USING MICROGRAVITY AND MICROMAGNETIC SURVEYS TO DETERMINE SUBSURFACE STRUCTURE OF EN ECHELON DIKE SEGEMENTS IN THE NORTHEAST DIKE OF SHIP ROCK, NEW MEXICO

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BACKGROUND

Radial dikes extend from the diatreme at Ship Rock, NM. The intrusion of the diatreme created radial fractures that allowed for dike emplacement following the formation of the diatreme. The dikes at Ship Rock are particularly interesting because most of them show evidence of en echelon dike structures that do not appear to be related to post emplacement deformation. This study focuses on the usefulness of microgravity and micromagnetic surveys to constrain the subsurface features under the en echelon dike structures and to help constrain the mechanism for generating en echelon dike structures in the absence of deformation.

PREVIOUS RESEARCH

In 1981, Delaney and Pollard conducted an in-depth study of the northeastern dike at Ship Rock. They created an extensive map that shows that the northeastern dike is composed of 35 en echelon segments with varying degrees of overlap. Delaney and Pollard modeled the propagation of en echelon dike segments in an attempt to determine the mechanics of dike emplacement of the northeast dike at Ship Rock. They found that the most accurate models were produced when the dike was modeled as 10 en echelon segments, rather than 35. Delaney and Pollard argued that, where segments were separated by less than 10 meters, the two segments were likely joined just below the surface and, therefore, behaved as a single segment during propagation.

Delaney and Pollard also concluded that the en echelon pattern of the dike was formed due to rotation of the principal horizontal stress direction as the dike propagated vertically. In anisotropic materials, these en echelon fractures can be related to changes in material properties. For example, a change in orientation of weak crystal boundaries can cause breakdown of a single fracture, which leads to the formation of en echelon fractures. In isotropic materials, a relatively sudden reorientation in stress field direction can cause breakdown of a single fracture, forming en echelon fractures. Delaney and Pollard argued that, as the dike propagated vertically, the principal horizontal stress direction rotated, causing breakdown of the single dike and forming en echelon dikes at the surface. They propose that a single dike should be located at depth below the northeastern dike, with the en echelon dikes rising and rotating from that single dike at depth (Fig. 1).

PURPOSE

The focus of this study is to constrain the subsurface structure beneath two en echelon dike segments of the northeast dike and thereby to determine the emplacement mechanism of the northeast dike. The research is broken down into two different sections: 1) to determine the effect of small changes in the subsurface (e.g. connection depth between two dike segments) on microgravity and micromagnetic readings at the surface, and 2) to apply this knowledge to microgravity and micromagnetic field data taken over a pair of en echelon dike segments to attempt to determine the subsurface structure under the dike segments and, therefore, determine the emplacement mechanism.

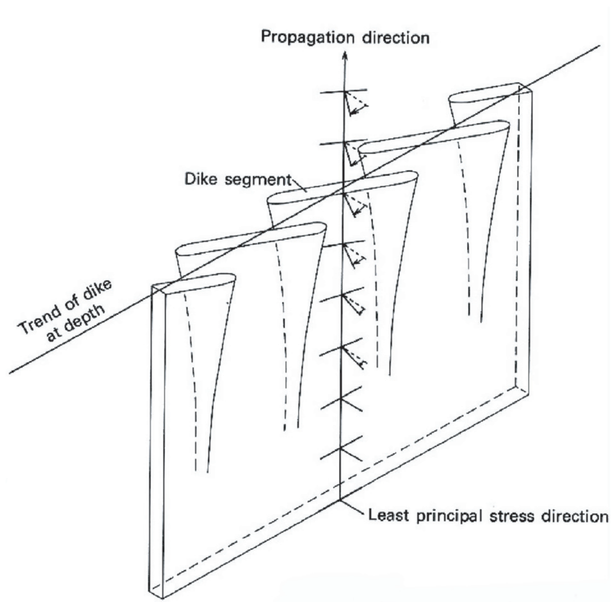

Figure 1. Diagram of the proposed subsurface structure of the northeast dike at Ship Rock, NM (Delaney and Pollard, 1981).

