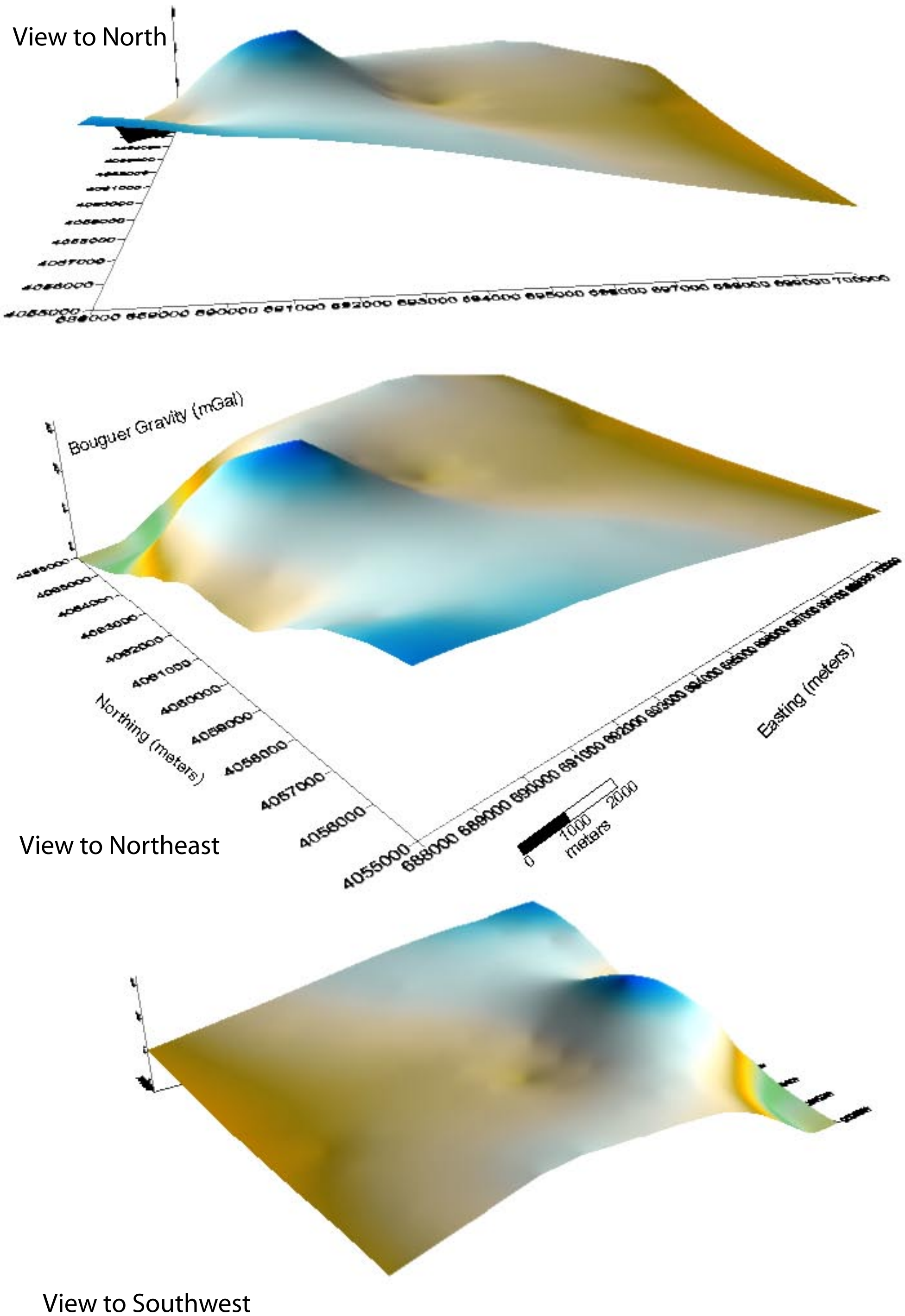

Figure 12.
These three-dimensional surface maps of regionally corrected Bouguer gravity values illustrate three views of the two main anomalies explored, as well as the general gradient of the region, mostly leveled after regional correction.

across the intriguing anomalies (Fig. 13). I developed one possible model for Ship Rock's subsurface geometry to explain observed Bouguer gravity anomalies (Fig. 14). Using the subsurface imaging software Grav2DC, designed by Dr. Gordon Cooper, the regional gradient-corrected Bouguer gravity data were plotted with their northing and easting positions. This computer program allows users to input virtual buried rock bodies, specifying their density contrast with the host rock, depth, width, and shape. The user can adjust these parameters, altering the factors determinant of the observed gravity anomaly as it would be detected on the surface, until the observed and modeled gravity anomalies resemble each other.

In this model, observed Bouguer gravity data points are represented by the post marks along an x-axis of easting in meters and an upper y-axis showing gravity value in mGal. The lower y-axis shows the depth of the subsurface body in kilometers. Two bodies have been modeled: the first, shown in orange, is placed underneath the larger of the two observed anomalies. It is buried shallowly, at a depth of roughly 3 km, with a density contrast of +0.165 g/cm^3 with the surrounding country rock, with a width of roughly 150 m. The second body, shown here in blue, is buried much deeper, at 75 km, and placed east of the anomalous low. Its width is 145 m, and its density contrast is +0.075 g/cm^3. These density contrasts are quite small given the densities of minette (3.0 g/cm^3), tuff breccia (2.1 g/cm^3) and shale (1.8 g/cm^3); although the modeled bodies fit the data, the parameters required for these sorts of deeply buried bodies to match the observed data are far from what is expected at Ship Rock.

