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June 19, 2002
Contract No. NRC–02–97–009
Account No. 20.01402.461

U.S. Nuclear Regulatory Commission
ATTN: Dr. John S. Trapp
Office of Nuclear Material Safety and Safeguards
Two White Flint North, Mail Stop 7 D13
Washington, DC 20555

Subject: Completion of Intermediate Milestone—Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region (IM 01402.461.215)

Dear Dr. Trapp:

Enclosed is the revision of IM 01402.461.215, entitled "Evaluation of Geophysical Information Used to Detect and Characterize Buried Volcanic Features in the Yucca Mountain Region." This revision incorporates your comments as detailed in the acceptance letter of June 10, 2002.

If you have any questions, please contact Dr. Brittain Hill at (210) 522-6087 or me at (210) 522-5183.

Sincerely,

H. Lawrence McKague
Element Manager, GLGP

HLM:rae

Enclosure

cc: J. Linehan, W. Reamer, B. Leslie, D. DeMarco, E. Whitt, B. Meehan, D. Brooks, J. Greeves, J. Schlueter, S. Wastler, T. Essig, K. Stablein, P. Justus, W. Patrick, CNWRA Directors, CNWRA Element Managers, B. Hill, J. Stamatakos, T. Nagy (SwRI Contracts)

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EVALUATION OF GEOPHYSICAL INFORMATION USED TO DETECT AND CHARACTERIZE BURIED VOLCANIC FEATURES IN THE YUCCA MOUNTAIN REGION

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–97–009

Prepared by

Brittain E. Hill
John A. Stamatakos

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

June 2002

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Our analyses and interpretations of magnetic data in this report have benefitted substantially from discussions with William Hinze, John Trapp, and Charles Connor. Additional discussions with H. Lawrence McKague, Philip Justus, Darrell Sims, and David Ferrill have also helped our interpretations of geophysical and tectono-magmatic processes. We thank Deborah Waiting and Marius Necsoiu for help with the GIS, Peter La Femina and Nathan Franklin for data processing assistance, and Rebecca Emmot for all her patience and expertise in preparing this report. Reviews by Charles Connor and Budhi Sagar helped to clarify the information in this report.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: CNWRA data contained in this report were generated in accordance with Quality Assurance Procedures. Data used to support conclusions in this report taken from documents published by U.S. Department of Energy (DOE) contractors and supporting organizations were also generated under the quality assurance program developed by the DOE for the Yucca Mountain Project.

ANALYSES AND CODES: Modeling of geophysical data was performed using the Oasis MONTAJ™ version 4.7.40, a commercial software code from Geosoft, Inc. MONTAJ™ is maintained in accordance with CNWRA Technical Operating Procedure TOP–018. Details of the specific procedures used to model the magnetic data in this report are contained in scientific notebook E088.

EXECUTIVE SUMMARY

The U.S. Geological Survey recently completed a large-scale aeromagnetic survey of the Yucca Mountain region. Interpretations of this survey and associated Center for Nuclear Waste Regulatory Analyses ground magnetic surveys indicates there may be twice as many basaltic volcanoes in the Yucca Mountain region than previously recognized. Additional volcanoes also may be present but undetected within approximately 20 km [12 mi] of the proposed repository site due to relatively low resolution of the aeromagnetic survey. Without direct information on the age and composition of these buried volcanoes, associated effects on probability models and risk calculations are highly uncertain. The potential risk significance of this uncertainty ranges from negligible to an order of magnitude increase in the probability of volcanic disruption of the proposed repository site. This uncertainty can be reduced through drilling of anomalies likely to be caused by buried basalt, and to a lesser extent by additional ground magnetic surveys. At present, the range of uncertainty in these interpretations and associated new information clearly exceeds uncertainties and information considered by the U.S. Department of Energy (DOE) during probability model development in 1995. An update to the DOE probability elicitation appears necessary for acceptable use in licensing.

1 INTRODUCTION

1.1 Purpose

Future basaltic igneous activity is estimated to be a leading source of postclosure risk to public health and safety at the proposed Yucca Mountain, Nevada, high-level nuclear waste repository site (CRWMS M&O, 2000a,b; NRC, 1999). A key component of the igneous risk analysis is quantifying the likelihood that a new basaltic volcano will form at the proposed repository site during the 10,000 year postclosure period. Igneous event probability has been the focus of intensive study sponsored by the U.S. Department of Energy (DOE), U.S. Nuclear Regulatory Commission (NRC), and State of Nevada during the last two decades.

Establishing the location, age, and composition of relevant igneous features are basic requirements for any probability evaluation. These characteristics of the Yucca Mountain region basaltic system were thought to be reasonably well established by the mid-1990s, with uncertainties in the probability estimates controlled primarily by different modeling approaches. By the late 1990s, additional ground magnetic and aeromagnetic surveys indicated the number of Yucca Mountain region volcanoes may have been underestimated. Recent aeromagnetic surveys by the U.S. Geological Survey (Blakely, et al., 2000), however, suggest that thirteen previously uncharacterized basaltic volcanoes may be buried beneath alluvium in the Yucca Mountain region. Simple comparisons with known basaltic volcanoes and the results of ground magnetic surveys show that the aeromagnetic survey data may only detect roughly half the known basaltic volcanoes in areas with complex aeromagnetic signal anomalies. In addition to the recognized anomalies that likely represent buried volcanoes, additional basaltic volcanoes could remain present but undetected in areas with complex anomaly patterns.

These uncertainties in the detection and characterization of buried volcanoes directly translate into uncertainties in estimates of volcanic recurrence rates. These uncertainties in estimated volcano recurrence rates may extend significantly the range of uncertainty currently used in probability models. In addition, the age and composition of these buried volcanoes could be different from recognized patterns of igneous activity, which could fundamentally change our understanding of the geologic processes that have focused basaltic igneous activity in this region for the last 11 million years. The cumulative effect of these uncertainties could significantly affect calculations of risk for the proposed high-level radioactive waste repository site at Yucca Mountain, Nevada.

The purpose of this report is to provide an independent evaluation of the new geophysical data and associated interpretations by the DOE and U.S. Geological Survey. Our goals are to (i) assign appropriate levels of confidence to the hypothesis that identified anomalies represent buried basaltic volcanoes, (ii) evaluate the data for additional anomalies that may represent buried basaltic volcanoes, (iii) determine the resolution of these data and consider if additional basaltic volcanoes may be buried but undetected in the survey area, (iv) assess the potential effects that these uncertainties may have on existing probability models and the DOE expert elicitation process, and (v) provide recommendations for reducing the likely uncertainty of these interpretations to a level acceptable for NRC licensing decisions.

1.2 Background

Additional background information on magnetic methods, including a detailed overview of the underlying principles used to survey and model buried basaltic features, is given in Connor and Sanders (1994). In summary, basalt in the Yucca Mountain region is laden with iron-rich minerals (e.g., magnetite). When the molten basalt cooled below the Curie temperature {approximately 550 °C [1,020 °F]}, remanence magnetic vectors became aligned parallel to the earth's magnetic field. This remanent magnetization in basalt is stronger than in most other rock types found in the Yucca Mountain region.

Geophysical surveys can detect subtle variations in the strength of the remanent magnetization in rocks as a magnetometer is passed over different types of rock. Surveys can be conducted with the same magnetometer using airborne or ground-based traverses. The resulting patterns of magnetic field strength produce magnetic anomaly patterns that can be modeled to yield information on the shape, depth, and character of buried volcanoes and intrusions. Some types of welded ignimbrite deposits, however, have magnetic characteristics similar to basalt and can create anomaly patterns that may appear indistinguishable from basalt. Thus, distinction between buried ignimbrites and basalts may be difficult. In addition, because the magnetic signal strength attenuates rapidly with increased distance between the source and the detector, additional details of buried magnetic features may be lost when the magnetic sensor is hundreds of meters above the ground surface.

