demonstrate that the bobsled-style course taken by the Ritter slide needed a velocity of about 40 meters per second, in order to form the trim line and to produce the mapped extent of the deposit. Before the cruise, in 2003, the main features of the Ritter tsunami observations were reproduced using a landslide model that also traveled underwater at a speed of approximately 40 meters per second (http://es.ucsc.edu/~ward/ritter_tsu_close_small.mov).

Now it appears that these models are simultaneously consistent with data from both the landslide deposit and the tsunami that the landslide created. Such agreements provide greater confidence in using similar approaches to predict what might happen when the flank of any other volcano heads for the ocean floor.

Understanding the potential risk of tsunamis from volcano collapse is important to an island nation such as Papua New Guinea, which suffered several thousand deaths in 1998 from a nonvolcanic landslide source [*Synolakis et al.*, 2002], an event that was smaller in magnitude and covered a much smaller area than the Ritter collapse of 1888.

The government and universities of Papua New Guinea have shown strong and continuing interest in this research, as seen by the avid participation of the Geological Survey of Papua New Guinea, the Rabaul Volcanic Observatory, the University of Papua New Guinea, and the Papua New Guinea University of Technology.

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Uncovering Buried Volcanoes at Yucca Mountain

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The hazard posed by small-volume basaltic volcanism to the proposed Yucca Mountain nuclear waste repository in Nevada has been a topic of scientific debate for well over a decade. In the past few years, debate has focused on the extent and age of buried volcanoes in alluvial-filled basins of the Yucca Mountain region (YMR) and their potential impact on volcanic hazard estimates.

To address this issue, the U.S. Department of Energy (DOE) has sponsored an exceptionally high resolution aeromagnetic survey, completed in 2004, and a presently ongoing drilling program to characterize the location, age, volume, and chemistry of buried basalt in the YMR (Figure 1). DOE has convened an expert panel that will use this information to update probabilistic volcanic hazard estimates originally obtained by experts in 1996. Partly on the basis of the unknown extent of buried volcanoes, *Smith and Keenan* [2005] suggested that volcanic hazard estimates might be 1–2 orders of magnitude higher than estimated by the 1996 expert elicitation.

This article presents results of the new aeromagnetic survey and drilling results obtained thus far. Aeromagnetic anomalies nearest the proposed repository site are interpreted to represent buried Miocene basalt that will likely have only minor impact on volcanic hazard estimates, contrary to the suggestion of *Smith and Keenan* [2005].

By F. V. Perry, A. H. Cogbill, and R. E. Kelley

Expert Elicitation

The 10 members of the current expert panel are recognized volcanologists, geophysicists, and geochemists selected from a group of more than 70 scientists and nominated through a formal selection process [*Geomatrix Consultants*, 1996]. The panel represents academia, government agencies, and private industry. Eight members of the current panel also served on the 1996 panel. The 1996 panel estimated that the mean annual probability of a volcanic disruption of the repository is 1.5×10^{-8} volcanic disruptions (vent or dike intersections) per year, equating to a probability of about one in 7000 in the next 10,000 years [*Geomatrix Consultants*, 1996].

The uncertainty distribution derived from the experts' assessments spanned about three orders of magnitude, from 10^{-7} to 10^{-10} disruptions per year. The main contributions to the uncertainty were from uncertainty in estimates of the volcanic recurrence rate and in selection of the appropriate models for the spatial distribution of future volcanism. An improved characterization of the extent and age of buried volcanoes in the YMR has bearing on both areas of uncertainty.

The 1996 expert panel primarily considered the post-Miocene (the past 5 Ma) volcanic history as important in assessing the volcanic hazard. With one exception at 3 Ma, basaltic volcanoes younger than 5 Ma occur to the south, west, and northwest of the repository site. This spatial distribution of volcanism was a significant factor in the 1996 hazard assessment. The discovery of buried Pliocene basalt to the east of Yucca Mountain in Jackass Flats could significantly change the current understanding of the spatial distribution of post–5 Ma basalt in the YMR and potentially increase the volcanic hazard. Conversely, because several Miocene basalt units crop out in Jackass Flats, discovery of additional buried Miocene basalt would likely have little effect on the hazard estimate.

