

GEOPHYSICAL INVESTIGATIONS OF SHIP ROCK AND THUMB IGNEOUS CENTERS, NEW MEXICO

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INTRODUCTION

Imaging the subsurface structure of two important volcanic centers of the mid-Tertiary Navajo Volcanic Field, on the Colorado Plateau, serves several purposes. Besides having specific implications for the formation of these particular features, our project will aid in understanding similar structures across the Colorado Plateau. Various researchers [e.g., Rubin, 1991; Mériaux and Jaupart, 1998; Segall et al., 2001] imagine the emplacement of a dike as vertical movement through host rock, often along preexisting faults or cracks, driven by magma pressure, and modified by the change in stress regime with depth. Other models [e.g., Delaney and Pollard, 1981; Quarení et al., 2001] allow magma to flow in pipes in addition to, and possibly following, its emplacement in dikes. Our results will provide valuable data against which to test such competing models of magma emplacement, and – in a wider sense – aid in understanding diverse processes like hydraulic fracturing, tensile fracturing, and dike-generated seismicity [Baer, 1991].

GEOLOGICAL AND CULTURAL SETTING

The Navajo volcanic field on the Colorado Plateau comprises more than 80 volcanic and intrusive features (see Semken [2003] for a recent summary). Ship Rock, near the town of Shiprock, NM, is the most prominent of these. Composed of tuff breccia with subsidiary

minette plugs, it intruded the surrounding Cretaceous Mancos shale in middle Oligocene times. Differential erosion has left Ship Rock towering 550 m above the surrounding plains (Fig. 1).



Figure 1: View of the Ship Rock diatreme from the South-East (Photo: Brett Mayhew)

Seven dikes of mafic minette (a potassic mica lamprophyre containing phlogopite) extend from the diatreme. The largest of these is up to 30 m high, about 2 m wide, and can be followed for about 9 km to the South. The formation of the diatreme remains unclear. Introductory geology textbooks present it as the classic erosional remnant of a volcanic diatreme or pipe [e.g., Chernicoff and Whitney, 2007; pages 85-87] and the dikes as radiating from the diatreme; such a scenario implies that the dikes formed after the pipe and should be mostly

radial to it; the possibility of a magma chamber beneath the field area is implied by this model. However, structure – and thus formation – of the complex may not be that simple. Delaney and Pollard [1981] model the propagation of an ascending dike and find that while magma will preferentially emplace within dikes, its main flow happens through plugs or pipes because movement there can be more rapid and less heat is being lost. This scenario puts emplacement of the dikes before the channelling of magma through pipes. A field of ascending dikes would not necessarily radiate from a central plug; and a subterranean magma chamber is not implied by this model.

The Thumb is a smaller diatreme about 20 km SW of Ship Rock just across the state line from Red Valley, Arizona (Fig. 2). While most diatremes in the Navajo Volcanic Field are associated with at least one dike, the Thumb seems to lack one. If indeed no dike is present, this has major implications for the origin of diatremes in the Navajo Volcanic Field because hypotheses linking the diatreme to pre-existing dikes would have to be ruled out.

Ship Rock is called in Diné (Navajo) culture Tsé bit'a'i, or “Rock with Wings”. It is a sacred site and features prominently both in Navajo creation stories and in their observation of nature [Semken, 2003]. Thus its significance is not purely geologic, and investigations should be considerate of Diné culture and non-intrusive. The Navajo Nation Minerals Department granted us permission for potential field studies and limited sample collection (for rock magnetism determination and thin-section preparation).

Navajo knowledge teaches that geologic features are the result of interactions between the Sky and the Earth; similar to the distinction between exogenic and endogenic processes in Euro-American Science [Semken and Morgan, 1997]. Landforms are the result of dynamic change, whereby male-like forces drive change,

and female-like forces re-establish balance. In such a bilateral Earth systems model gravity occupies an interesting aspect in that it acts both as a changing and balancing force. Gravity as a tool for subsurface imaging is therefore a link to Navajo understanding of Nature.



Figure 2: Satellite image (from Google Earth) of Four-Corners region with study areas around Ship Rock and Thumb igneous centers highlighted as red boxes. Length of South dike visible in satellite image is 9km.

METHODOLOGY

Gravity and magnetometry measure deviations in naturally occurring potential fields caused by a contrast in density or magnetic susceptibility between a target and the material surrounding it. Such deviations can be used to image the subsurface. However, geophysical results are always an interpretation of that data and subject to ambiguity [e.g., Hinze, 1990]. Geophysics applied to any geological problem involves seven steps [Jones, 2005]: setup, properties, surveys, data, processing, interpretation,

synthesis. Existing data sets [Hildenbrand et al., 2002; Kucks et al., 2001] are interpolated from a sparse grid and thus not suitable for subsurface imaging of the volcanic centres. A preliminary survey [Gruen et al., 2003] established that the visible dikes had a strong property contrast, and that close station spacing would be necessary.

