MAGNETIC EXPLORATION AND MODELING OF THE THUMB, NAVAJO VOLCANIC FIELD

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INTRODUCTION

The study of the formation of the diatremes and their associated dikes in the Navajo Volcanic Field (NVF) is important for understanding the evolution and ascent of magma. Many of the diatremes surrounding Ship Rock and Ship Rock itself are emplaced along dikes. Early geologists observed that the dikes merge with the diatremes at depth (Williams, 1936; McGetchin, 1968).

The origin of the diatremes and their associated dikes in the NVF remains unclear. Introductory textbooks describe diatremes as the remnants of eroded volcanoes with underlying magma chambers, implying that the radial dikes formed after the emplacement of the diatreme (Chernicoff & Whitney, 2007). However, the formation of this type of volcanic complex may not be that simple. Delaney & Pollard (1981) suggested that ascending magma is preferentially emplaced within dikes but will propagate through pipes because magma can flow faster and less heat will be lost. The pipes eventually become the diatremes. This hypothesis puts the formation of the dike before the diatreme. Dikes will not necessarily radiate from a central diatreme and a magma chamber at depth is not implied by this model. For this second model to work, every diatreme in the NVF should have at least one associated dike. The United States Geological Survey (USGS) has mapped the NVF using aeromagnetic methods as recently as 2001 (Kucks et al., 2001), and there is at least one diatreme that does not have an apparent dike – The Thumb (see Figure 2 from Ship Rock Project Director Report). In this research, ground magnetic techniques were used to investigate The Thumb to obtain a detailed picture of its subsurface structure and to study more thoroughly the mechanism of intrusion and test whether any plugs formed without dikes.

The data from this survey allow us to test: A) the hypotheses above, B) the dimensions and magnetic characteristics of the anomaly, and C) the effects of topography on magnetic data acquisition. The detailed picture of The Thumb igneous center was compiled from magnetometer and GPS data. The complexity of the subsurface structure of The Thumb is revealed in this magnetic data. Data filtering steps include reduction-to-the-pole, upward continuation and the analytic signal.

GEOLOGIC BACKGROUND

The Oligocene and Miocene-age intrusives that form the Navajo Volcanic Field are situated atop a greater physiographic province called the Four Corners Platform of the Colorado Plateau. The platform consists of a thick sequence of gently-folded sedimentary layers that is bounded to the east and west by Laramide-age monoclines. The intrusive features cluster along the monoclines, and are believed to postdate the monoclines. Though no faults are present at the surface, magma ascent was probably facilitated by generally NE-SW trending Laramide fractures at depth (Delaney & Pollard, 1981; Semken, 2003; Baldridge, 2004). The characteristic NVF magma is a greenish, ultramafic potassic lamprophyre known as minette (Semken, 2003). This minette is enriched in magnetically susceptible minerals including magnetite and iron, which provides an optimal setting to magnetically detect these rocks that outcrop in sedimentary strata.

PRINCIPLES OF MAGNETISM

Overview

Magnetic survey instruments have been successfully used in the past to study the minette intrusives of the NVF (Gruen et al., 2003). These instruments record the total magnetic field of the Earth. Blakely (1996), Kearey, Brooks & Hill (2002), Singh (2002) and Gruen et al (2003) outlined applications of magnetic surveys in studying subsurface geology and demonstrated that this method can accurately locate and measure the dimensions and magnetic characteristics of subsurface mafic volcanic features. Large-scale aeromagnetic surveys and topographic maps have been used to map the distribution of volcanic features across the NVF (Kucks et al., 2001) and in this study were compared to a small-scale ground magnetic study of The Thumb volcanic center to provide a detailed magnetic picture of a subsurface volcanic system.

Magnetic Properties of Rock and Magnetic Anomalies

A magnetic survey is a powerful tool that exploits the difference in magnetic susceptibility of upper crustal rock. Ultramafic rock such as minette has a high susceptibility (~0.012 cgs), whereas sedimentary rock such as sandstone has a low susceptibility (~0.00005 cgs). Magnetic survey instruments record the total magnetic field of the Earth, which includes the geomagnetic field and any other fields produced by nearby magnetic bodies, including buried magnetic bodies such as minette dikes. If a highly-susceptible ultramafic dike is buried within nearly non-susceptible sandstone, magnetometer surveys that cross the dike will record a magnetic anomaly, or change in the total field value, due to the susceptibility contrast between the minette and sandstone. In the applied geological context of the NVF, these anomalies might reveal buried dikes extending from a central diatreme.