The important caveat in gravity modeling is the plurality of "correct answers." A model can successfully fit data without successfully fitting the geological context of a

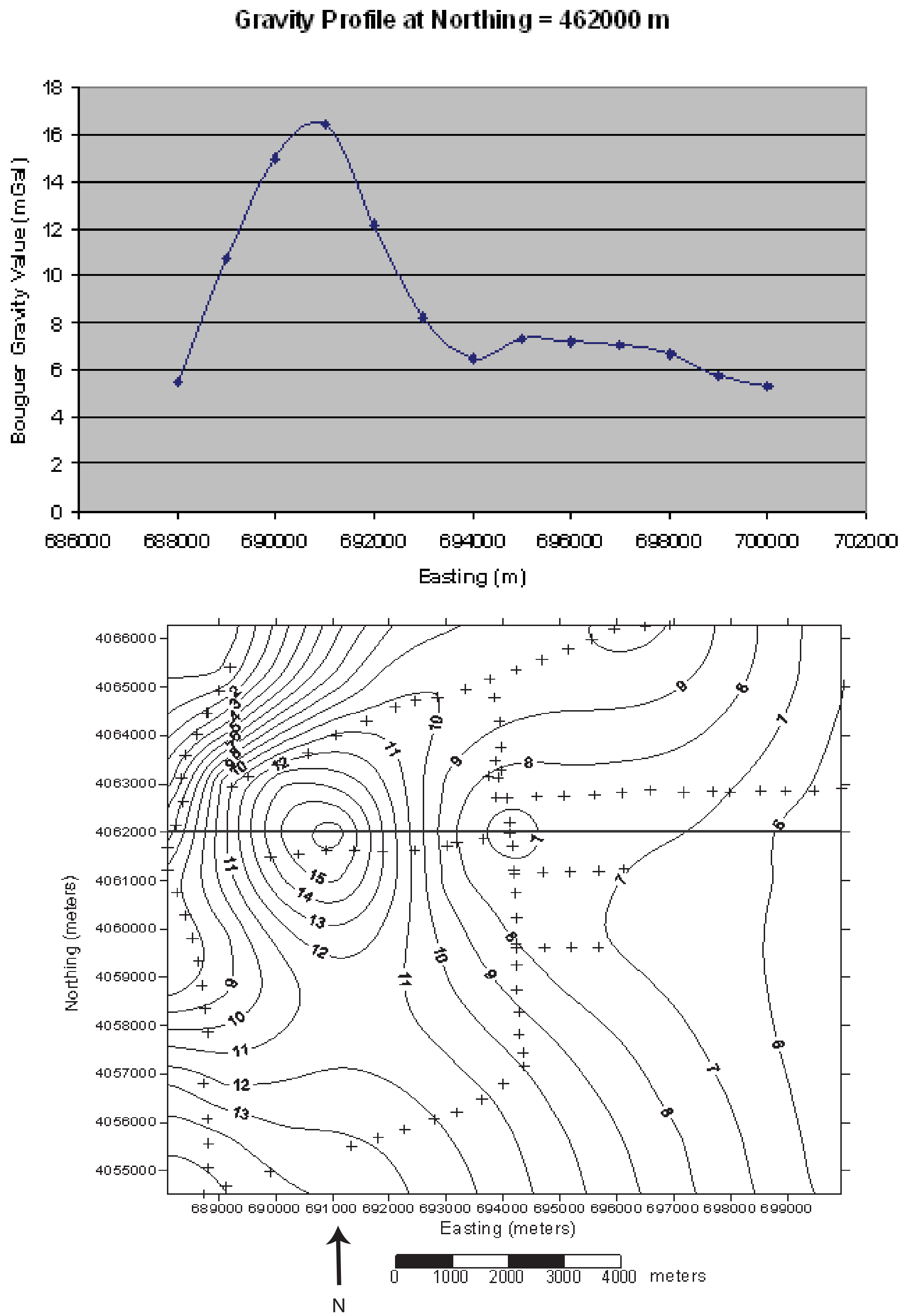

Figure 13.
At top is a profile of regionally corrected Bouguer gravity data along the Northing = 4062000 m line. The location of this line is shown on the contour map at bottom. This profile strikes across the centers of the two observed anomalies, and data along this line were modeled for subsurface geometry.