Numerous magnetic surveys have been conducted with ground based and airborne sensors in the Yucca Mountain region for a variety of site characterization goals. Regional-scale surveys have been conducted with airborne sensors to determine general bedrock characteristics (Boynton and Vargo, 1963; Boynton, et al., 1963; Kane and Bracken, 1983; Bath and Jahren, 1984; Langenheim, et al., 1991; Earthfield Technology, 1995). Based largely on interpretations from these surveys, detailed ground magnetic surveys were conducted by the U.S. Geological Survey over some anomalies thought possibly to represent buried basaltic volcanic features (Langenheim, et al., 1993; Langenheim, 1995; Ponce and Langenheim, 1995) and the Center for Nuclear Waste Regulatory Analyses (CNWRA) (Stamatakos, et al., 1997a; Connor, et al., 1997; Magsino, et al., 1998). Locations of the CNWRA surveys in relation to important geologic features of the Yucca Mountain region are shown in Figure 1-1.

After these surveys, the DOE (CRWMS M&O, 2000a) concluded that the data in Earthfield Technology (1995) were mislocated and thus no interpretations of buried igneous features are possible from these data (Hill and Connor, 2000).

High-resolution aeromagnetic data were collected in the Amargosa Desert region by the U.S. Geological Survey during the summer of 1999 (Blakely, et al., 2000). This survey was funded by Nye and Clark Counties, Nevada; Inyo County, California; and the National Park Service, to support ongoing geologic and hydrologic studies for Death Valley ground water flow system. As part of the prelicensing issue resolution process, NRC requested that DOE evaluate these aeromagnetic data for the presence of additional buried basaltic volcanoes that had not been included in igneous probability models.[1] If additional buried basaltic volcanoes

[1]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (August 29–31, 2000)." Letter (October 23) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

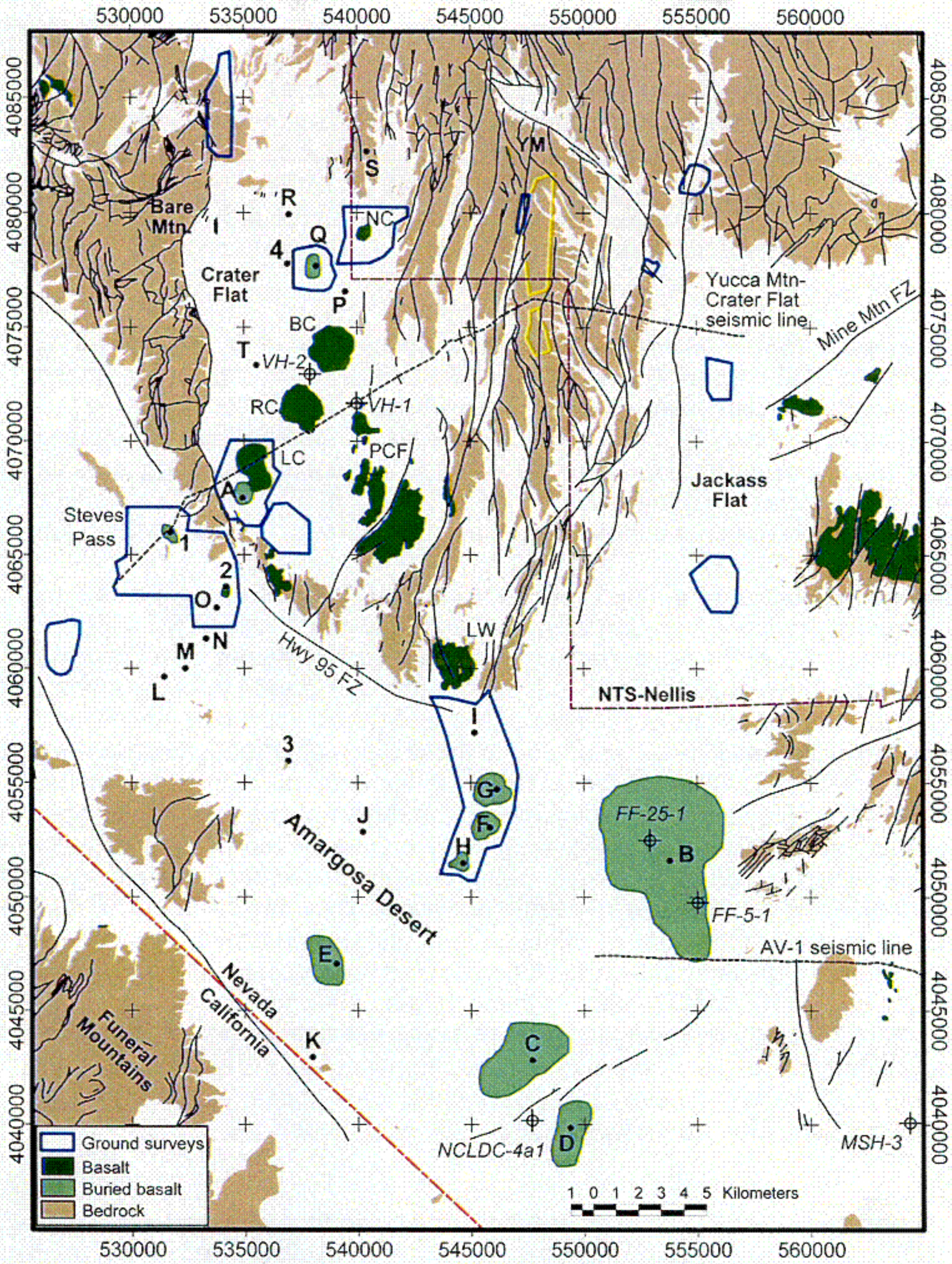

Figure 1-1. Location Map of Features Relevant to the Yucca Mountain Region Aeromagnetic Survey. Bedrock Geology and Faults from Slate, et al. (2000). Blue Outlines of CNWRA Ground Magnetic Survey Areas from Magsino, et al. (1998). Bold Letters and Numbers Refer to Magnetic Anomalies Referenced in Text. Additional Abbreviations are LC—Little Cones, RC—Red Cone, BC—Black Cone, NC—Northern Cone, PCF—Pliocene Crater Flat, and YM—Yucca Mountain. Proposed Repository Outlines are in Yellow, Dashed Lines Show Seismic Reflection Lines.

C01

were identified from these data, the DOE agreed to evaluate the effect of these new volcanoes on probability models.[2] The requested analysis for detecting previously uncharacterized, buried basaltic volcanoes in the Crater Flat basin was presented in O'Leary, et al. (2002). Based on their review and modeling of the 1999 aeromagnetic data, O'Leary, et al. (2002) concluded there may be thirteen basaltic volcanoes buried in this area that were not included in current DOE probability models (i.e., CRWMS M&O, 1996; 2000a). In addition to the thirteen identified anomalies, O'Leary, et al. (2002) suggest that additional basaltic features of the scale of Black Cone volcano could be present but undetected in areas underlain by strongly magnetized bedrock.

Three to seven igneous events generally were used to define most of the recurrence rates and source zones used in DOE probability models (CRWMS M&O, 1996). Intuitively, adding thirteen events should increase event recurrence rates by potential factors of two to four and proportionally affect any probability model using these data. These possible increases in recurrence rates are coupled with a factor of 1.3 increase in potential repository area since the original probability calculations (CRWMS M&O, 1996; 2000a), in addition to numerous other uncertainties in models for igneous consequence calculations (e.g., CRWMS M&O, 2000b).

Igneous events are inconsistently defined in CRWMS M&O (1996) and can combine both intrusive and extrusive components. Similarly, "undetected events" in CRWMS M&O (1996) are inconsistently defined. Six of the ten experts defined "undetected events" to represent the number of undetected intrusions that could extend to within 300 m [984 ft] of the surface without erupting, or for additional intrusions associated with a recognized volcanic event. The probability-weighted increases in recurrence due to these types of unrecognized events ranged from factors of 1.1 to 3.2 (i.e., CRWMS M&O, 1996). In contrast, only three experts used "undetected events" to represent buried volcanoes in the region of interest. These types of "undetected events" allowed for a probability-weighted increase in recurrence from factors of 1.01 to 1.04. One expert combined all these types of "undetected events" into a single factor that allowed for a factor of 1.1 increase in event recurrence. Thus, for the types of "undetected events" relevant to evaluating the number of present but undetected basaltic volcanoes in the Yucca Mountain region, a maximum of one additional volcano represents the consensus of relevant judgment in CRWMS M&O (1996). If these thirteen interpreted features (O'Leary, et al., 2002) actually represent individual basaltic volcanic events, the number of new volcanoes would clearly exceed the "average undetected event factor" (i.e., only one additional event) in CRWMS M&O (1996). These new aeromagnetic data appear to show a lack of calibration to site conditions for the methods used to develop models and parameters in CRWMS M&O (1996).