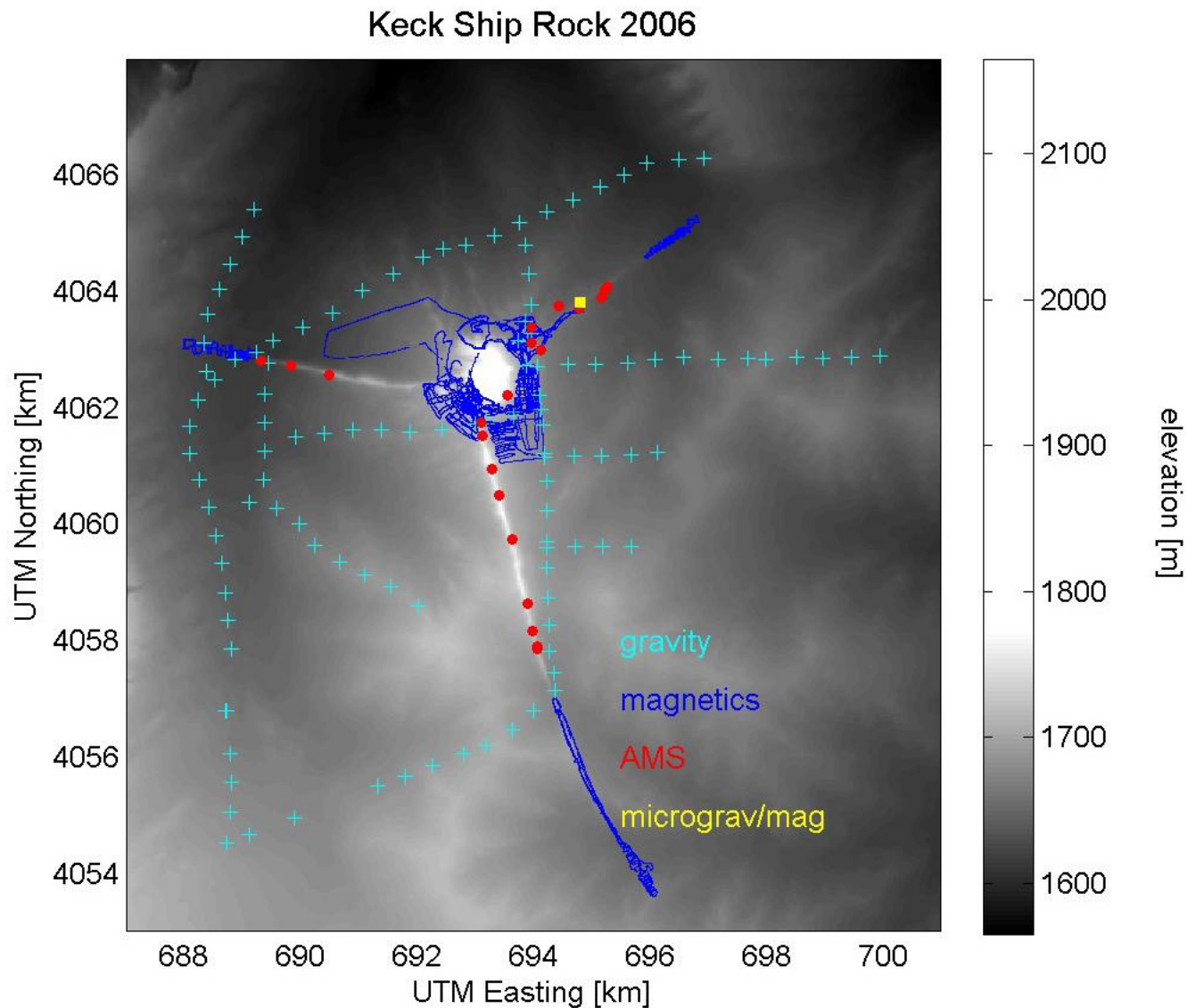
Anisotropic Magnetic Susceptibility (AMS), when corroborated by orthogonal thin-sections, has become a fast way to determine flow directions in igneous rocks. Knowing the flow directions along the dikes at Ship Rock provides essential information on the formation of the structure. In addition, susceptibility values as well as large remanent magnetizations are necessary to adequately process and interpret the magnetic field data.

OVERVIEW OF STUDENT PROJECTS

Our team collected a total of ~120 gravity data points, ~70,000 magnetic field values, and 24 rock samples (Fig. 3). Students have been focussing on the following individual projects:

Large-scale gravity study around Ship Rock
Sarina Yospin and Brett Mayhew have analyzed 121 gravity values along 10 lines with approximately 500 m station spacing. One of the key hypotheses they are testing is that there is no dense body below Ship Rock.

Figure 3: Data collection sites on DEM of Ship Rock.
Area corresponds approximately to red box in figure 2.



Magnetic map around Ship Rock and at edges of the exposed dikes

Andisheh Beiki has been working on approximately 60,000 data points along many kilometers of criss-crossing lines. Our team circumnavigated the diatreme (although data coverage is sparse in the NW) and investigated the ends of the exposed dikes in an attempt to determine whether or not the dikes are connected to the diatreme, whether the magnetic data show additional dikes not exposed, and how far the exposed dikes extend underground.

Microanalysis of feathered portion of NW dike Carolyn Tewksbury collected about 110 gravity data points and about 1,100 magnetic total field and gradient data points in an 80 m by 80 m area across a feathered portion of the NE dike. This microstudy may confirm or disprove existing models for the dike structure at this location, with implications for the dike's propagation.

Palaeomagnetism and anisotropic susceptibility along dikes

Denise Hardman collected 24 rock samples along the exposed dikes to analyze in the lab for AMS and remanent magnetization. Our request for drilling at inconspicuous locations along the dikes was not granted by the Navajo Nation, but we were allowed to collect float.

Magnetic survey at "The Thumb" intrusive centre

Jonathan Rotzien used 17,000 total magnetic field readings and 600 gradient readings around the Thumb diatreme to verify the existence of an associated underground dike, and to determine location and depth to the top of that dike.

Perception of force fields and Western science in Navajo culture

Cassandra Sandoval is a member of the Navajo Nation and has pursued an ethnogeologic component in our research. She interviewed elders to find out the Navajo perception of Earth's gravity and magnetic fields (and the associated phenomena) and to explain our

geophysical approach to the Navajo community.

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