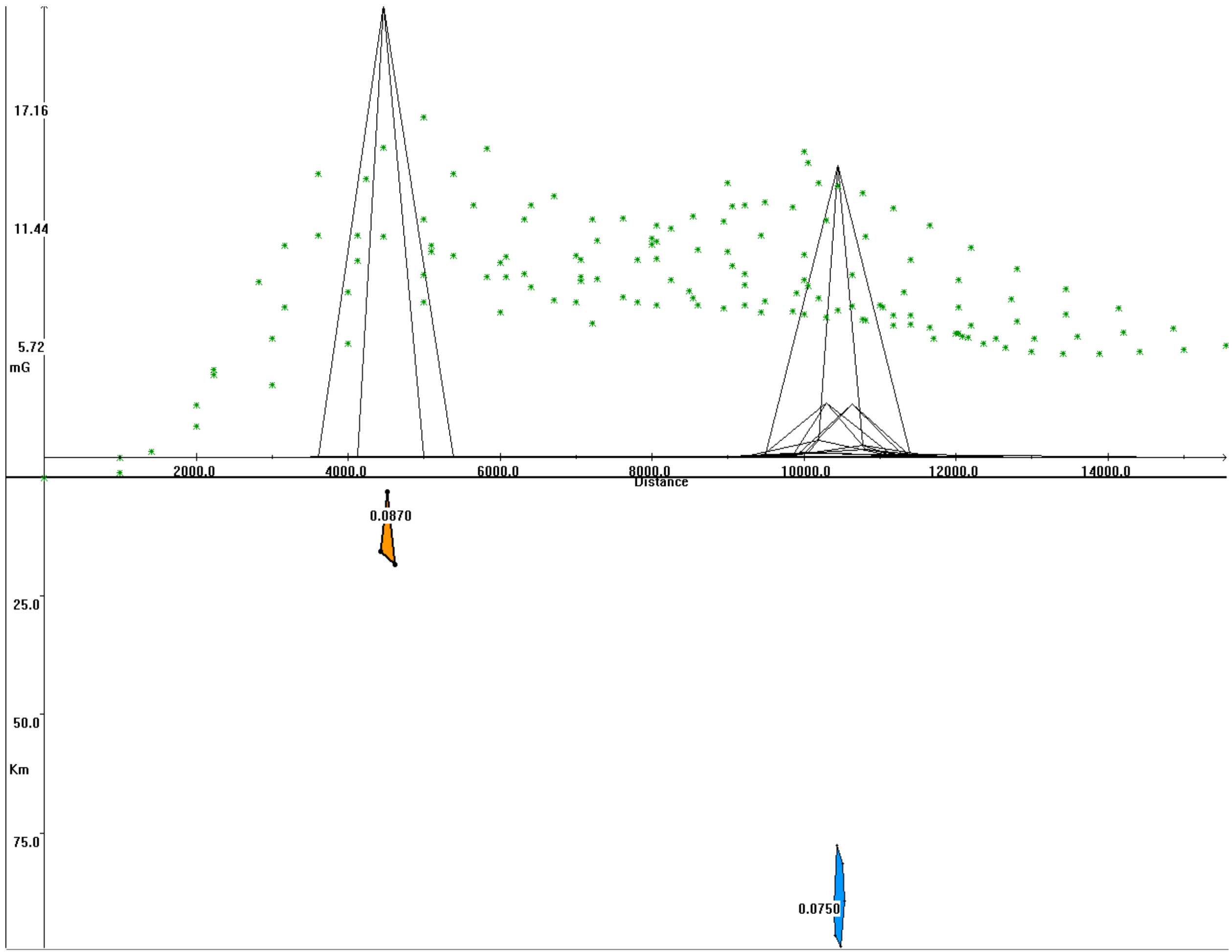

Figure 14.
Alongside observed, regionally corrected Bouguer gravity from the observed paired anomaly (post marks), hypothetical anomalies are plotted (black lines), as would be caused by the two modeled subsurface bodies. These properties were manipulated until the modeled anomalies most closely fit the observed anomalies. Shown on the model above are Easting (x-position), gravity value in mGal (upper y-axis position), subsurface burial

feature. Various combinations of geometry, burial depths and density contrasts can yield the same result, so one must enter into the modeling process with a set of hypotheses that would satisfy the geologic context of the study subject. Differentiating a small, deep body from a broad, shallow body is difficult given the nature of gravity data collection. Figure 15 shows what an ideal (and not realistic) buried mass of high density could produce in the way of a Bouguer gravity anomaly according to various parameters, showing that similar gravity profiles can be produced by multiple combinations and variations in depth and mass of a buried body. With the caveat in mind that multiple "correct" interpretations are possible given one observed gravity anomaly, my model must be discussed, criticized and expanded upon.

Interpreting the Model

Interpretation #1: Diatreme Pipe and Magma Chamber

Assuming that, as my model basically fits the observed data, its subsurface geometries are reasonable and applicable given the feature's context, I will provide one interpretation of the model. The high gravity anomaly could be a result of the continuation of Ship Rock's diatreme pipe, a volcanic throat filled with brecciated material. This would mean that the pipe continues to the west of the Rock itself, as the anomaly is not located directly beneath Ship Rock. This body would be very shallowly buried, extending as it would down from the surface, in accordance with the large and steep gravity anomaly detected.