Bechtel SAIC Company, LLC (2001) concluded including these thirteen anomalies as new volcanoes in DOE probability models would have a minor to negligible effect on the resulting probability value, in part due to the presumed Miocene age of the basaltic rocks producing these magnetic anomalies. None of these anomalies, however, have been drilled or dated. Bechtel SAIC Company, LLC (2001) also indicated this data uncertainty was already included in a "hidden event factor" derived from (CRWMS M&O, 1996) that, on average, allowed for a 20 percent increase in volcano recurrence rates due to present but undetected igneous events.

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[2]Schlueter, J.R. "U.S. Nuclear Regulatory Commission/U.S. Department of Energy Technical Exchange and Management Meeting on Igneous Activity (August 29–31, 2000)." Letter (October 23) to S. Brocoum, DOE. Washington, DC: NRC. 2000.

This reported uncertainty in recurrence rates, however, is not consistent with the information in CRWMS M&O (1996) discussed above.

The combined effects of all these uncertainties on risk may be significant (i.e., Bechtel SAIC Company, LLC, 2001). This report provides an independent assessment of the existing and new geophysical and geological information and evaluates the effect of the new information on the number, ages, and compositions and associated uncertainties of basaltic volcanism in the Yucca Mountain region.

2 ANALYSIS

2.1 Yucca Mountain Region Aeromagnetic Survey

The comprehensive Amargosa Desert aeromagnetic survey reported in Blakely, et al. (2000) was designed to support regional-scale models of tectonic and hydrologic processes. This survey used east-trending flight lines spaced 400 m [1,312 ft] apart connected with north-trending flight lines spaced 2,300 m [7,546 ft] apart. For this report, we used a subset of the Amargosa Desert survey to reduce data processing requirements and to emphasize the range of magnetic anomalies in the area most likely to contain buried basaltic volcanoes that affect probability calculations for the proposed repository site. We refer to this subset of the Amargosa Desert survey as the Yucca Mountain Region survey throughout the remainder of this report. The Yucca Mountain Region survey is bounded on the north by the Amargosa Desert survey limits, and covers a 40 by 60 km [25 by 37 mi] area that encompasses the likely extent of the Crater Flat basin basaltic magma system (Figure 1-1). Approximately 110,000 data points are used to construct the aeromagnetic maps discussed in this report.

Flight line altitudes within the Yucca Mountain Region survey area range from 107–1,116 m [351–3,662 ft] above the ground surface, with an average survey altitude of 370 m [1,214 ft] (Figure 2-1). Knowing the altitude of the aeromagnetic measurement is important because the magnetic signal strength decreases as distance from the causative body increases (e.g., Dobrin and Savit, 1988). Anomalies defined by higher altitude surveys will have lower peak-to-peak signal amplitudes, less prominent gradients at anomaly edges, and lower overall spatial resolution than lower altitude or ground-based surveys (e.g., Connor and Sanders, 1994). Examples illustrating the effects of survey altitude on the attenuation and interpretation of aeromagnetic anomalies are presented in a subsequent section of this report.

Data processing for this report was performed using the Oasis MONTAJ™ software from Geosoft, Inc. Data grids were generated using a standard minimum curvature algorithm that constructs the smoothest possible surface between the data points and grid nodes. A grid-node spacing of 100 m [328 ft] was selected for consistency with the original data processing technique (Blakely, et al., 2000; O'Leary, et al., 2002). The contouring algorithm used to prepare the maps contains a histogram stretching routine to equalize the relative areas of each contour interval. Thus, maps in this report have contour intervals that are irregular. Anomaly names used herein are consistent with the named anomalies in O'Leary, et al. (2002).

A simple grid and contour plot of the Yucca Mountain region survey shows the distribution of magnetic anomalies for the Yucca Mountain region (Figure 2-2). Although the overall anomaly patterns in Figure 2-2 and associated maps are comparable to maps in O'Leary, et al. (2002), small differences in contour intervals arise due to different ranges of anomaly strength across the different map areas. Figure 2-2 shows that isolated, reversely magnetized basaltic volcanoes covered by hundreds of meters of alluvium in the Amargosa Desert (e.g., anomalies "C," "F–H") can be interpreted from prominent magnetic anomalies over normally magnetized bedrock. Reversely magnetized basalt refers to basalt that acquired remanent magnetization during a time when the earth's magnetic field had polarity opposite to the present "normal" field orientation.

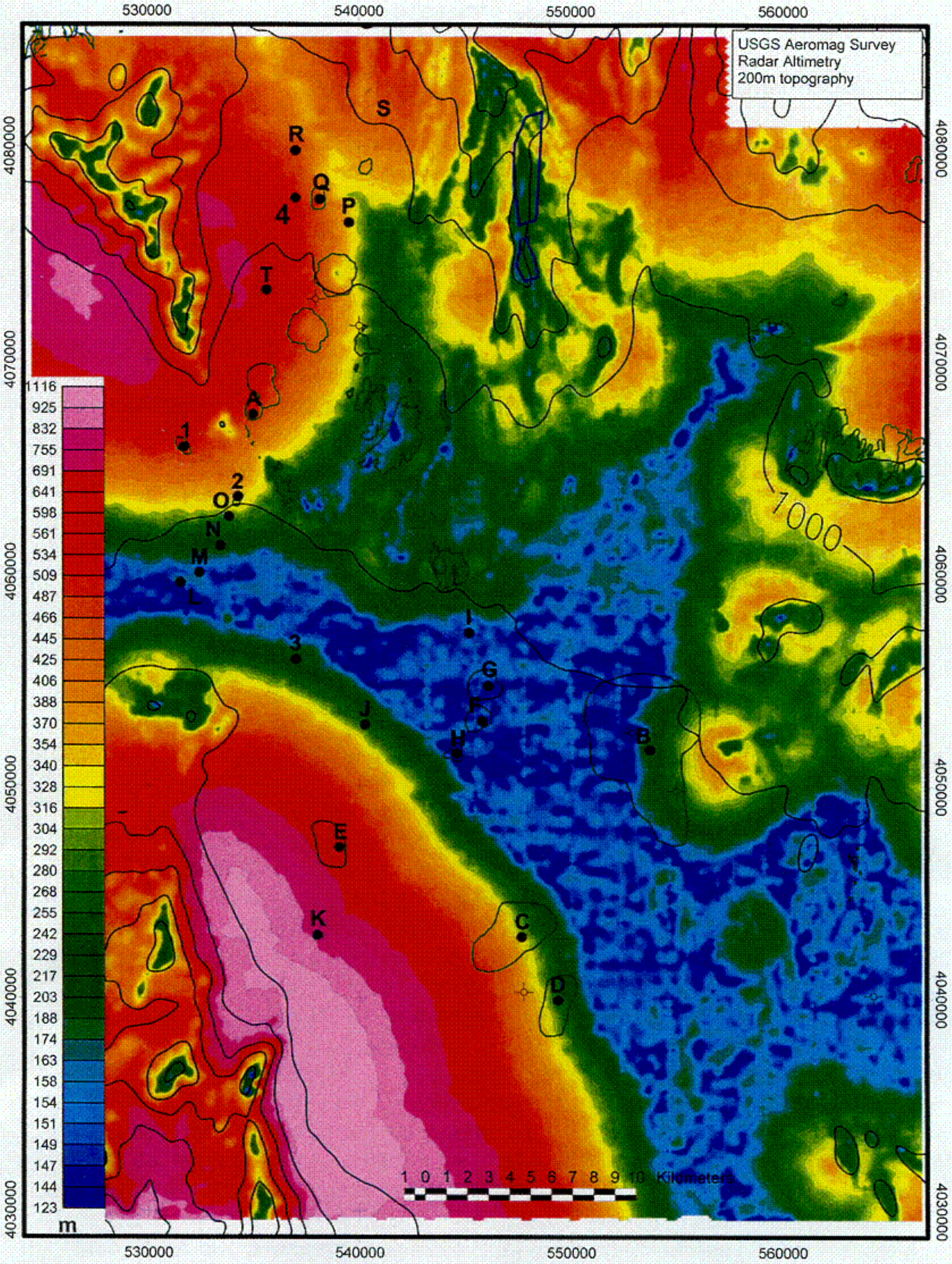

Figure 2-1. Distance above Ground Level of Magnetic Detector Used for Yucca Mountain Region Aeromagnetic Survey, Measured with a Radar Altimeter (Blakely, et al., 2000). Topographic Contours in Black Line are Calculated from Regional Digital Elevation Model at 200 m [656 ft] Contour Intervals.