METHODOLOGY

Overview

Two portable magnetometers (Gem Systems Overhauser Proton Precession Magnetometer GSM-19 v. 5.0), one base magnetometer (Geometrics G-856) and GeoXT handheld GPS were used to examine The Thumb diatreme system in detail. In reconnaissance magnetic surveys at The Thumb, a NE-SW trending linear anomaly was found running beneath The Thumb. Two grids were selected, one on the NE portion of the anomaly and one on the SW portion of the anomaly, for detailed magnetic gradient surveys of the subsurface anomaly.

Paleomagnetic Analysis

Two hand-sized samples were taken from The Thumb for paleomagnetic and susceptibility laboratory analysis at the University of Toronto-Mississauga with the key assumption that the samples have the same magnetic characteristics as the subsurface anomaly. Paleomagnetic and susceptibility analyses use alternating field demagnetization and Sapphire Instruments susceptibility meter techniques, respectively. Paleomagnetic analysis reveals the intensity, declination and inclination of remanent magnetization. Susceptibility analysis reveals the magnetic susceptibility of the rock. The intensity, declination, inclination and susceptibility are important values that help refine the profile models of the data.

RESULTS

The magnetic data reveal a strong linear anomaly trending NE-SW beneath The Thumb (Fig. 1). The presence of an anomaly and paleomagnetic analysis of the minette allows for MATLAB modeling (Singh, 2002) of dimensional and magnetic characteristics of the anomaly. Twenty MATLAB codes were created in this thesis for modeling the anomaly.

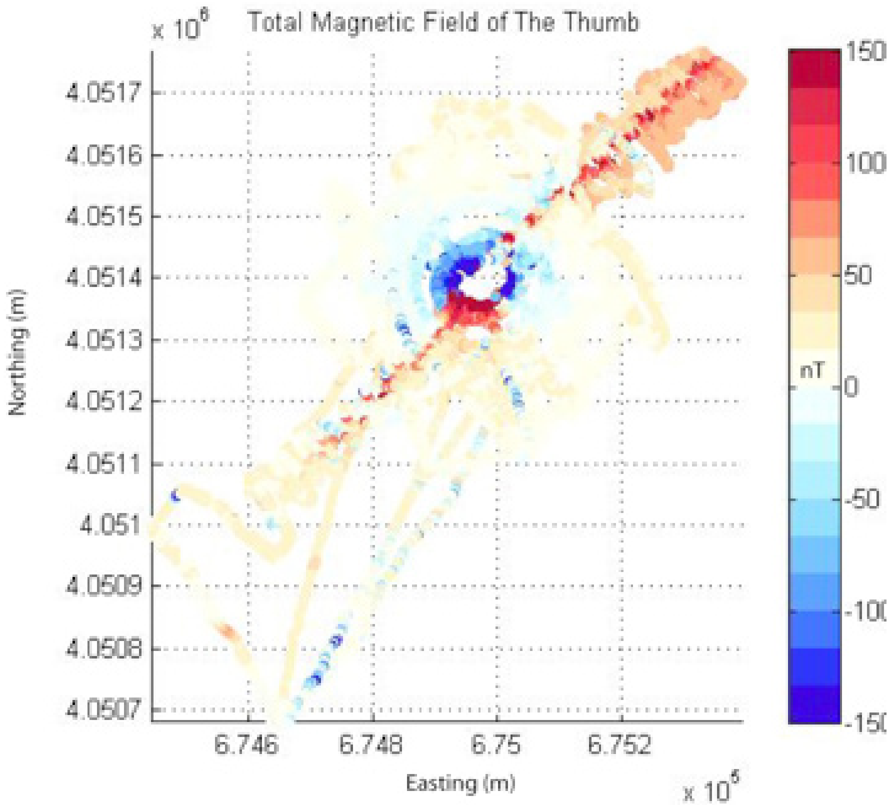

Fig. 1. Total field magnetic map of The Thumb compiled from ~18,000 magnetometer data and GPS position points in UTM 13 coordinates in Northwest New Mexico. Note presence of The Thumb near the center of the map and the NE-SW trending linear anomaly. No data points were taken atop The Thumb.