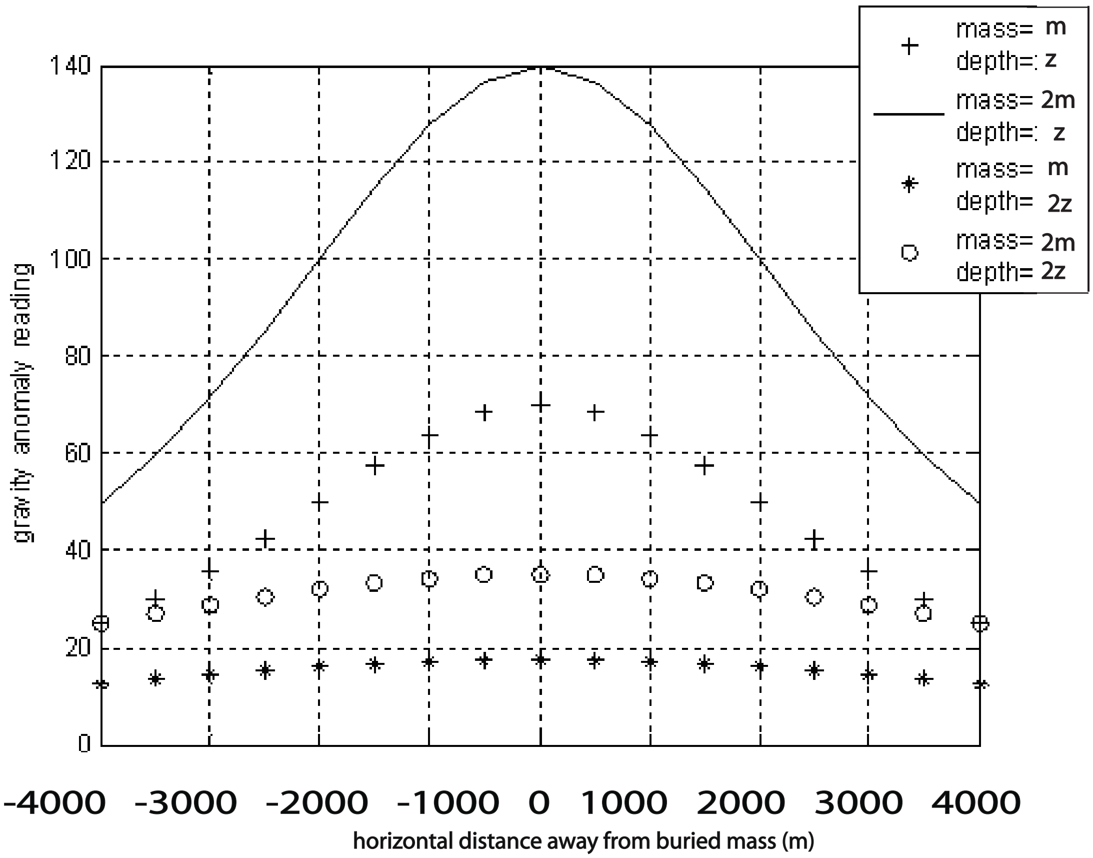

Figure 15.
This graph shows modeled gravity anomaly readings as they would respond to buried bodies of varying mass and depth properties, at different horizontal distances away from the buried body. The model assumes that these buried bodies contain all of the proposed mass in one point at a finite depth -- this is not actually possible. The importance of this figure, however, is that it shows how similar anomalies can be observed as a result of very different characteristics of subsurface bodies; there is a plurality of "correct" answers to explain any gravity anomaly data.

The second buried body could be interpreted as being a deeper feature with a positive but low (relative to its surrounding gravity values) gravity signature, perhaps a buried magma chamber with hollowed-out components. At Ship Rock, this magma chamber would reasonably be located far deeper than the features it fed, and would be greater in width than either the dikes or the buried diatreme pipe. However, with the rather small modeled width of 145 m, this chamber is not large enough to have fed the formation of a giant volcanic neck, and this interpretation would therefore fit with the postulated dike-diatreme model. This feature is interpreted, according to this model, as having a lower density contrast with the surrounding rock than does the diatreme pipe, even though a magma chamber could be expected to contain higher density minette rather than explosion-formed tuff. This discrepancy between the expected and the modeled could be explained by a hypothesis that the magma chamber is partly hollowed out, after being emptied by the Ship Rock explosion and the dikes' formation, which would greatly decrease its gravity signature. A diatreme, on the contrary, is considered to be composed of solid rock. Diatremes modeled in cross-section, such as Black Butte in Montana by Everson and Roggenthen (1988), are usually shown to be made up of a combination of breccia and pyroclastics, containing little to no high-density basaltic/ minette material (Fig. 16).

Breccia pipes usually extend straight downwards to their source magma chambers, but they are sometimes inclined (Everson and Roggenthen, 1988). Given that the general shape of Ship Rock diatreme, if outlined from above, is a roughly NE-SW trending ellipse (Fig. 4), it could be interpreted as a diatreme pipe oriented at an angle, so that its surface expression is not perfectly circular. This orientation direction can be