Aeromagnetic Survey and Drilling

Structural basins filled with up to 500 meters of alluvium surround Yucca Mountain to the east, south, and west. In the past several decades, nearly 50 holes have been drilled in these basins, mainly for Yucca Mountain Project site characterization and the Nye County Early Warning Drilling Program. Several of these drill holes have penetrated relatively deeply buried (300–400 meters) Miocene basalt ranging in age from 9.5 to 11.3 Ma. Pliocene basalt dated at 3.8 Ma was encountered at a relatively shallow depth (100 meters) in the northern Amargosa Desert (anomaly B in Figure 1). On the basis of the new aeromagnetic survey and a more regional aeromagnetic survey completed in 1999 by the U.S. Geological Survey [*O'Leary et al.*, 2002], eight drill holes have been sited to better characterize buried volcanoes in the YMR (Figure 1).

The new aeromagnetic survey provides much higher spatial resolution than previous surveys and covers an area of 865 square kilometers, including Yucca Mountain and adjacent basins to the east, west, and south (Figure 1). A total of 16,000 kilometers of east-west survey lines were flown by helicopter at a flight-line spacing of 60 meters and an instrument height that was typically 40–45 meters over flat terrain. Principal instrumentation was a total-field cesium-vapor magnetometer. The resolution of the survey is nearly equivalent to ground magnetic surveys previously conducted locally in the region [*Connor et al.*, 2000], but coverage over the survey area is uniform, permitting detection of volcanic and structural features that were not well resolved by previous aeromagnetic surveys.

A regional aeromagnetic survey conducted in 1999 [*O'Leary et al.*, 2002] revealed a complex pattern of aeromagnetic anomalies in Jackass Flats that highlighted the uncertainty regarding the nature of buried basalt in this key area. The most prominent magnetic feature revealed by the new survey in Jackass Flats is a broad linear positive anomaly (anomaly U) that parallels the eastern edge of the survey from central Jackass Flats to the northern edge of anomaly B at the southeastern edge of the survey (Figure 1).

Anomaly U is interpreted to represent buried Miocene basalt for two reasons. First, it includes a 9.6 Ma, fault-bounded basalt outcrop near its north end. Faults evident in the aeromagnetic data adjacent to this outcrop both laterally displace buried basalt to the northeast and down-drop buried basalt to the west (Figure 1). Farther to the south, the buried basalt is progressively down-faulted to the southwest as indicated by increasingly attenuated anomaly amplitudes bounded by northwest trending faults.

Second, drill hole 23P near the south end of the anomaly intersected a 10-meter-thick basalt at a depth of 400 meters and dated at 9.5 Ma (Michael Kunk, personal communication, 2003). A series of deep (>350 meter) drill holes to the west of anomaly U intersected alluvium and Miocene tuff, but not basalt, providing further evidence that buried Pliocene basalt is not present in Jackass Flats.

Three of the drill holes in the current program have been completed to date. A sequence of thin basalt flows intersected at anomaly Q in northern Crater Flat at a depth of 140 meters lies beneath alluvium and landslide deposits of Paleozoic strata emplaced during the Miocene uplift of Bare Mountain. These stratigraphic relationships are identical to those encountered in drill hole VH-2, five kilometers south of anomaly Q, and in outcrop at the southern margin of Crater Flat (Figure 1), where both basalts have been dated at 11.3 Ma, indicating the basalt of anomaly Q is the same age. Nearby anomalies with the same characteristics (R and 4) thus also likely represent buried Miocene basalt.

At anomaly A in southern Crater Flat, 62 meters of massive basalt was encountered beneath alluvium at a depth of 148 meters. Lack of flow features, overall thickness, and evidence of internal differentiation suggest this basalt is a sill-like intrusion or possibly a ponded lava flow. At anomaly O, south of Crater Flat, Miocene tuff was encountered beneath alluvium at 163 meters, importantly demonstrating that not all anomalies represent buried basalt and that similar anomalies L, M, and N probably also represent Miocene tuff (Figure 1).