METHODS

Several areas along the northeast dike were examined in order to select the location for this study. The goal of this search was to select an area that represented the typical style of en echelon dike segments and that exhibited a simple structure. It was decided to determine if microgravity and micromagnetic surveys can be used to develop models of the subsurface under a simple structure before studying a more complex en echelon structure. The study site that was selected has two en echelon dike structures that overlap with approximately the same overlap as the other en echelon segments of the dike (Fig. 2).

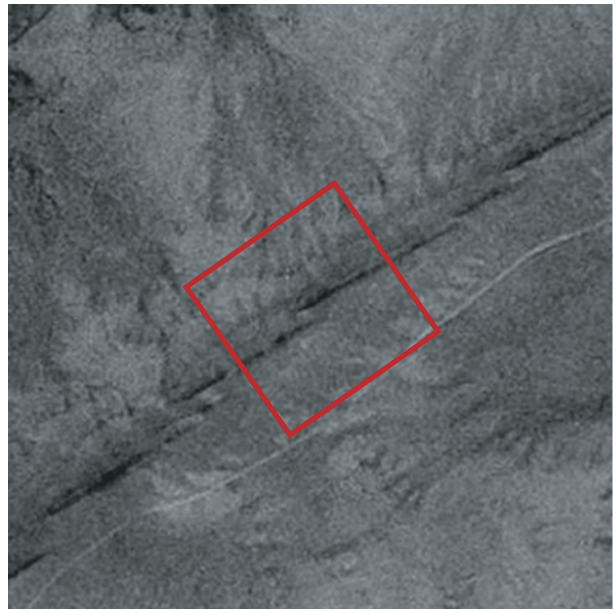

Figure 2. Orthophoto of the northeast dike at Ship Rock, NM. Red square indicates the study area.

GRAVITY

Once the location was selected, gravity lines were distributed over key areas on the dike. The final grid is approximately 70 m by 50 m, with gravity lines running across the tips of each dike segment, across the overlap of the two segments, and over each dike segment by itself. The gravity readings are spaced at approximately two meters, but are spaced closer to each other over the dike itself. The corners of the grid were located using a GPS configured for the UTM coordinate system and with a NAD 83 datum. All gravity stations were located within the grid using a total station by determining the horizontal angle, vertical angle, and distance to a given point. By measuring the total station angles to the corners of the grid, the UTM coordinates of all of the gravity stations within the grid were determined.

The gravity at each station was measured using a Lacoste and Romberg Model G gravimeter from Colorado College, which provides readings to a tenth of a microgal. Some gravity readings were taken at key points that do not lie along the gravity lines. For example, two extra stations were measured along the two dike segments: one along the main part of each dike segment, and one in line with, but just beyond, the end of each dike segment. Preliminary computer modeling suggests that a deeply buried main dike will produce a long wavelength anomaly, whereas the shallower dike segments will produce highly localized anomalies. The gravity stations beyond the gravity lines help determine whether or not a long wavelength anomaly is present. Finally, a base station was established and used to correct for tidal variations in the gravity field.

Once gathered, the gravity data were entered into Matlab. The data were corrected for tidal variations by examining the base station and correcting the measurements so that the base station gravity reading remained constant over time.

In most studies, gravity is tied to an absolute gravity station, so the relative gravity at data points can be used to determine absolute gravity at those locations. In this study, gravity was not tied to an absolute gravity station because of time considerations. Therefore, theoretical gravity was calculated for the base station by calculating absolute gravity based on geographic position and elevation. This number was added to the entire data set, which preserved the relative changes in gravity, but raised the overall magnitude to a number that conventional gravity reduction programs could use.

The gravity data was corrected for latitude using the equation published in Burger, Sheehan and Jones (2006). The data was then corrected for elevation (Free Air correction) and, finally, the Bouguer correction was applied to the data. Figure 3a shows the simple Bouguer gravity.