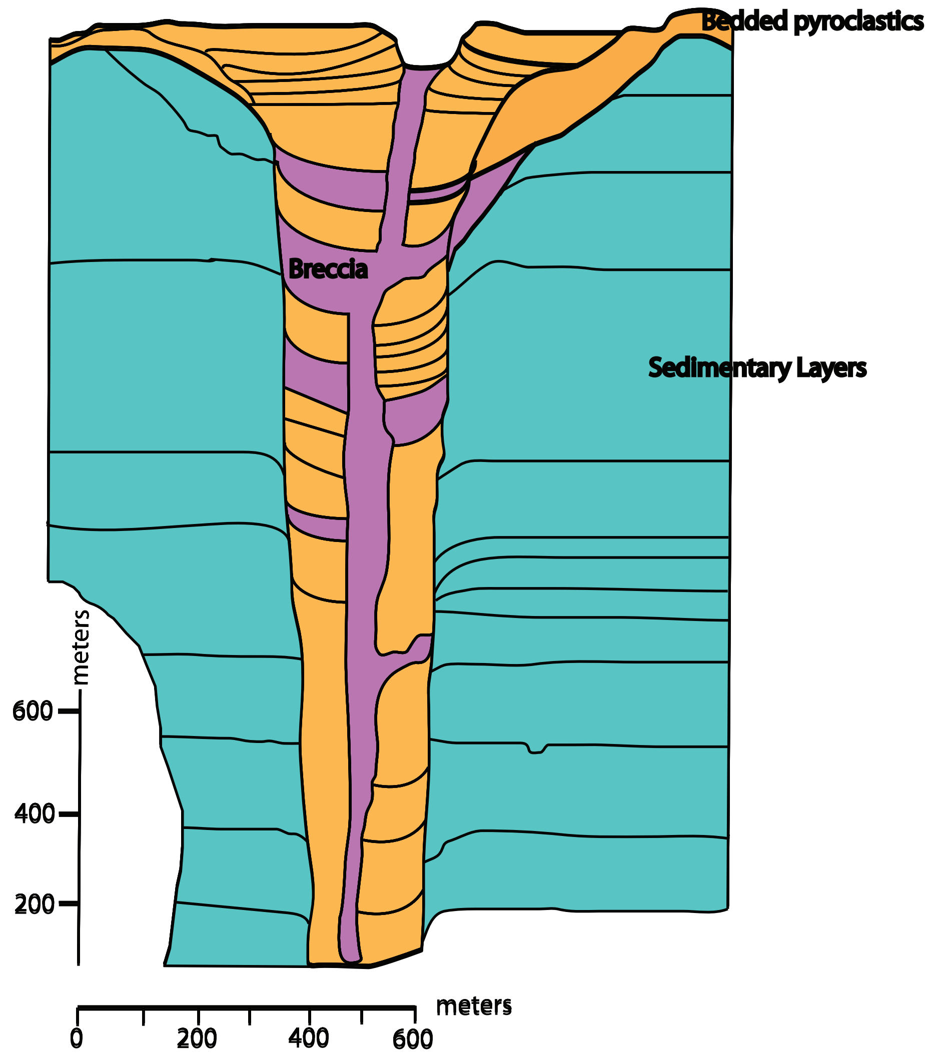

Figure 16.
This diagramatic cross-section of the Black Butte diatreme in Montana shows that the feature consists mostly of bedded pyroclastics and some breccia, cutting thorugh sedimentary layers.
(Adapted from Everson and Roggenthen, 1988)

inferred from the gradient of gravity data increase in various directions around the anomaly. The fact that the observed gravity anomaly is steepest towards the northwest of the circular anomaly supports the diatreme pipe's orientation slanting downwards SE, so that the feature is closest to the surface in the NW, producing a sharp gravity gradient in that region. According to this proposed model, the diatreme pipe could be sloping towards the magma chamber at its base, buried at depth.

Interpretation #2: Volcanic Plug

Many aspects of the first interpretation of gravity data are inconsistent with the specific context of Ship Rock and with the geometry of other dike-diatreme systems, so an alternative to the model is proposed. In general, a subsurface feature does not exceed in depth the breadth of its gravity anomaly as detected at the surface; as both detected gravity highs are expressed as narrow-range surface anomalies, their depths of emplacement should be quite shallow, likely under 2 km. A magma chamber would be buried, and a diatreme pipe would extend, deeper than this estimate. Given the evidence, it is more likely that the observed anomalies indicate a shallowly emplaced feature, in the case of the gravity high, and Ship Rock itself, in the case of the gravity low.

Above the surface, many relatively small, dense minette features exist in the vicinity of Ship Rock as satellites of the main feature, mostly line with the dikes arranged radially around the Rock (Fig. 17). The volcanic plugs, as they are called, are made of highly dense minette, rather than tuff breccia. Given the presence of these features above surface, perhaps a shallowly buried volcanic plug just east of Ship Rock is producing the observed gravity anomaly high. The geometry of these plugs' emplacement above-

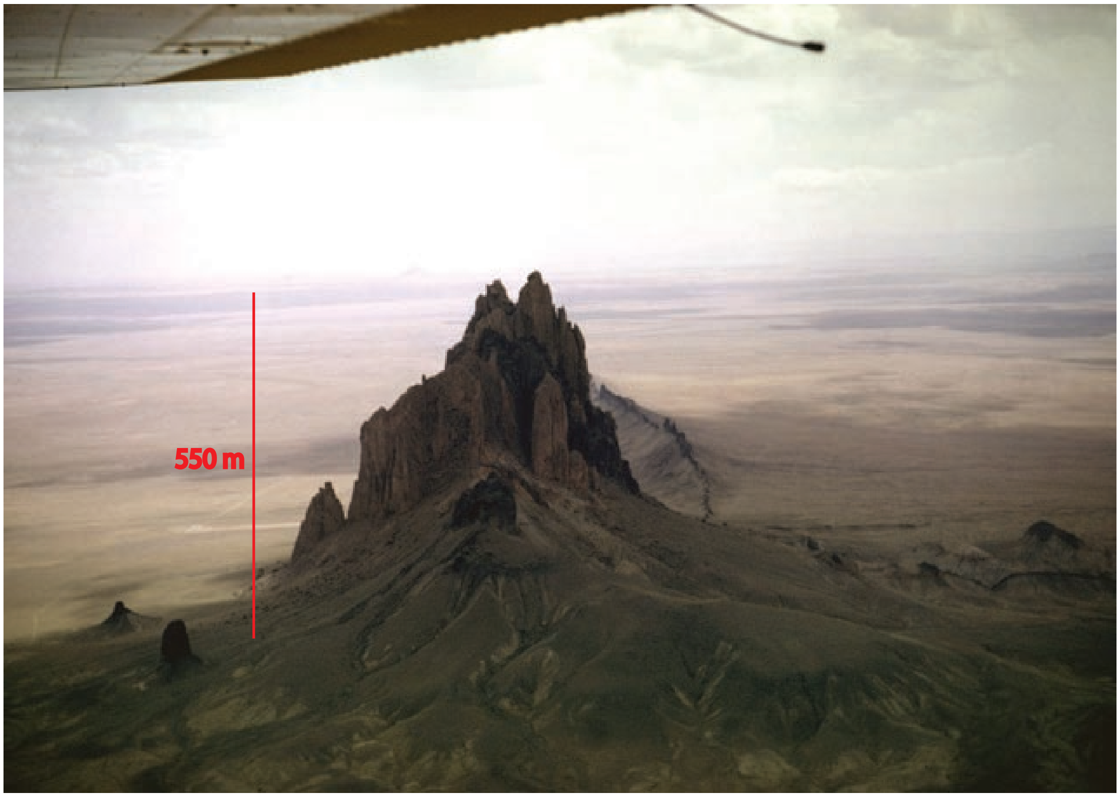

Figure 17.
This aerial photograph view of Ship Rock to the SSE shows small satellite volcanic plugs (lower left). Such bodies, buried to the east of Ship Rock, may be responsible for the observed gravity anomaly high. (Photo: from Maher, 1966)

surface has not been the subject of much geological or geophysical research, although they tend to be arranged around Ship Rock in alignment with an associated dike.

