Magnetic Surveys Help Reassess Volcanic Hazards at Yucca Mountain, Nevada

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Natural disasters like volcanic eruptions occur infrequently, but if they occur near nuclear power plants or high-level radioactive waste repositories, local and global communities can be threatened. Ideally, such facilities should be constructed only where geologic risk is very low. Estimating the probabilities of such events requires a comprehensive understanding of site geology and the geologic processes operating in the site region on timescales of $10^4$ to $10^7$ years. In light of these requirements, geologists and geophysicists must continually improve techniques for site characterization.

Volcanic hazards at Yucca Mountain, the proposed site of the first U.S. high-level radioactive waste repository, were recently reassessed with new data from three ground magnetic surveys. These surveys provide one example of how state-of-the-art geophysical instrumentation will improve site characterization and hazard assessment. The surveys combined magnetometer measurements with differential GPS results to return real-time, geographically referenced magnetic data to the survey team. Real-time feedback allows for flexibility in survey design as the survey progresses.

At Yucca Mountain, this instrumentation helped characterize past episodes of volcanism and the relationships between volcanoes and tectonism in the region. Recognizing these relationships is crucial to evaluating the probable distribution of future volcanic eruptions in the Yucca Mountain region and the link between crustal structures and the distribution of volcanoes.

The Risk
If the Yucca Mountain site meets several criteria that ensure the protection of public health and safety, plans call for the disposal of 70,000 metric tons of waste at the facility. First, the probability of volcanic disruption of the repository must be shown to be low. Given the duration of waste radioactivity and toxicity (on the order of $10^4$-$10^5$ years) and the dispersive nature of volcanic eruptions, most recent criteria [Code of Federal Regulations, 1994] require that the consequences of volcanic eruptions be considered if the probability of eruptions is greater than $10^8$ yr$^{-1}$.

Volcanic eruptions are a potential hazard at the proposed site of the repository because Yucca Mountain is located within an active basaltic volcanic field. Small-volume basaltic eruptions have occurred in the Yucca Mountain region during the last 8 million years at a low rate, on the order of 3 to 7 eruptions per million years. During the last one million years, most of these eruptions occurred 10–25 km from Yucca Mountain. The most recent eruptions formed Lathrop Wells volcano approximately 100,000 years ago [Turrin et al., 1991], 20 km from the site of the repository.
Contour interval is 10 nT. These data and those shown on the following maps (Figures 3 and 4) are drift-corrected, and the International Geomagnetic Reference Field (IGRF) is removed. Original color image appears at the back of this volume.

Fig. 2. Ground magnetic map of Amargosa Anomaly A showing three aligned anomalies. The high-resolution magnetic survey elucidates structure in the magnetic anomalies, such as their reversed magnetization with steep inclinations and the elongate character of individual anomalies. Such detail in the magnetic map supports the interpretation that these anomalies are produced by a buried alignment of three volcanoes. Contour interval is 10 nT. These data and those shown on the following maps (Figures 3 and 4) are drift-corrected, and the International Geomagnetic Reference Field (IGRF) is removed. Original color image appears at the back of this volume.

The Magnetic Surveys

Magnetic readings were obtained using a cesium-vapor magnetometer interfaced to a global positioning system (GPS). High remanent magnetizations of basalt (10–20 A m⁻³) preclude the use of proton-precession magnetometers in some parts of the survey areas. Real-time differential corrections were made on position data and sent, via RS232 cable, as a string in National Marine Electronics Association (NMEA) protocol to the magnetometer, where the data were stored with magnetic measurements. Ground resolution of this particular differential GPS is better than 5 m and is typically 1–2 m.

The data were downloaded into a geographic information system (GIS) for post-processing. The base station for these surveys included a proton-precession magnetometer, which continuously recorded diurnal variations in the magnetic field, and the GPS base station, consisting of a GPS receiver and telemetry. Although the error associated with the cesium-vapor magnetometer is on the order of 0.1 nT, total error in the survey is typically 1 nT due to errors in position, and it reaches 10 nT in areas of high magnetic gradients associated with basalt cover.

This instrumentation allows investigators to traverse the area, quickly locating anomalies while continuously recording magnetic field and position data. Because the instrumentation provides real-time feedback, the survey team can make rapid and informed decisions to increase survey density where anomaly wavelengths are short enough to warrant it, and leave less interesting areas more sparsely sampled. The three surveys each consist of more than 25,000 magnetic measurements distributed along approximately 60 km of traverse lines. Line spacing varied between 25 and 500 m, depending on wavelength and complexity of observed anomalies. Our surveys were completed in about two weeks and represent the first detailed ground magnetic maps made of the region for site characterization, which has previously relied on aeromagnetic surveys.