MAGNETICS

The micromagnetic survey was conducted in a similar fashion. The survey was conducted over a 70 m by 70 m grid, which extends twenty meters east from the eastern edge of the gravity grid. Magnetic readings were taken along lines running NW-SE that were spaced 5 m apart. Readings were taken every one meter along the lines using two proton precession magnetometers from Colorado College and Smith College. In addition, a magnetics base station was set up away from the dike and was used to correct for diurnal variations in the Earth's magnetic field.

The magnetic data were entered into Matlab, and corrected for the diurnal variations in the Earth's magnetic field using the base station data. Two points were removed from the data at the end of one line because the values of these points were well outside the range of the other data points in the set.

The magnetic data was not located using GPS, but one magnetic data line was run along the gravity line, containing the gravity base station. Since the magnetic data were taken on an evenly spaced grid, the points were plotted on a grid relative to the first station. The data set was then rotated using a rotational matrix until the magnetic line overlapped the gravitational line. Figure 3b shows the magnetic data gathered over the en echelon dike segments of the northeast dike.

MODELING

The geologic nature of the study area means that the data must be modeled using a 3-dimensional program. 2-dimensional modeling assumes that the 2-D model extends to infinity along a line perpendicular to the transect that is being modeled. Therefore, if a transect that crosses both dike segments is considered, the model would assume that both dike segments extend to infinity in either direction. Since each dike segment is clearly finite, and this study specifically considers the relationship between the end of the dikes and the magnetic and gravitational fields produced by the dikes, the dikes cannot be approximated as extending to infinity. For this reason, 3-dimensional modeling must be used to accurately investigate the subsurface features around the northeast dike.

depth. The fourth model (Fig. 4d) is based on the model developed by Delaney and Pollard. This model has an average depth connection between the dikes, but also shows that the dike segments are rotated with respect to the main dike at depth. This model will help determine the effect the orientation of the main dike has on the observed data.

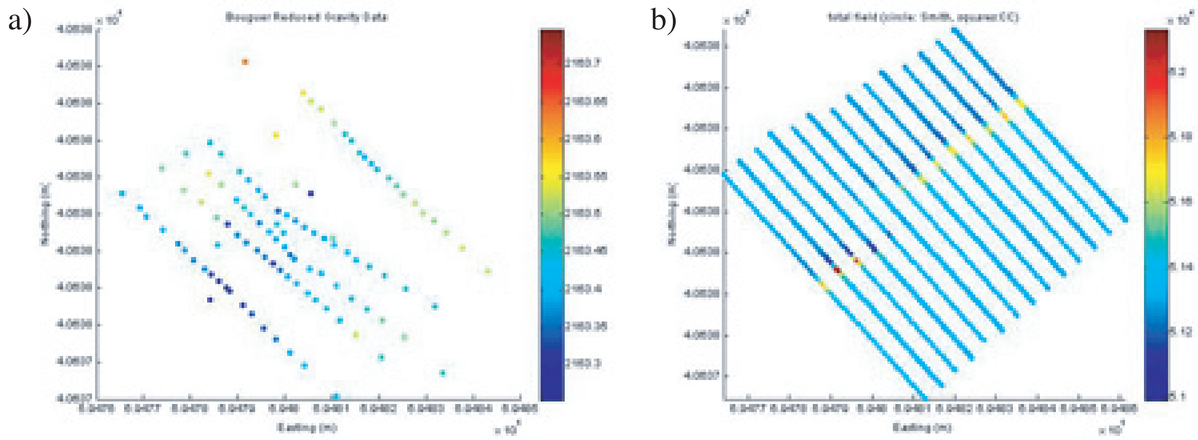

Figure 3. a) Graph of the Bouguer-reduced gravity data.b) Graph of the magnetic data. Both data sets show strong trends along the en echelon dike segments.

To conduct the modeling, four models have been developed that are geologically viable. One model is used as an end member (Fig. 4a). This model shows two parallel dike segments separated by the distance observed in the field and not connected in the subsurface. While it is unlikely that the dike segments are not connected at some depth, this model can be used to determine whether a connection between the dike segments at depth will make enough difference in the observed data at the surface for our instruments to detect a change. The second model (Fig. 4b) shows two parallel dike segments that are connected in the subsurface, while the third model shows two parallel dike segments that are connected in the very shallow subsurface (Fig. 4c). Delaney and Pollard (1981) determined that the two dike segments used in this study were not connected in the shallow subsurface, but by modeling two end members – one with a deep connection and one with a very shallow connection – this study attempts to determine how the observed data varies with changes in the connection at depth.