C02

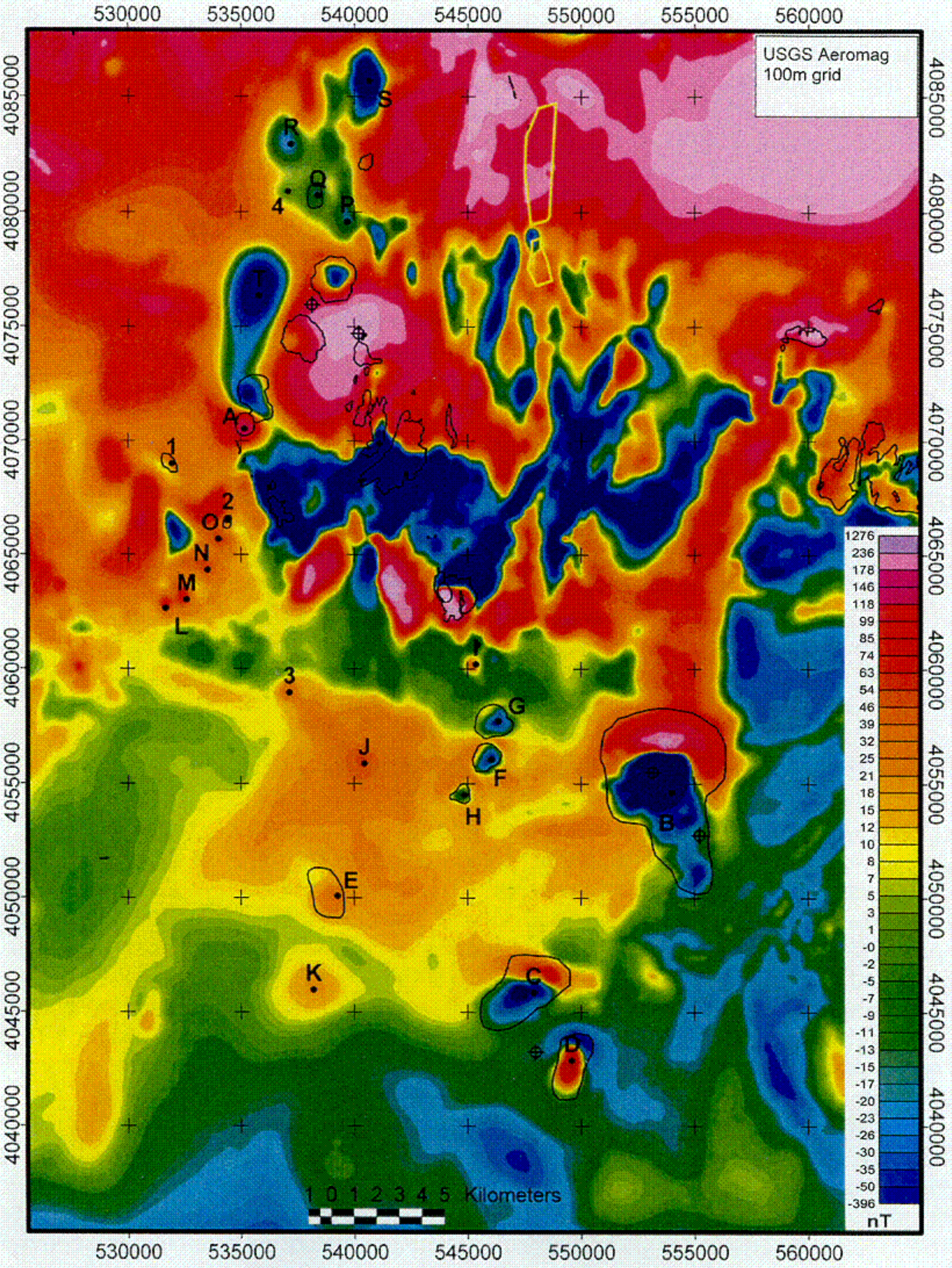

Figure 2-2. Magnetic Anomalies of the Yucca Mountain Region, from Blakely, et al. (2000). Contoured Colors Show Magnetic Field Intensities Relative to the International Geomagnetic Reference Field. Data Processing and Labeling Discussed in Text. Neogene–Quaternary Age Basalt, Including Previously Recognized Anomalies, Outlined in Black.

C03

Welded ignimbrite deposits can create irregular magnetic anomaly patterns due to channeling or ponding during deposition (i.e., Riehle, 1973; Bath and Jahren 1985; Rosenbaum, 1986). Faulting also can juxtapose ignimbrites of contrasting magnetic intensity or polarity. In the Yucca Mountain region, the distribution of many outcrop patterns is controlled by fault patterns (e.g., Frizzell and Shulters, 1990; Day, et al., 1998). A map of contoured aeromagnetic anomalies overlain on bedrock outcrops demonstrates the correlation between faulting, bedrock distribution, and numerous aeromagnetic anomalies in the Crater Flat basin (Figure 2-3). In particular, anomaly "S" is clearly related to an outcrop of reversely magnetized 11.6 Ma Ammonia Tanks Tuff (Frizzell and Shulters, 1990) and does not correspond to buried basalt.

These aeromagnetic data were combined with recently compiled gravity surveys (Ponce, et al., 2001) to evaluate the structural setting of Yucca Mountain region basaltic volcanism. The Crater Flat basin (e.g., Stamatakos, et al., 2000) is part of a regional, generally north-trending deep structural trough truncated by the Timber Mountain caldera (Christiansen, et al., 1977; Snyder and Carr, 1984). The Crater Flat basin is bounded on the west and east by steep gravity, and at in some locations aeromagnetic, gradients (Figure 2-3). All basalt erupted since approximately 11 Ma within the Crater Flat basin has similar geochemical and mineralogical characteristics, whereas basalt located outside the Crater Flat basin shows evidence of significant crustal contamination[1] (i.e., Crowe, et al., 1986). Aeromagnetic patterns produced by faulted ignimbrite outcrops clearly continue into the subsurface in the northern part of the Crater Flat basin. In contrast, the southern part of the basin lacks aeromagnetic anomalies related to extensively faulted ignimbrite deposits. The gravity and aeromagnetic data also show that the proposed repository site is located in the same structural basin as past basaltic activity (cf. CRWMS M&O, 1996).

2.2 Comparison with Known Basaltic Volcanoes

The Amargosa Desert aeromagnetic survey (Blakely, et al., 2000) was not specifically designed to detect basaltic rocks in the Yucca Mountain region. O'Leary, et al. (2002) suggest that basaltic features smaller than Black Cone may remain undetected by the aeromagnetic survey. Detection of these features, however, depends on size, magnetization, survey height, and the magnetic properties of nearby rocks. Additional information is needed to determine the actual resolution limits of this aeromagnetic survey. CNWRA staff previously collected relatively high-resolution ground magnetic data over known and inferred basaltic features in the Yucca Mountain region (Magsino, et al., 1998; Connor, et al., 2000). Analysis of these ground magnetic survey data provides useful information to test resolution limits of the Yucca Mountain Region aeromagnetic survey.

Staff conducted a ground magnetic survey over the 1 Ma Northern Cone volcano (Figure 2-1) to examine the possible controls of shallow subsurface structure on the ascent path of basaltic magma (Magsino, et al., 1998). These survey data are averaged onto a minimum curvature grid with 100 m [328 ft] node spacings and contoured using a histogram stretching algorithm identical to the processing methods used on the Yucca Mountain Region aeromagnetic survey. These data are shown in Figure 2-4, along with the aeromagnetic data and survey flight lines. Average flight altitudes over the area shown in Figure 2-4 are 380 ± 30 m [1,246 ± 98 ft] above ground level. Note the large change in anomaly intensity scale between each map in

[1]Hill, B., Unpublished Research. 2002.