Because the sampling density is shown to be insufficient for illustrating the presence of a feature so small as a minette dike, these data cannot be used to determine whether this possible plug is associated with a buried dike, and, if so, the orientation of such a dike.

The + 7 mGal low to the east of the high anomaly is a small anomaly given the values surrounding it. Given the position of this anomaly as shown with the DEM in Figure 11, the gravity low is most likely a result of the effects on gravity signature of Ship Rock as a massive above-ground feature. The presence of so much dense material on the surface would be expected to lower gravity signature enough to produce a gravity low near Ship Rock. To estimate this terrain correction, the vertical attraction due to Ship Rock, approximated by a box-shaped object 500 m up, and 500 m x 500 m at its base, was calculated. A density of 2670 kg/m^3 (standard Bouguer density) was assumed. Correction values for stations close to the diatreme are about 2.5 mGal. As expected, this basically removes the simple Bouguer gravity low S of Ship Rock (Fig. 18).

Focusing on interpretation of the circular high of + 16 mGal, its emplacement at such a shallow depth could be examined in light of the known stratigraphy of the area. Stratigraphic surveys have estimated the thickness of the Mancos shale at 200 m near Ship Rock given present-day surface elevation. Perhaps in the space available at the contact between the Mancos and the underlying basement rock, at a depth of roughly 200 m, these volcanic plugs formed, with a vertical orientation but taking advantage of the

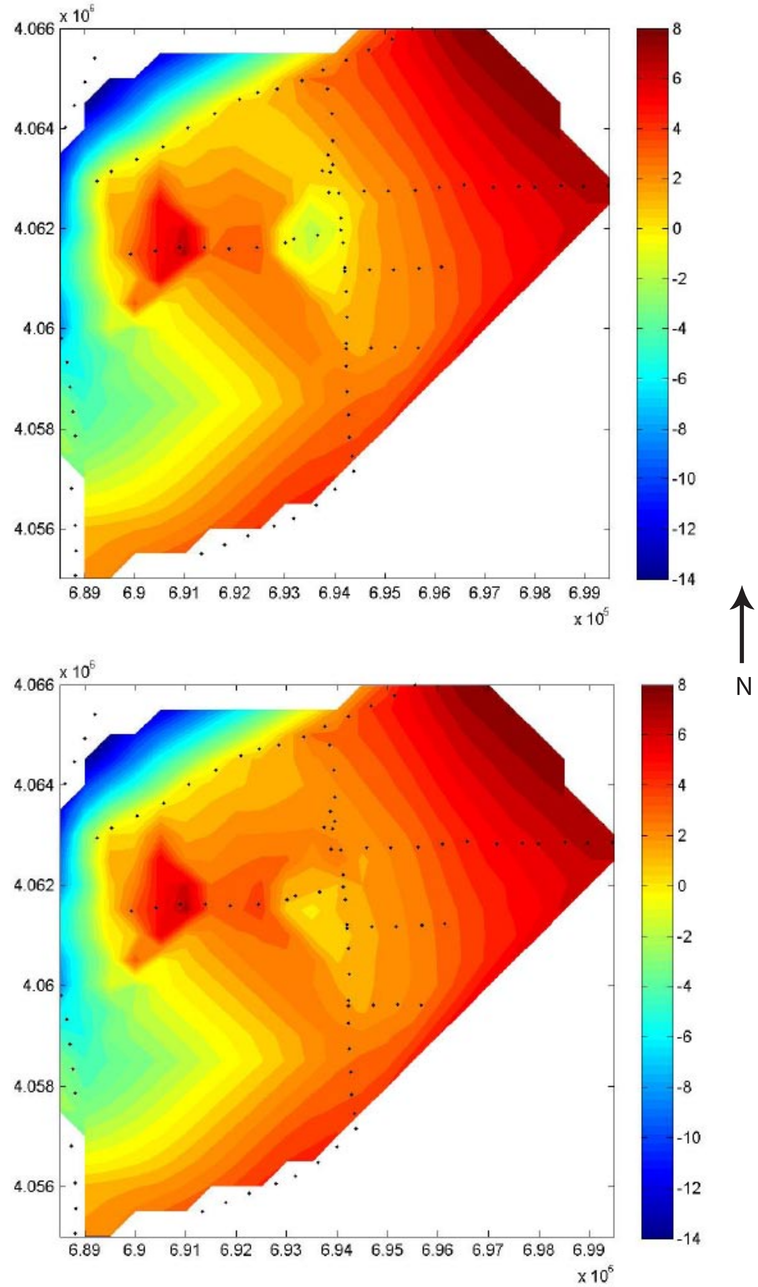

Figure 18.
These contour maps of Bouguer gravity values show the difference between layers as color changes, as opposed to line countours. The contour map at top shows gravity values with all but terrain correction applied; note the yellow/green anomaly low. The contour map at bottom shows gravity data after the effect of Ship Rock's terrain has been removed., by modeling the Rock as a large, dense box-shape. Note in this figure that the gravity anomaly low has lessened in intensity. The low graivty anomaly is shown to be a result of thedata points' extreme proximity to Ship Rock.

roughly horizontal plane of weakness. A ~ 200 m emplacement depth would fit the observed data relatively well, and offers one explanation for the feature's burial depth.