The modeling will be conducted using the Grav3D and Mag3D programs produced by the University of British Columbia Geophysical Inversion Facility. These programs will plot both the magnetic/gravity data and a model and mesh. The model-mesh program can forward model for both magnetic and gravity data and produce predicted data, which will be brought into Excel and then brought into ArcGIS. Once in ArcGis, the data will be converted to a raster and subtracted from the actual data. By comparing the predicted data with the actual data in this way, it should be possible to determine the model that produces the closest results to the observed data over the NE dike.

CONCLUSIONS

By using these four models, we hope to determine how much the subsurface structure affects the data gathered at the surface. Three of the models should determine whether variable depth in connection between the two dikes produces measurably different data at the surface, and the fourth model should determine whether the orientation of the dike segments relative to the main dike at depth will produce different surface data than if the dike segments were oriented parallel to the main dike.

Once we have determined what changes in the subsurface can actually be measured by a microgravity and micromagnetic survey, we can look at the data collected for the northeast dike to constrain its subsurface structure as much as possible.

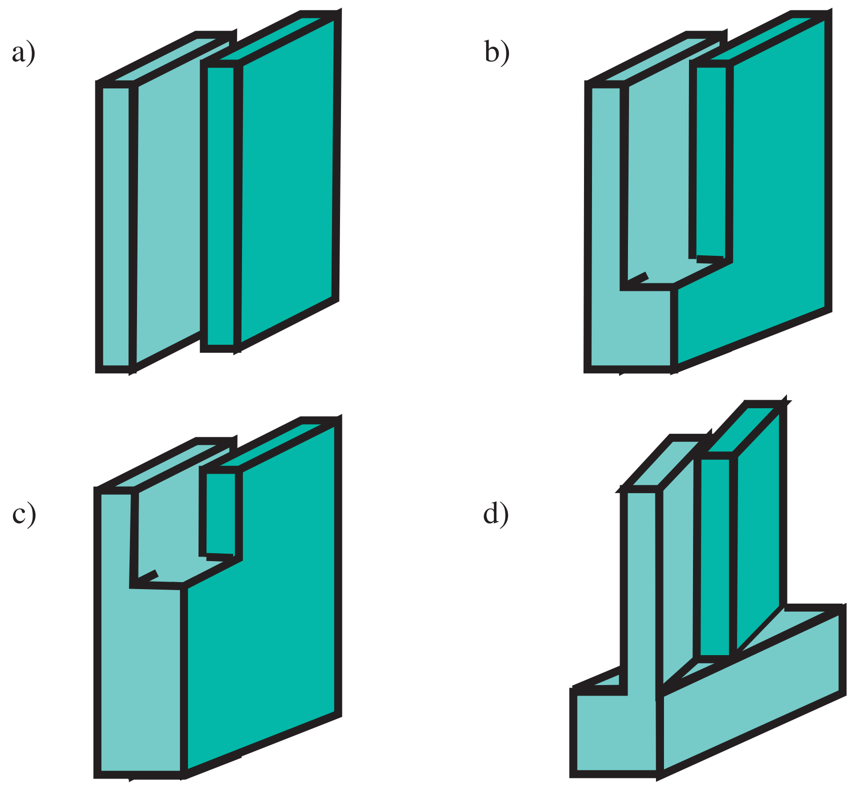

Figure 4. a) The dike segments are not connected. b) The dike segments are connected in the deep subsurface, c) The dike segments are connected in the shallow subsurface, d) The dike segments are rotated with respect to the main dike.

REFERENCES

Delaney, P. T. and Pollard, D. D., 1981, Deformation of host rocks and flow of magma during growth of minette dikes and breccia-bearing intrusions near Ship Rock, New Mexico: Geological Survey Professional Paper, v. 1202

ACKNOWLEDGMENTS

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.