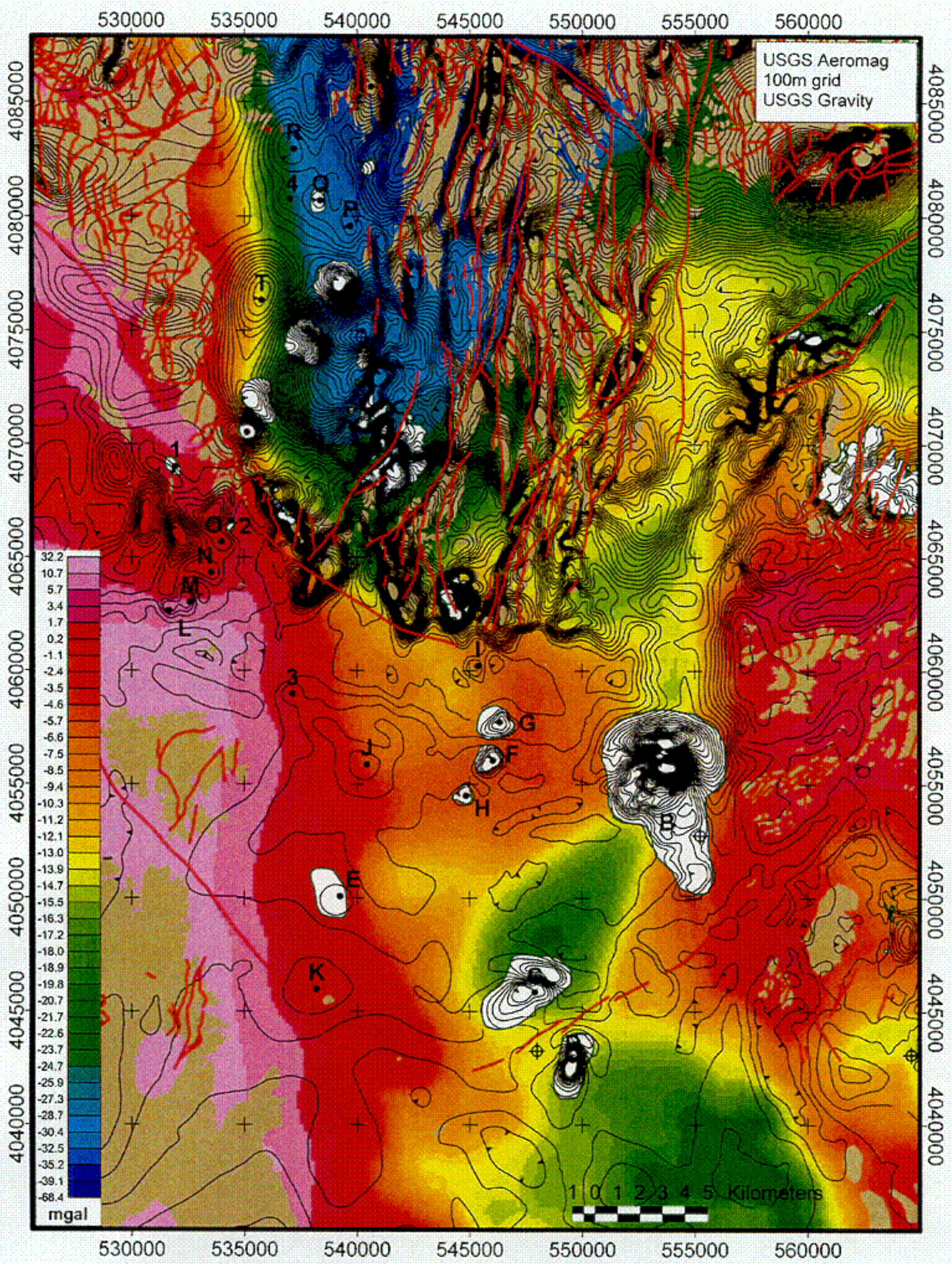

Figure 2-3. Bedrock Outcrops of the Yucca Mountain Region in Tan (Slate, et al., 2000) Overlain by Contoured Magnetic Anomalies from the Yucca Mountain Region Aeromagnetic Survey (Blakely, et al., 2000). Background Image is the Map of Regional Isostatic Gravity Anomalies from Ponce, et al. (2001). Prominent Gravity Low of the Crater Flat Basin Contains Most of the Basaltic Volcanoes in the Region. Neogene and Quaternary Age Basalt and Previously Identified Magnetic Anomalies Shown in White. Note Influence of Faults (in Red) on Magnetic Anomaly Patterns and Trends in the Northern Half of the Figure.

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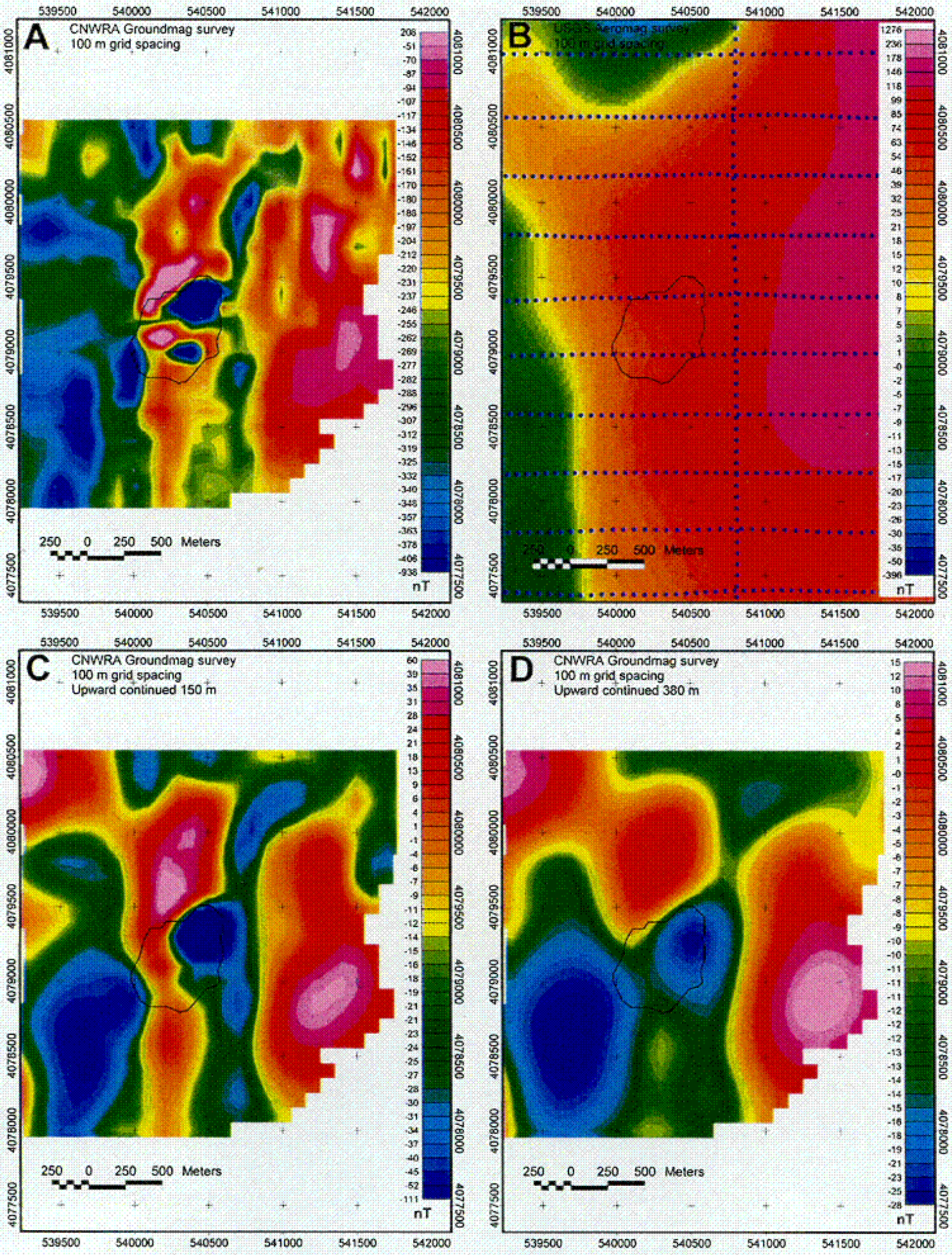

Figure 2-4. Comparison of Ground Magnetic and Aeromagnetic Survey Data for Northern Cone Volcano. Extent of Northern Cone Lavas Shown in Black Line. (a) Ground Magnetic Survey Data from Magsino, et al. (1998) Interpolated on a 100 m [328 ft] Grid. (b) Yucca Mountain Region Aeromagnetic Survey Anomalies (Blakely, et al., 2000) for Same Location. (c) Ground Magnetic Data from (a) Upward Continued to 150 m [492 ft] above Horizontal Ground Level. (d) Data from (a) Upward Continued to 380 m [1,247 ft] above Horizontal Ground Level, Which is the Average Aeromagnetic Survey Altitude for this Map Area.