Amargosa 'Anomaly A'

Five anomalies were identified in Amargosa Valley by Langenheim et al. (1993) as potentially buried volcanoes or related igneous features. The five anomalies have been incorporated as volcanic events in some probabilistic volcanic hazard analyses for potential future volcanic eruptions at Yucca Mountain [e.g., Connor and Hill, 1995], but not in others [e.g., Geomatrix, 1996], possibly because of their uncertain origin. Of these anomalies, Amargosa Anomaly A (Figure 1) is the most complex and difficult to interpret from aeromagnetic maps. Yet, anomaly A is of great interest because of its proximity to the Lathrop Wells cinder cone and because it is the closest of the Amargosa Valley anomalies to the proposed repository site (Figure 1). With these factors in mind, we completed a ground magnetic survey of anomaly A to constrain its origin and to better resolve its distribution in the subsurface.

The ground magnetic map of data collected over Amargosa Anomaly A delineates three separate anomalies associated with shallowly buried, reversely magnetized rock (Figure 2). These anomalies are distributed over 4.5 km on a northeast trend, and each has an amplitude of 70–150 nT. Although these features can be partially resolved with aeromagnetic data [Langenheim et al., 1993], trench detail emerges from the ground magnetic survey that are important to volcanic hazard analyses and tectonic studies of the region. Such details include the character of the southernmost anomaly, which has a smaller amplitude than those to the north but is nonetheless distinctive, and the northeast-trending structure within the negative portion of the central anomaly, which mimics the overall trend of the alignment. The ground magnetic data also enhance the small positive anomalies north of each of the three larger amplitude negative anomalies, reinforcing the interpretation that anomaly A is produced by coherent basalt edifices with strongly reversed remanent magnetizations.
silicic volcanism ended during the mid-Miocene. Southern Crater Flat volcanism that has persisted through time in the Yucca Mountain region and supports theocene. Deposition of young alluvial sediments has repeatedly occurred since large-volume basaltic volcanism.

The identification of the northeast trend of the anomaly A is a key result of this survey. The trend is similar to the orientation of an alignment of five Quaternary cinder cones in Crater Flat (Figure 1) and to the Sleeping Butte cinder cones, a Quaternary vent alignment 40 km to the northeast. Although the age of the Amargosa Valley alignment is not known, it suggests that development of northeast-trending cone alignments is a pattern of volcanism that has persisted through time in the Yucca Mountain region and supports the idea that future volcanism may exhibit a similar pattern [Smith et al., 1990].

Southern Crater Flat

Southern Crater Flat is a structural half-graben where small-volume basaltic volcanism has repeatedly occurred since large-volume silicic volcanism ended during the mid-Miocene. Deposition of young alluvial sediments has partially or completely buried volcanoes in the southern part of the basin, obscuring the volcanic history of southern Crater Flat. Northern Cone consists of approximately 0.4 km$^2$ of highly magnetized (10–20 A m$^{-1}$) lava flows, near-vent agglutinate, and scoria aprons resting on a thin alluvial fan. Large-amplitude, short-wavelength anomalies were observed over the cone. No evidence of northeast-trending structures were discovered that could directly relate Northern Cone to the rest of the Quaternary Crater Flat cinder cone alignment. Instead, prominent linear anomalies surrounding Northern Cone trend nearly north-south and have amplitudes of up to 400 nT (Figure 4). These anomalies likely result from offsets in underlying tuff across faults extending beneath the alluvium.

The relationship between faults and the Northern Cone is clear when the ground magnetic map is compared with topographic and fault maps [Frizzell and Schulters, 1990; Langenheim, 1995]. The anomaly is beautifully symmetric, with maximum positive and negative peaks separated by 750 m and a peak-to-peak amplitude of 1100 nT. The smaller, negative portion of the anomaly is truncated by anomalies associated with the Little Cones lava flows. This anomaly suggests that this buried volcano is comparable in volume to the Little Cones and implies more persistent magmatism in southern Crater Flat than previously realized from geologic mapping.

A third prominent magnetic feature was discovered near outcrops of Miocene basalt. This feature is a linear magnetic anomaly extending from the southern end of the survey area to the north-northwest for approximately 4.5 km (Figure 3). The anomaly is probably caused by a shallow dike associated with the Miocene basalts. Our survey method allowed us to identify the feature in the field and immediately modify our survey to better define the shorter wavelengths and smaller amplitudes observed in this area. Thus the magnetic map reveals a sequence of volcanic activity in southern Crater Flat accompanying basin subsidence. Probability models for volcanic hazards in the area need to account for this pattern of clustering.