Filtering Steps

Geophysical data must be processed to prepare it for modeling and analysis. Filtering steps include reduction-to-the-pole, upward continuation and the analytic signal. Reduction-to-the-pole changes the geomagnetic inclination at the survey area to vertical, which shifts the anomaly to sit directly above the magnetic body (Fig. 2). Upward continuation changes survey height and, in turn, the anomaly magnitude, which allows for comparison of ground magnetic and aeromagnetic surveys (Kucks et al., 2001) that were taken at different heights (Fig. 3). The analytic signal visually enhances boundaries of buried magnetic bodies (Fig. 4).

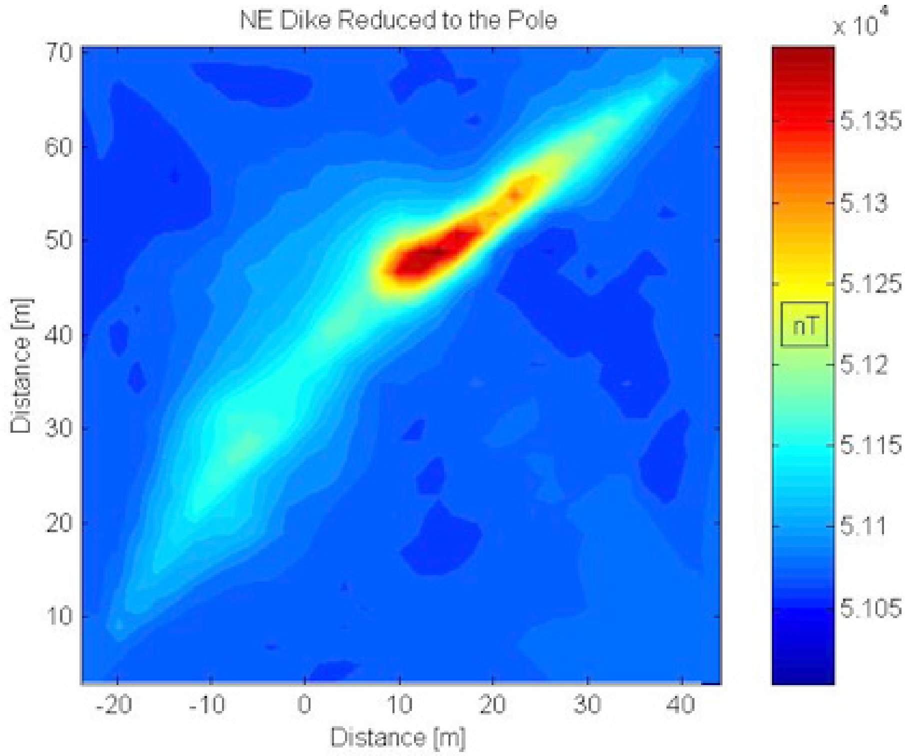

Fig. 2. Contoured total field values from the northeast grid rotated in the geomagnetic field and reduced to the pole. Note the irregular intensity of the dike anomaly and the skewness to the northwest. The broadness and heightened intensity in the northern portion of the grid may indicate dike shallowing and thickening. The skewness to the northwest may indicate a northwest dip of the dike. Dike disappears at both ends due to rotation of grid.