C05

Figure 2-4. The relatively small size of Northern Cone presents a small target area for 400-m [1,312-ft]-wide survey lines (Figure 2-4b). In addition, the presence of Northern Cone is further obscured because of significant attenuation of the anomaly signal between the surface lavas and airborne magnetic detector (e.g., Connor and Sanders, 1994). This expected signal attenuation is illustrated by upward continuation of the ground magnetic data to altitudes of 150 m [492 ft] (Figure 2-4c) and 380 m [1,247 ft] (Figure 2-4d) above the ground surface. As distance above ground surface increases, large attenuations occur in the dynamic range of the magnetic signal and greatly obscure the presence of Northern Cone volcano.

Similar attenuation effects are shown for ground magnetic data surveyed over the Steve's Pass area (Figure 1-1). Two anomalies ("1" and "2", Figure 2-5a) were previously identified as likely buried basalt based on steep high-intensity magnetic gradients associated with well defined dipolar anomalies (Magsino, et al., 1998). Interpolating these ground magnetic data onto a 100 m [328 ft] grid still results in discernable, strongly magnetized anomalies (Figure 2-5a) relative to the aeromagnetic data (Figure 2-5b), although these features are better defined on a 50 m [164 ft] grid (Figure 2-5c). Upward continuation of the ground magnetic data to the average flight altitude of the aeromagnetic survey in this area {306 ± 136 m [1,004 ± 446 ft]}, however, completely obscures anomaly "2" and renders anomaly "1" indistinguishable from low amplitude anomalies related to bedrock faulting (Figure 2-5d).

Bedrock with relatively high amplitude or short wavelength magnetic anomalies further degrade the ability of the aeromagnetic survey to detect and characterize buried basaltic volcanoes. Known volcanoes in Crater Flat basin (Figure 2-6) often produce subtle to negligible aeromagnetic anomalies, largely due to the strong magnetic anomalies produced by faulted, welded ignimbrite deposits. The anomalies associated with Black Cone and perhaps Lathrop Wells have characteristics of isolated basaltic bodies, however, Red Cone and Little Cones are nearly obscured by larger-scale bedrock anomalies (Figure 2-6). Exposed basaltic volcanoes and lavas would be extremely difficult to discern at Northern Cone, Pliocene Crater Flat, and the Miocene volcanic center in southern Crater Flat (Swadley and Carr, 1987). Also undetectable are the subsurface basaltic lavas from 360–390 m [1,181–1,280 ft] depth in drillhole VH-2 (Carr and Parish, 1985), shallow buried basaltic lavas along the Yucca Mountain-Crater Flat seismic line between Little Cones and drillhole VH-1 (reflector "H," Brocher, et al., 1998), and basaltic lavas in drillholes Felderhoff Federal 25-1 and 5-1 (Carr, et al., 1995) and Nye County Land Development Corporation-4a1 (Walker and Eakin, 1963). Not surprisingly, small but important dikes located at the headwalls of Solitario Canyon (e.g., Day, et al., 1998) and dikes extending from the Miocene volcanic center in southern Crater Flat also appear undetectable with the aeromagnetic survey technique (Figure 2-6).

Based on these empirical comparisons, surface basaltic volcanic features with areas smaller than approximately 1 km^2 [0.4 mi^2] appear generally undetectable in the Yucca Mountain Region aeromagnetic survey data. Volcanoes larger than 1 km^2 [0.4 mi^2] appear generally detectable in areas underlain by relatively low intensity, longer wavelength bedrock anomalies. In areas underlain by relatively high intensity or short wavelength anomalies characteristic of northern Crater Flat basin, basaltic volcanic features larger than 1 km^2 [0.4 mi^2] often do not appear discernable in the aeromagnetic data. In some cases, however, additional filtering of these data could enhance the magnetic anomaly characteristics that suggest the likely presence of buried basaltic volcanoes (e.g., Connor and Sanders, 1994). Examples of these filtering techniques are applied in the next section of this report.

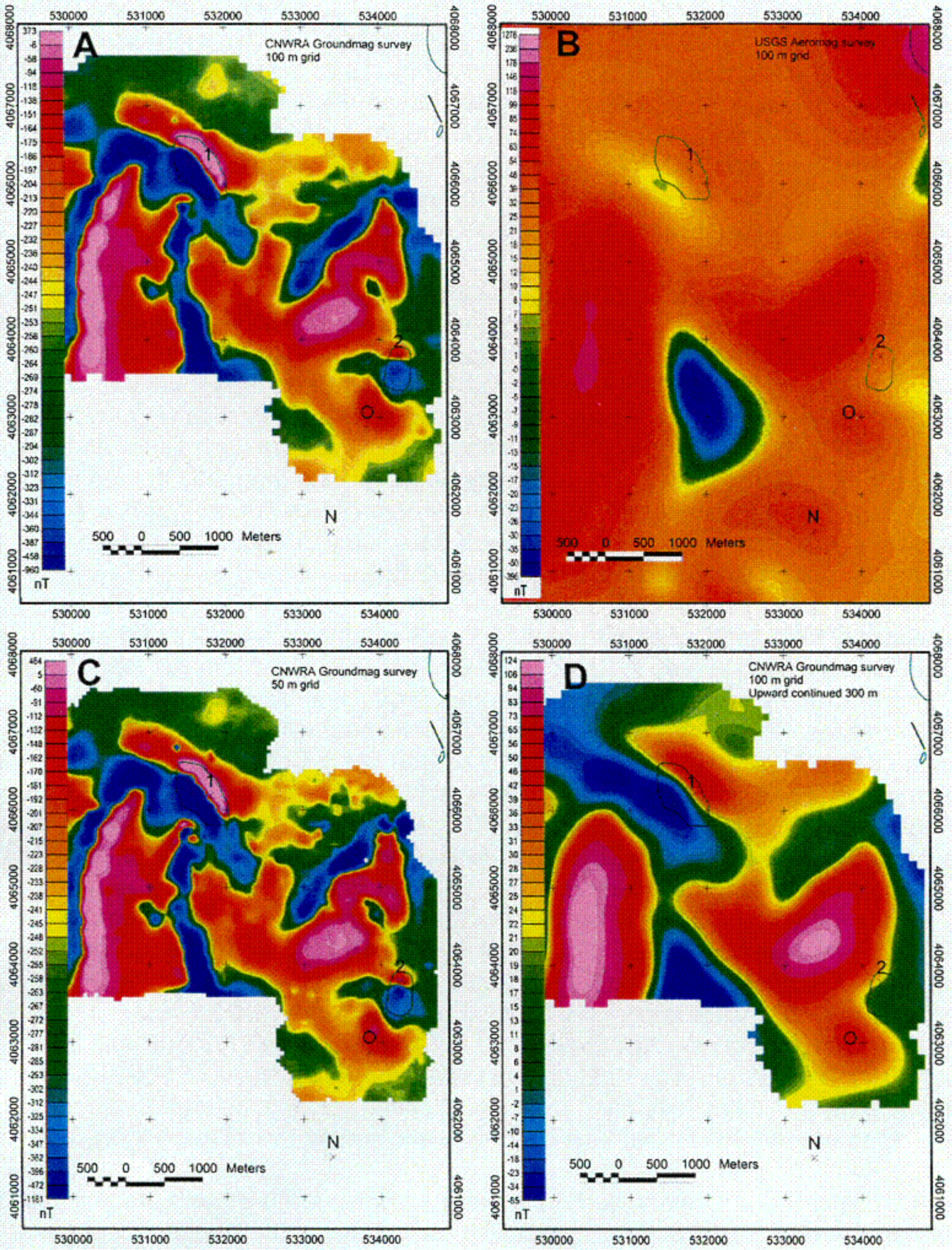

Figure 2-5. Comparison of Ground Magnetic and Aeromagnetic Survey Data for the Steve's Pass Area. (a) Ground Magnetic Survey Data from Magsino, et al. (1998) Interpolated on a 100 m [328 ft] Grid. (b) Yucca Mountain Region Aeromagnetic Survey Anomalies (Blakely, et al., 2000) for Same Location. (c) Note Increases in Anomaly Resolution as Survey Data in (a) are Interpolated on a 50 m [164 ft] grid. (d) Data from (a) Upward Continued to 300 m [984 ft] above Horizontal Ground Level, Which is the Average Aeromagnetic Survey Altitude for this Map Area.