Perhaps this plug feature, vertical in nature, strikes NW-SE and dips at a fairly steep angle, producing the steeply graded gravity data to the NW of the anomaly and the evenly decreasing values in all other directions outward from the anomaly. This orientation was suggested for a diatreme pipe in the first interpretation of the data and the proposed model. This second interpretation has shown that the diatreme pipe is unrealistic, but the inclined cylindrical feature aspect of the first interpretation still seems viable when applied to this possible volcanic plug. Perhaps a diatreme pipe anomaly was not detected because Ship Rock itself, located directly above the continuation of its own diatreme pipe, cancels out the detectable gravity anomaly.

Interpretation #3: Large-Scale Magma Chamber

My data show a local + 4 mGal anomaly and another local –1 mGal anomaly, deviating from a fairly steadily sloped gravity gradient with a roughly 16 mGal range. This suggests that gravity values indicate a broad and high plateau, with two main deviations. This could arguably be used as evidence in favor of a large magma chamber's presence; perhaps the entire plateau of values for the study area is a result of this magma chamber. To this argument, I would respond that the similarity of gravity gradients in our small-scale study and the larger scale New Mexico study, as recorded by Heywood et al. (1992), shows that the plateau of values is part of a larger, regionally-scaled trend in gravity, rather than reflective of a large Ship Rock magma chamber.

Summary of Inferred Subsurface Geometry

The subsurface geometry, as can be best inferred from the proposed model and from the critique of the proposed model of gravity data, is characterized by a shallowly-emplaced dense feature, likely a volcanic plug striking NW-SE and dipping downwards at a moderate angle; this is the interpretation of the gravity high. The low is interpreted as a small deviation from a steadily decreasing gravity gradient to the east of the high anomaly, a result of the terrain effect of Ship Rock's above-ground mass. This gravity survey did not detect significant gravity anomalies that could be interpreted as dikes around the Ship Rock area. This is to be expected; dikes are extremely narrow features (those at the surface do not exceed 2 m in width) that produce quite small gravity anomalies. Evidence to support a magma chamber buried at depth was not found in this study, for either a small or a large magma chamber.

DISCUSSION

I will review the questions outlined in the plan of this study, and discuss how and why the study was or was not able to provide answers to these questions.

The gravity survey was able to detect anomalies that likely show evidence for at least one buried dense body. This body is almost certainly not a deep magma chamber, a narrow dike, or a continuation of the diatreme pipe of Ship Rock. The survey sampling was too sparse to pick up on anomalies caused by extremely narrow dikes; other surveys of local-scale gravity anomalies that have been able to detect such subsurface features have had far more data points in a given area than did the Ship Rock survey, and have tended to cover a much larger area.

In the 2003 study by Hofmann et al., gravimetric modeling was done to detect the existence and geometry of a possible source of mantle upwelling or a magma chamber, as related to the occurrence of swarm earthquakes in Vogtland/NW-Bohemia region. Gravity data in the Hofmann study was gathered as 17000 data points, covering a total area 142.2 x 165.2 km^2 to construct a Bouguer gravity map. Hofmann's survey, then, is far larger than this survey of the Ship Rock area. The authors of the Bohemia study, however, put full confidence in the spacing of their data points to provide good resolution of local structures, and high resolution of deep structures (Hofmann et al., 2003). Our data surveying, on the other hand, did not record anomalies from features so small as minette dikes, likely because our survey was not of a dense enough resolution to focus on each; perhaps, with our density of spacing over a larger area, as in the Hofmann et al. study of 2003, resolution would have been sufficient to detect such small features and confidently describe their geometry.

In their 2003 study, Hofmann et al. also made use of a deep borehole within their study area, an excellent tool for confirming or denying theories of subsurface geological composition and geometry. However, in Ship Rock, such a data resource would be offensive, according to Navajo tradition, and illegal, according to United States law. Purely non-invasive geophysical methods have been employed for this Ship Rock study.

This study's gravity data were used to make modeled subsurface bodies roughly fitting the observed Bouguer anomalies, but the model is shown to be non-viable given the context of Ship Rock. Gravity data can be shown to support the presence of a shallowly emplaced volcanic plug, but gravity values do not provide a unique picture of subsurface geometry. Other gravity studies address the non-unique solution problem of subsurface gravity modeling. Everson and Roggenthen (1988) detected a buried chamber and modeled it experimentally as a cylinder, a cone, and as a combined cylinder-cone shape, all of which could be made to roughly fir their observed data. The study of a Galapagos volcanic system by Chadwick and Dietrich (1995) modeled three idealized shapes for a buried magma chamber/ diatreme of brecciated material as well: a sphere, oblate spheroid (flattened at the poles), and prolate spheroid (egg-shaped). The models they choose in their studies are the ones that most closely fit their gravity data, and, just as importantly, the predicted context of their features; the same must be said of my study. Given these previous studies' work to define the shape of diatreme pipes, some hypotheses on Ship Rock's diatreme pipe geometry can be said independent of gravity data.

Through modeling these shapes, Chadwick and Dietrich as well as Everson and Roggenthen suggest that in a dike-diatreme system, the most likely shape of such a pipe is something a vertical, cylindrical conduit. This is useful for examining Ship Rock, which has an elliptical cross-section as expressed at the surface. Based on this, the inclined diatreme pipe seems a viable possibility, even if this study's gravity data do not reveal the shape or extent of the diatreme pipe. Perhaps no anomaly reminiscent of a diatreme pipe was detected because the gravity effect of the buried diatreme pipe was cancelled out by the gravity effect of the above-ground diatreme pipe (Ship Rock itself) situated above it.