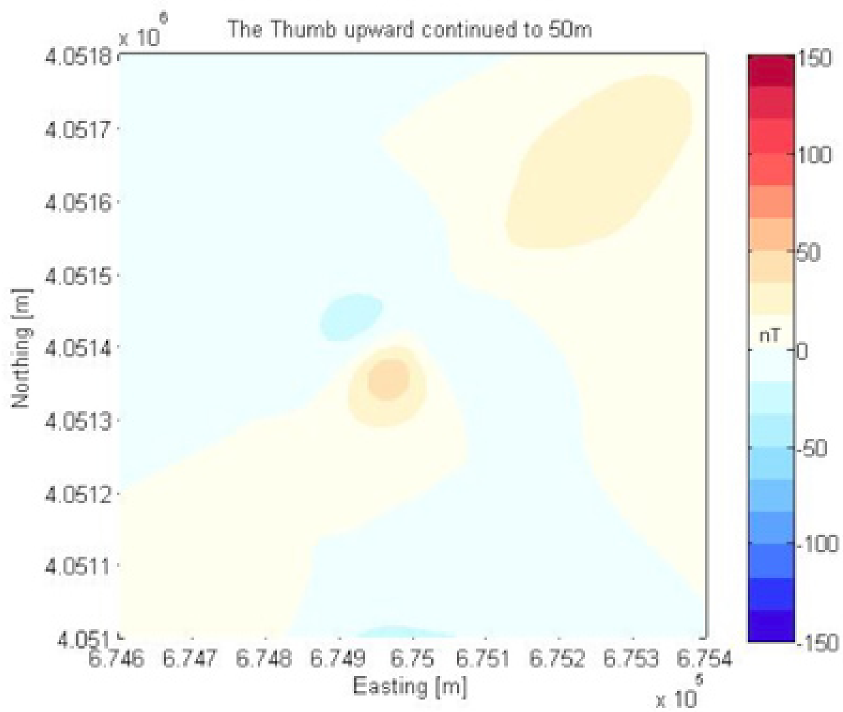

Fig. 3. Contoured total field magnetic map of The Thumb upward continued to 50m. At a height of 50m, the anomalies of The Thumb and dike are barely visible. Upward continuation to 305m – the survey height of the USGS New Mexico aeromagnetic map (Kucks et al., 2001) – reveals no anomaly for The Thumb, linear anomaly or magma chamber at depth. The Thumb anomaly is probably not visible at 305m because no data were collected atop The Thumb. The absence of anomalies at a survey height of 305m indicates the necessity for ground magnetic surveys to reveal small-scale magnetic features.

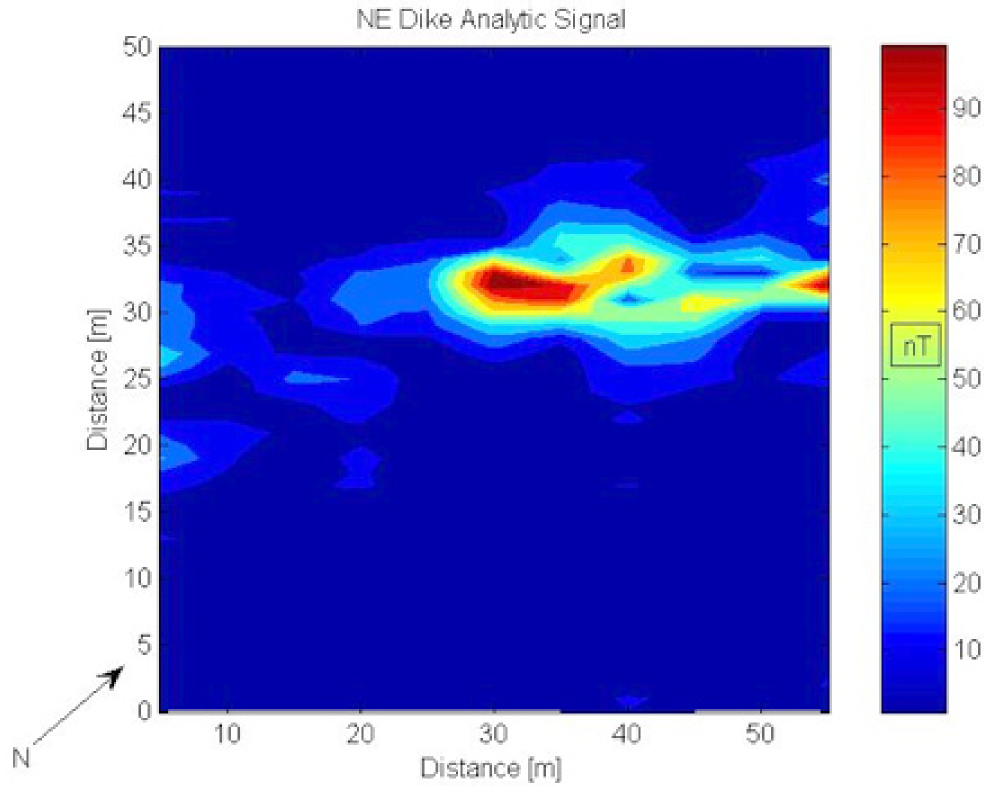

Fig. 4. Contoured analytic signal for total field values from the northeast grid (not rotated). Maxima diverge at ~x=35 m and converge at ~x=50m. This observation may represent thickening of the buried body. This observation may also represent en echelon segmentation of the buried body, which is consistent with the segmentation of the NE dike of Ship Rock (Delaney & Pollard, 1981).