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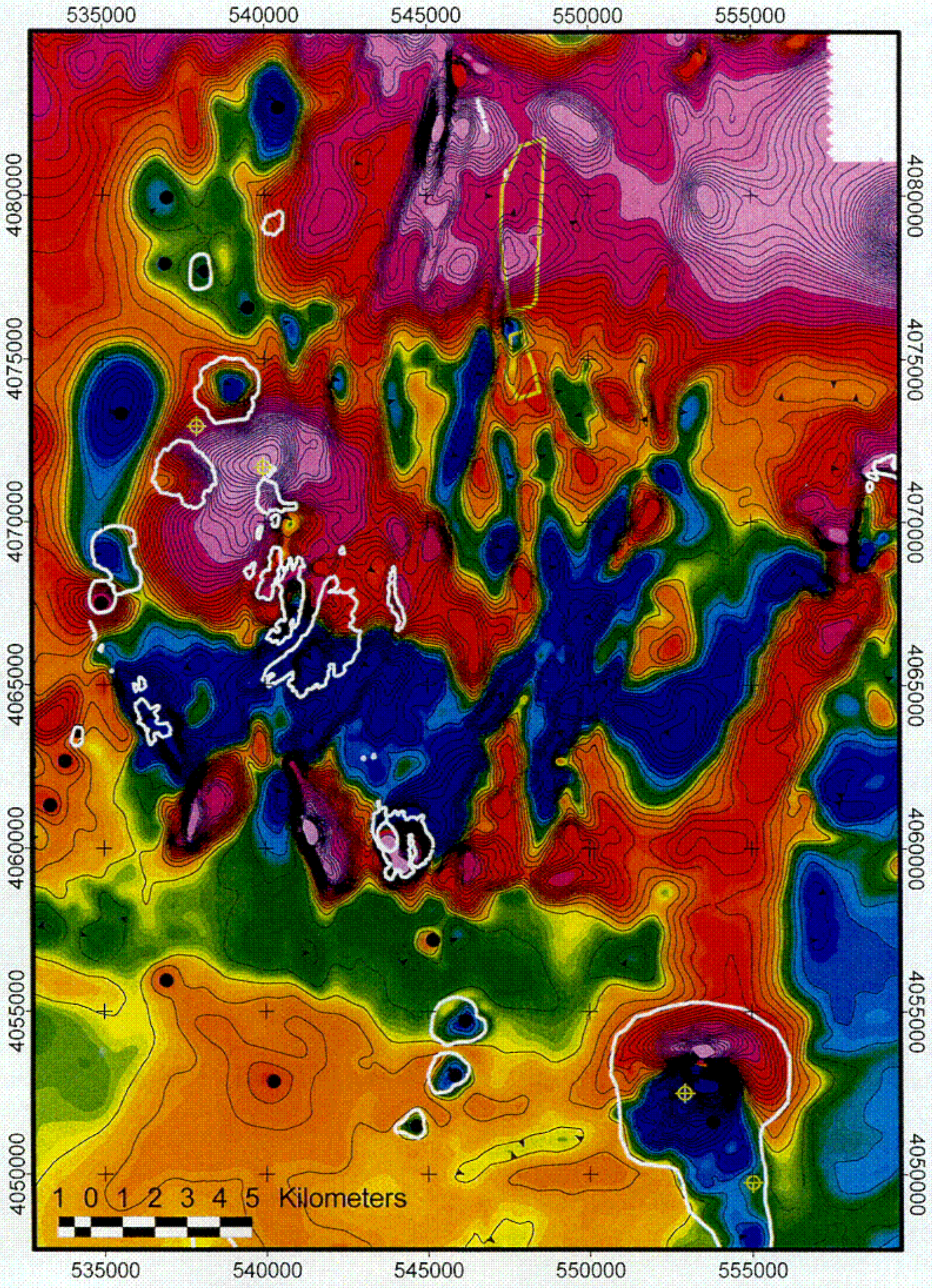

Figure 2-6. Larger Scale Map of the Crater Flat Basin, Focusing on Known Surficial or Reasonably Inferred Subsurface Basaltic Volcanic Features Outlined in White. Magnetic Anomaly Contour Lines from the Yucca Mountain Region Aeromagnetic Survey (Blakely, et al., 2000) Superimposed on a Color Contour Map to Assist Identification of Known Basaltic Features.

C07

2.3 Data Filtering and Enhancement

Magnetic data can be transformed from the spatial domain into the frequency domain using well-accepted Fast Fourier Transformations (e.g., Dobrin and Savit, 1988). Translation into the frequency domain permits the use of digital filters to enhance the magnetic data. For the evaluation of possible buried basaltic volcanoes, the most useful digital filters separate localized, short wavelength features from regional, long wavelength features or enhance gradients in the magnetic field measurements (e.g., Connor and Sanders, 1994). In this section, we provide brief explanations of these filtering techniques and general observations of filter effects on the Yucca Mountain Region aeromagnetic survey data. Specific filtering effects on individual anomalies are discussed in the following section of this report.

A residual filter is used to remove the magnetic anomalies caused by larger scale features from the anomaly data, leaving only the contribution from smaller scale features. The magnetic component of the long wavelength feature is removed from the total-field anomaly by using a 2D-Gaussian filter to smooth the aeromagnetic map. This smoothed map is subtracted from the original map to yield the residual signal. The coherence of the residual map is a direct function of the wavelength selected (i.e., the standard deviation of the Gaussian filter) for the regional feature. A regional wavelength that is unreasonably short will produce a residual map of small, meaningless anomalies of similar intensity, whereas a regional wavelength that is too long produces a residual map that closely resembles the original anomaly map. Through experimentation, we determined that a 5-km [3.1-mi] cutoff wavelength provided the most useful residual anomaly map for delineating known basaltic features in the Yucca Mountain Region survey (Figure 2-7). This residual filter significantly enhances anomalies in the Amargosa Desert and provides better definition of the Quaternary Crater Flat volcanoes (i.e., O'Leary, et al., 2002). In addition, the overall structural elements of the Crater Flat basin are preserved, which distinguishes anomalies within the basin from anomalies with similar characteristics located in areas of Paleozoic bedrock.

An analytic signal filter is used to calculate the absolute strength of an anomaly from the magnetic field's three mutually orthogonal spatial (x, y, z) derivative terms, where the z-derivative is estimated following the method of Hsu, et al. (1996). This filter provides a simple comparison of the anomaly strength between features with normal and reverse remanent magnetization, and is often used to delineate the edges of source bodies. For the Yucca Mountain Region aeromagnetic data, the analytic signal map (Figure 2-8) clearly distinguishes the highly magnetized tuffs in Crater Flat basin from lower intensity rocks in Amargosa Desert. The analytic signal map illustrates the complexities and limitations of anomaly interpretations in the Crater Flat basin, due to the abundance of tuffs with high remanent magnetizations. Note that known basaltic features in the Crater Flat basin are not particularly well defined by application of the analytic signal filter. Anomalies within the Crater Flat basin potentially related to buried basalt, however, generally have higher analytic signal strengths than surrounding bedrock-related anomalies (Figure 2-8).