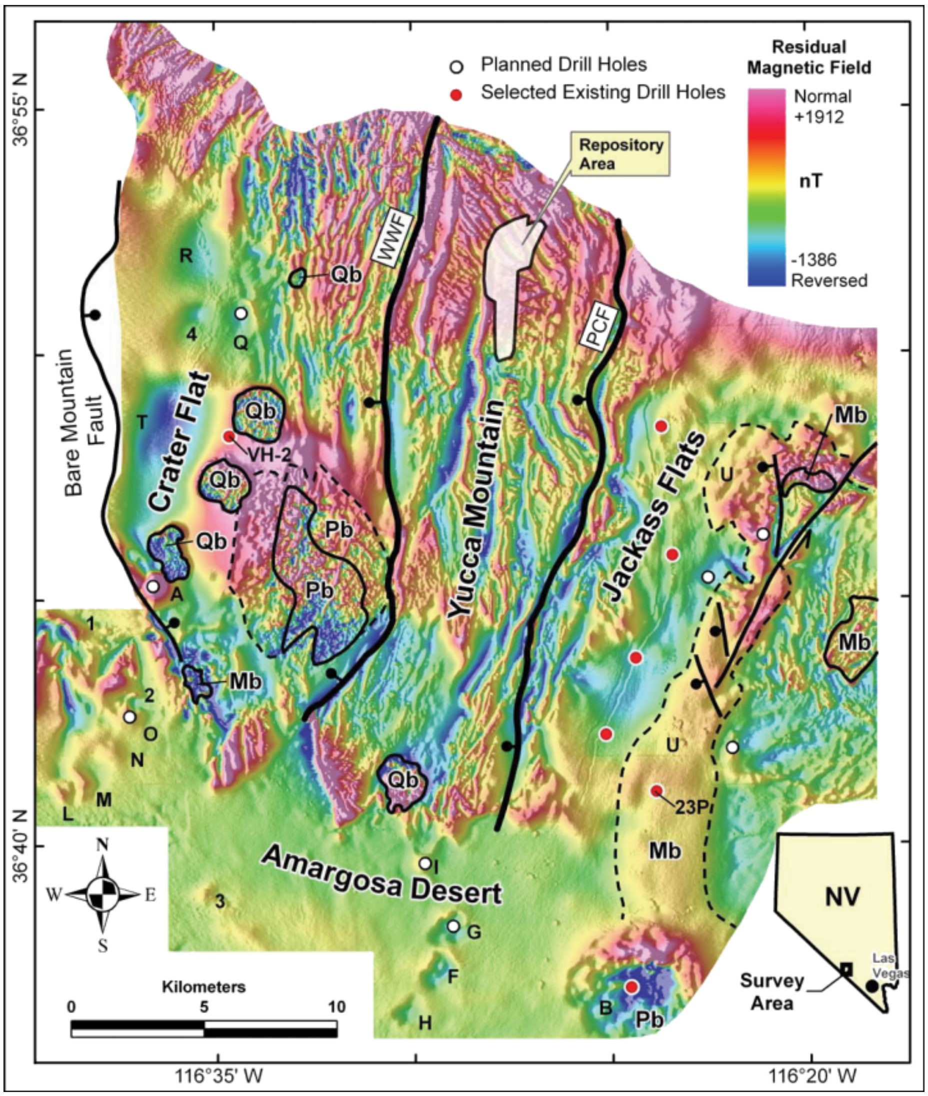

Fig. 1. Residual magnetic field (measured total field minus the International Geomagnetic Reference Field) from the 2004 aeromagnetic survey for Yucca Mountain and surrounding basins. Windy Wash Fault (WWF) and Paintbrush Canyon Fault (PCF) in the central part of the survey area define the approximate boundaries between uplifted Miocene tuffs of the Yucca Mountain range block and the Crater Flat and Jackass Flats basins. The Bare Mountain Fault defines the western edge of the Crater Flat Basin. Single-character alphanumeric labels indicate anomalies suspected of representing buried basalt. Solid lines enclose outcrops of Quaternary (Qb), Pliocene (Pb), and Miocene (Mb) basalt. The four Quaternary basalts in Crater Flat are 1 Ma volcanoes (scoria cones and flows). The Quaternary basalt south of Yucca Mountain is the 77 ka Lathrop Wells volcano. Dashed lines enclose areas of inferred buried basalt associated with outcrops of Pliocene and Miocene lava flows. Red circles indicate selected existing drill holes, and white circles indicate drill holes planned in the current drilling program. The bar and ball symbols on faults denote the downthrown side.

Alternative Models

Although confirmation awaits the completion of drilling and sample dating, interpretation of aeromagnetic data and drilling results to date suggest that magnetic anomalies near Yucca Mountain in Crater Flat and Jackass Flats are due to buried Miocene volcanic features.

Sensitivity analyses, based on models used in the 1996 expert elicitation, indicate a fivefold increase in the volcanic hazard if one assumes that all anomalies in the YMR represent buried Pliocene volcanoes and that nine or more buried Pliocene volcanoes are present in Jackass Flats [*Bechtel SAIC Company*, 2004]. On the basis of the much more limited extent of buried Pliocene volcanoes suggested by the new aeromagnetic data and drilling results thus far, it is likely that the impact on hazard estimates due to buried Pliocene volcanoes alone will be much less than an order of magnitude.

Alternative models that predict a significant increase in future recurrence rates could also increase the hazard estimate. *Smith and Keenan* [2005] proposed such a model, suggesting that the Lunar Crater volcanic field (LCVF), 150 kilometers to the NNE of the YMR, is linked to processes in the YMR through a common and anomalously hot mantle source in the asthenosphere .