Given the data collected, even after all the corrections had been performed, an accurate model of the diatreme pipe cannot be realistically constructed from this survey of the Ship Rock area. As for the magma chamber, this study's data cannot classify the shape or depth of any magma chambers; no such body was detected. This absence, though, is an important result: a small magma chamber was postulated to be a possibility in this diatreme system, as opposed to a large magma chamber that would be expected to fuel a volcanic neck system. No magma chamber of any size was detected in this survey, meaning that the process of Ship Rock's formation was not fed by a magma chamber at all. This evidence firmly refutes any sort of volcanic neck model in application to Ship Rock, in addition to the fact that the brecciated material of Ship Rock further distinguishes it from a volcanic neck, which would be composed of rock formed of molten material (Everson and Roggenthen, 1988).

POTENTIAL PROBLEMS AND SOURCES OF ERROR

Possible problems could arise from the gravimeters' machine error. Sources of this error include wind blowing while readings were taken, which can throw off the leveling of the gravimeter. Extreme heat on the machine could have affected the internal spring's extension, although it is unlikely given that the spring resides inside a temperature-controlled box, which uses most of the machine's battery power for constant temperature maintenance. Imprecise instrument placement of the gravimeter, GPS roving unit, and total station could reduce the accuracy and consistency of readings, due to human error or to the shifting of the crumbling Mancos Shale. Error could also arise from inconsistency in how readings were taken by multiple people and on multiple machines.

Drift, machine and tidal, was assumed to be linear between base station readings, but this is not exact, and could be a source of error in the study. By completing approximately hourly loops back to base stations, we hope that our study accounted for this drift. However, if drift is not really linear, then even hourly loops may not adjust for it.

It is also possible that our site spacing (0.3 km) was too broad to pick up on all gravity anomalies. The area the study covered in its survey was large and the bodies which this study hopes to locate could be too small; the dikes expressed on the surface are at most ~ 2 m thick, and other features may also be small. It is possible that, in order to catch such gravity anomalies, the grid on a gravity survey would need to be tighter.

Our data reductions could be imprecise. For our horizontal positions, GPS differential correction using carrier phase data gives good, but not perfect, precision. Depending on satellite configuration in the sky at any given moment, an abundance of satellites could be contributing position data, and at another moment, it could be that no satellites' signals would be received. For this reason, we allowed for several minutes of GPS data collection at each gravity site, but even with this method, GPS position could have been slightly inaccurate.

FURTHER QUESTIONS AND FUTURE WORK

As discussed, many of the questions outlined in the plans for the study could not be answered by the data gathered. Future work could expand on our data set and more densely sample the area to further investigate the geologic story behind Ship Rock.

Producing a fully terrain-corrected Digital Elevation Map (DEM) with our data would be useful to future gravity surveys of the Ship Rock area. Many gravity surveys are published without any complete terrain correction, because computing them is timeconsuming and requires expensive software. Data is not entirely meaningful unless all of the appropriate corrections have been performed and performed correctly; some of this study's data is questionable or unexplainable, possibly because terrain corrections were not performed. If our data could be used to build a highly accurate terrain map of the area, then future geophysicists would have a much easier job of getting accurate gravity data for the area and further investigating questions of Ship Rock's formation.

Future work on this topic could expand our study by putting together our area gravity map with an area map of magnetic anomalies. Magnetic anomalies would be expected to parallel gravity anomalies, because both magnetic signature and gravity field are stronger for minette than for shale. Magnetic field is higher over these dikes because minette has a much higher percentage of iron, as well as other magnetic minerals, than is found in shale. Other students working on this same KECK project conducted a magnetic survey of the same area with the same questions for their studies: finding and understanding the geophysics of subsurface minette dikes. If more studies of the same area are done in gravimetry and magnetometry, these data could be compiled and layered over the accurate map for which this study's survey was completed.

Putting these studies together could strengthen hypotheses on the presence and locations of subsurface minette dikes, shedding more light onto how the Ship Rock diatreme formed and propagated. More work could be done in areas where we detected slight gravity anomalies, where finely-tuned microgravity surveys could reveal small but significant variations. One student on this KECK project, Carolyn Tewksbury of Smith College, executed microgravity and micromagnetic surveys over a small area of a dike which had experienced en echelon faulting. Her findings on detailed dike geometry at a small scale could perhaps be unified with this study's larger scale surveys, to model more precisely how subsurface dikes could be formed.

Gravity surveying has been done on a larger scale in New Mexico (Heywood, 1992) but never in order to investigate a specific and small-scale subsurface geological/ geophysical question. This study shows, however, that even on such a small scale, sampling for gravity data must be done more densely to show very small or narrow subsurface bodies (as in dikes) or to further constrain data for gravity models. Studies have been done to investigate the emplacement history of Ship Rock, but gravity surveying and subsurface imaging based off of that data are unprecedented methods for the Ship Rock area. More dense gravity surveying should be done in our study area and in the Four Corners region for regional, dense-sampling gravity comparison and composite data gathering.

The implications of this study need not end in Shiprock, New Mexico; our findings can, I hope, be applied to researching other diatreme systems and testing the dike-fed diatreme model at other volcanic centers.

A question separate from this field study, but of special interest to this author, is that of how geologic research on sacred Native American land can be conducted non-invasively, and without disrespecting the stories already in place to explain such geologic features. Science need not be separate from its setting, geographic or cultural. How can research be done without discrediting or devaluing other stories humans use to explain their world? Although not addressed in this paper, these questions should be addressed, through reflection on how scientific research is conducted in connection with American Indian nations in the United States and, more globally, scientific research in conjunction with indigenous cultures and peoples. All work done to make gravity surveys and subsurface imaging more effective methods, will also be progress made towards the success of non-invasive methods used for answering questions of geologic history. In the specific case of Ship Rock, efforts in this direction give hope for an increasingly positive relationship between the geoscientific investigation of an exhumed diatreme and Navajo ways of knowing about Tse Bit'a'i.

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