Northern Cone

Northern Cone, located in Crater Flat approximately 8 km from the repository site, is the closest Quaternary volcano to Yucca Mountain. Its proximity to the site of the proposed repository makes the structural setting of Northern Cone of particular interest to volcanic hazard assessment. We surveyed primarily along east-west trending lines 100 m apart over rugged alluvial topography.

The extent of Quaternary lava flows from the Little Cones is shown on the ground magnetic map by the distribution of short-wavelength, large-amplitude anomalies (Figure 3). Lava flows from the Little Cones only crop out up to 400 m south of the cones. Ground magnetic surveys indicate the Little Cones lavas are about 1 order of magnitude more voluminous than indicated by outcrops, extending approximately 1.5 km south of the Little Cones. The flows are buried 15–30 m beneath a nearly featureless alluvial plain. So, rather than being incongruously small volcanic features compared to nearby cones, the Little Cones and their lava flows exemplify the final stages of inundation and burial of two young cinder cones in an actively subsiding basin [Stamatakos et al., 1997].

The magnetic map shows the position of an older, completely buried volcano 2 km south of the Little Cones (Figure 3). This large-amplitude positive anomaly was first observed on aeromagnetic maps [Kane and Bracken, 1983; Langenheim, 1995]. The anomaly is beautifully symmetric, with maximum positive and negative peaks separated by 750 m and a peak-to-peak amplitude of 1100 nT. The smaller, negative portion of the anomaly is truncated by anomalies associated with the Little Cones lava flows. This anomaly suggests that this buried volcano is comparable in volume to the Little Cones and implies more persistent magmatism in southern Crater Flat than previously realized from geologic mapping.

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Faulds et al., 1994]. The north-trending anomalies at Northern Cone roughly coincide with mapped faults just north of the survey area that have topographic expression resulting from large vertical displacements. These mapped faults and faults inferred from the magnetic map are all oriented north to north-northeast, trends favorable for dilation and dike injection in the current stress state of the crust. Thus the Northern Cone magnetic survey further supports the idea that volcanism on the eastern margin of Crater Flat was localized along faults.

Cumulatively, these three magnetic surveys provide unequivocal evidence of the spatially clustered nature of volcanism, the prevalence of northeast-trending vent alignments, and the association of volcanoes and faults near Yucca Mountain. Useful probability models for volcanic hazards to the proposed repository must account for these geologic relationships.

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Fig. 1. Location of ground magnetic surveys near Yucca Mountain. Plio-Quaternary volcanoes are shown in yellow (locations of aeromagnetic anomalies are shown as solid green circles). The proposed repository is marked. Faults [Frizzell and Schulters, 1990] are indicated by red lines and roads by black lines. Coordinates on this and following maps are Universal Transverse Mercator (Clarke 1866 projection).

Fig. 2. Ground magnetic map of Amargosa Anomaly A showing three aligned anomalies. The high-resolution magnetic survey elucidates structure in the magnetic anomalies, such as their reversed magnetization with steep inclinations and the elongate character of individual anomalies. Such detail in the magnetic map supports the interpretation that these anomalies are produced by a buried alignment of three volcanoes. Contour interval is 10 nT. These data and those shown on the following maps (Figures 3 and 4) are drift-corrected and the International Geomagnetic Reference Field (IGRF) is removed.
Fig. 3. Ground magnetic map of southern Crater Flat. High-amplitude, short-wavelength, predominantly negative anomalies are produced by the reversely magnetized Little Cones lava flows. A long-wavelength positive anomaly is produced by a normally magnetized body about 0.52 km in area, 20–40 m thick, and buried at 150–200 m. The small north-northwest-trending magnetic anomaly in the southernmost part of the survey area is related to Miocene basalt outcrops just south of the map. This survey was completed in 5 days and consists of about 33,000 measurements. Contour interval is 100 nT.
Fig. 4. Processing the ground magnetic data within a GIS facilitates comparison of anomalies with other mapped features, such as faults and topography. Here the ground magnetic map of Northern Cone is superimposed on digitized topographic contours. Mapped faults of Fitzell and Schulters [1990] are shown in red (also see Figure 1), and dirt roads are shown as black lines. Northern Cone is located in the central portion of the map, as indicated by high-amplitude, short-wavelength anomalies. The color scale is truncated where magnetic gradients are very high (such as on the cone). Contour interval of topography is 20 ft and changes to 40 ft across a map boundary in the northern part of the figure.