The key implication in this model is that recurrence rates in the YMR could increase to rates typical of the LCVF in the future. This hypothesis is inconsistent with the Quaternary volcanic history of the two volcanic fields, which for the past million years have differed significantly in terms of recurrence rate and eruption volume. Compared to the eight Quaternary scoria cones in the YMR (with a total eruption volume of <0.5 cubic kilometers), there are approximately 80 Quaternary scoria cones in the LCVF, with a total eruption volume that is 1–2 orders of magnitude greater than that of the YMR in the Quaternary. These major differences, as well as major differences in neodymium (Nd) and strontium (Sr) isotopic composition [*Farmer et al.*, 1989], are consistent with models of hotter asthenospheric mantle and colder lithospheric mantle sources for the LCVF and YMR, respectively. The contrasting eruptive histories of the LCVF and YMR, and mantle sources with different magma production potentials, suggest the two should not be linked for purposes of assessing volcanic hazard at Yucca Mountain.

The charge to the expert panel is to evaluate all alternative models and data they consider pertinent to assessing the volcanic hazard. The aeromagnetic and drilling data, although key, are not the only new data that the experts will consider. Alternative models and data interpretations, such as those presented by *Smith and Keenan* [2005], and in this article, will be independently evaluated by the panel, which is scheduled to complete its assessment in 2006.

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The Public's Changing Interpretation of the Aurora

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At the end of medieval times and the beginning of modern times, people in northern Germany and the rest of Europe were frequently terrified by mysterious optical phenomena in the sky [cf. *Brekke*, 1995; *Schröder*, 1984]. These included meteorites, unusual rings around the Sun and Moon, and colorful phenomena, all of which astonished them and often caused anxiety. These phenomena and their common interpretation took place against the political chaos of the Reformation, which added to the fears of the average person.

As the sky was previously considered everlasting and unchangeable, these phenomena—when "frightening faces" and "awful signs of miracles" appeared that were as diverse as they were unexplainable—seemed to forecast something terrible. Any deviation from the pre-determined, divine, cosmic order deeply shocked people during that time.

The northern lights, or aurora, were considered among this class of phenomena.

Although auroras have been observed since ancient times, relatively few were observed in middle Europe during a long period between 1645 and 1715, and they became unfamiliar to several generations. Consequently, the spectacular aurora of 17 March 1716, widely observed across Europe [see also *Halley*, 1716], shocked and even terrified the general public, who saw it as a sign from God of terrible times to come.

This article traces the basis for such fears and describes how one contemporary scientist, Christian von Wolff, sought to allay these fears with a rational explanation that was comprehensible to the ordinary person. Perhaps for the first time, thanks to Wolff, the atmosphere was regarded not merely as the place of God, but as a natural laboratory where many physical processes were taking place and leading to striking optical displays.

Role of the "Miraculous Signs"

The aurora is a physical phenomenon of the high atmosphere that is closely connected with solar activity. This was unknown in past centuries and is still unknown to some people today who confuse the appearance of great (usually red) auroras at midlatitudes with fire. When puzzling celestial events confront even people today, it should not be surprising that medieval and early modern people saw exceptional significance in unusual celestial phenomena.

The phenomenon of celestial signs can be considered from several points of view, including the theological background of the period discussed here—the seventeenth and eighteenth centuries—and its specific historical circumstances. With the advent of the Reformation, extreme religious and sociopolitical changes occurred. It can be seen as no wonder that, for Christians of this era, the end of the world was expected and Christ's return was only a question of time. Full of fear for their lives and surrounded by unexpected radical changes, people projected their deep horror to the sky. There, phenomena appeared now and again that they could observe, and that appeared to them to indicate signs of approaching disaster and God proclaiming the end of the world.

This interpretation encompassed all celestial phenomena outside the range of normal events. Comets, meteors, unusual rainbows, auroras, solar and lunar eclipses, and even unusual halo phenomena around the Sun and Moon were inexplicable and interpreted as portents.

In such circumstances, a new understanding of the world could not be found among the masses, many of them illiterate. With life full of troubles, and military turmoil during and after the Reformation, "food from the daily work and from sweat of the brow" (see e.g. *Schröder*, 1984) was of fundamental importance. Any academic discussion of a new image of the world was, for the public, not relevant. Superstitious people faced these celestial signs in a completely helpless way—as did the scientific community of the time.

Since the invention of printing, theological tracts were in common circulation. Subjects included "miraculous signs," and tracts presented images of auroras as allegorical transformations of the actual events. Different forms (such as rays, surfaces, and crowns)

By W. Schröder