Synthetic and Field Data Modeling

Synthetic data modeling is important to understand the anomalies that can be produced by intrusive features. MATLAB code was used to compare the effects of body width, depth to top and base of body, azimuth, susceptibility, remanent magnetization as well as inclination, declination and total field value of the geomagnetic field on an anomaly. Then, actual profile data from the NE and SW grids were modeled against the synthetic anomaly profile data to determine best fit models (Fig. 5). The grid profiles reveal characteristic dike-like anomalies.

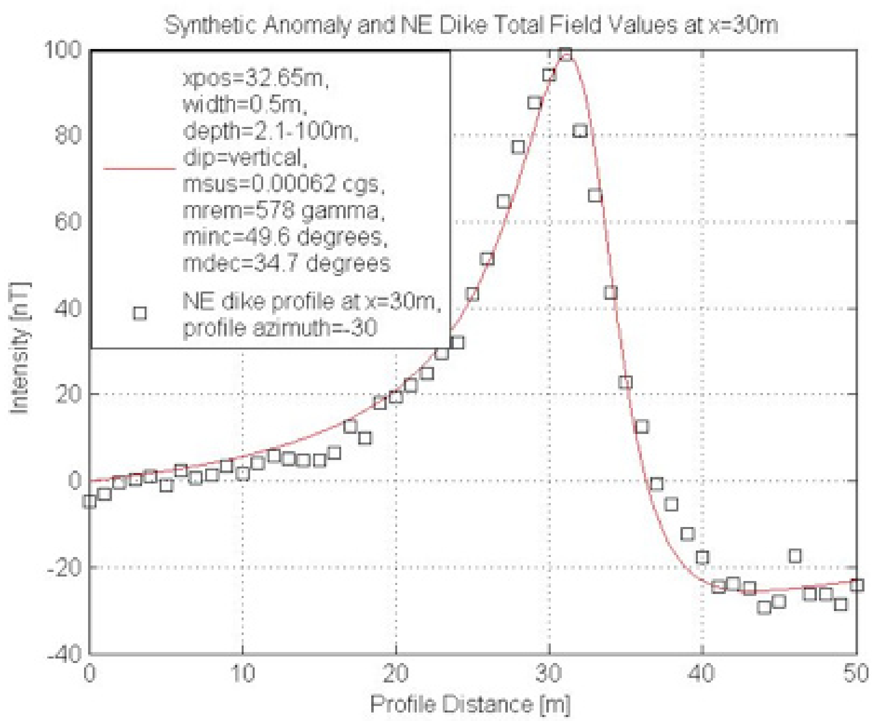

Fig. 5. Profile of transect x=30 m taken on the northeast grid (Fig. 4). The actual data (black squares) are plotted against a calculated profile (red line) with assigned values (see Legend). Geomagnetic northwest is to the right; anomaly is centered at 32.65 m; msus is average susceptibility of the minette samples; mrem is average remanent magnetization intensity; minc is average remanent inclination; mdec is average remanent declination. Fit of the anomaly is qualitatively acceptable, suggesting that the subsurface anomaly is a dike. The dike probably possesses magnetic and physical characteristics similar to the assigned values. Other profile models from the NE grid reveal that the dike is ~0.5 m wide, ~2.5 m deep and dips steeply to the northwest.

CONCLUSIONS

We interpret the NE-SW trending linear anomaly to be a dike beneath The Thumb. Now, every diatreme in the NVF is associated with a dike. The dike may display en echelon segmentation. Upward continued data shows no magma chamber at depth. Both results support the bud hypothesis of Delaney & Pollard (1981). The NE-SW dike is geometrically consistent with the regional reactivated Laramide faults of the Four Corners platform (Delaney & Pollard, 1981; Erslev, 2001; Behr et al., 2004). Ongoing analysis of the data aims to model the effect of topography on magnetic data acquisition.

ACKNOWLEDGEMENTS

Field work on the Navajo Nation was conducted under a permit from the Navajo Nation Minerals Department, and persons wishing to conduct geologic investigations on the Navajo Nation must first apply for, and receive, a permit from the Navajo Nation Minerals Department, P.O. Box 1910, Window Rock, Arizona 88515, telephone (928) 871-6587. Thank you to my advisors and Keck team – Charly Bank, Jeff Noblett, Megan Anderson, Steve Semken, Rob Varga, Glenn Kroeger, Henry Halls, Alan Lovette, Luis Melara, Denise Hardman, Carolyn Tewksbury, Brett Mayhew, Sarina Yospin and Andisheh Beiki.

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