In the frequency domain, the second derivative also can be calculated from the aeromagnetic data. The second derivative (e.g., Connor and Sanders, 1994) essentially calculates the gradient in the magnetic anomaly field, emphasizing steep gradients and attenuating longer wavelength features. This calculation enhances shallow local anomalies using an approach similar to a high-pass filter, without the need to define cutoff wavelengths for the background

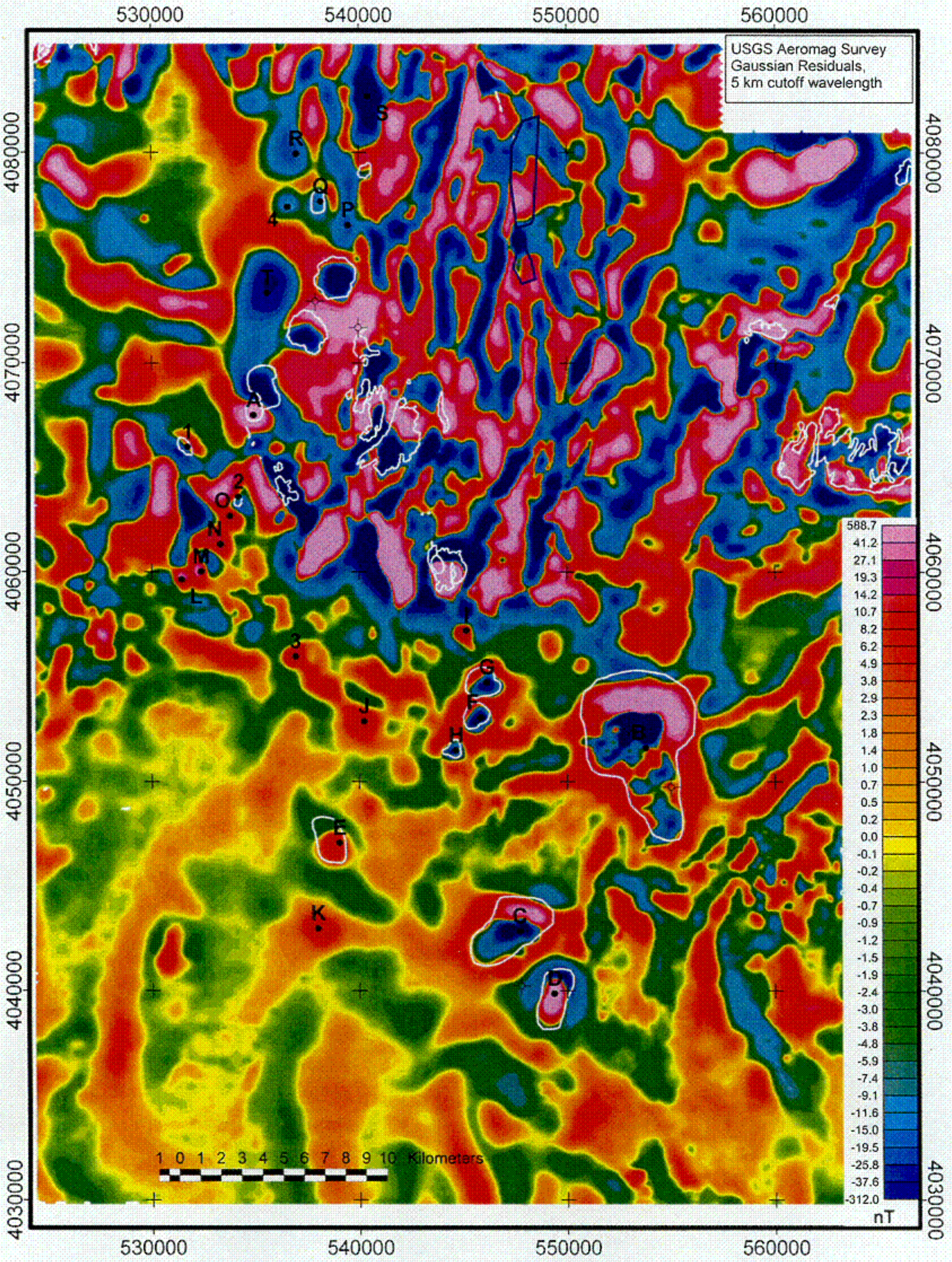

Figure 2-7. Residual Magnetic Anomalies for the Yucca Mountain Region Aeromagnetic Survey (Blakely, et al., 2000). Known or Previously Inferred Basalt Outlined in White. Residual Anomalies Were Calculated Using a 5-km [3.1-mi]-Long Cutoff Wavelength, as Discussed in Text.

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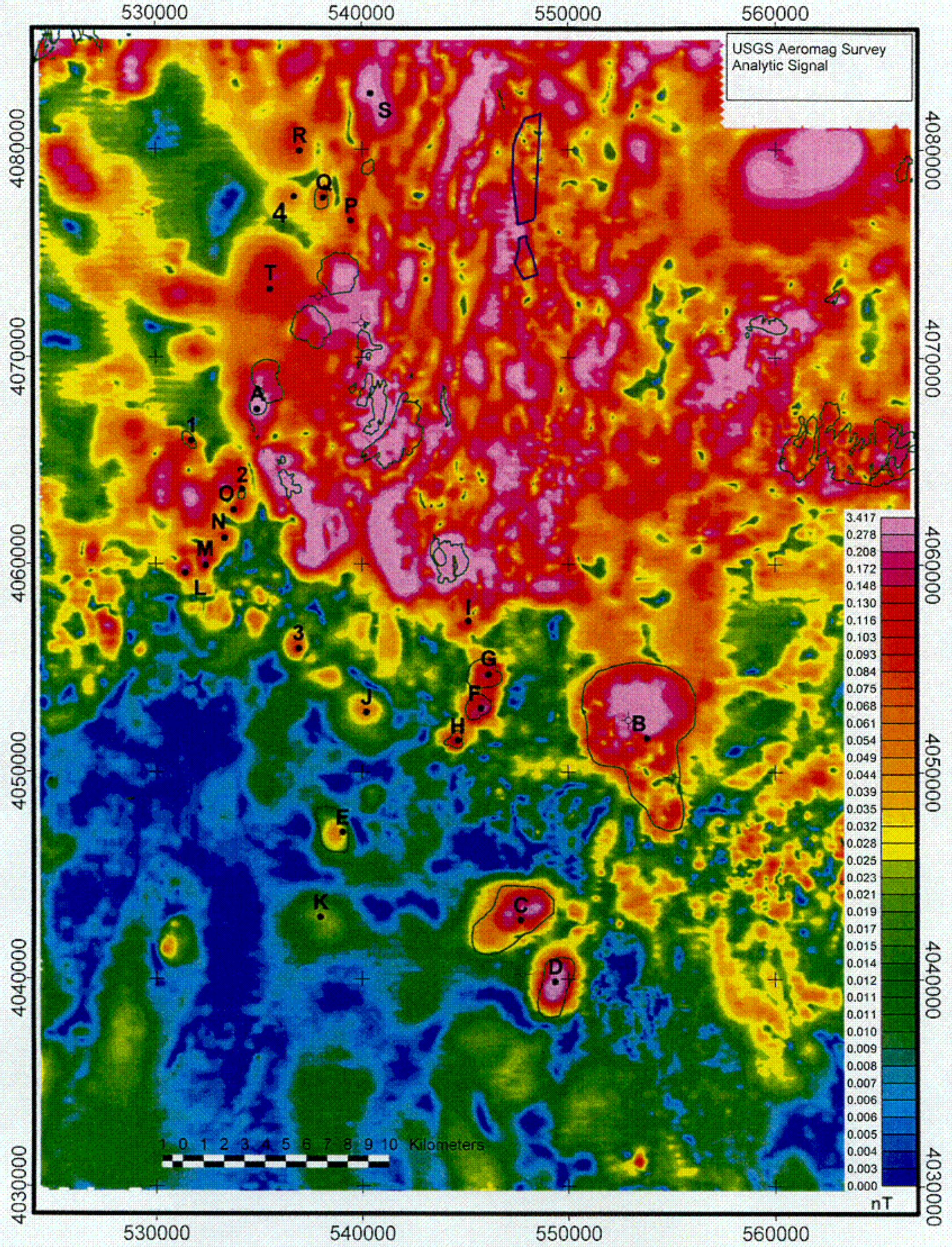

Figure 2-8. Analytic Signal Map for the Yucca Mountain Region Aeromagnetic Survey (Blakely, et al., 2000). Known or Previously Inferred Basalt Outlined in Green. Rocks With Strong Remanent Magnetization Have a Large Analytic Signal Regardless of Polarity Orientation.

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features. A second derivative of the Yucca Mountain Region aeromagnetic data greatly enhances the definition of most identified anomalies (Figure 2-9). In addition, this filter emphasizes the complex, north-northeast-trending structural grain within the Crater Flat basin due to faulting of welded ignimbrite deposits. The abundant, steep magnetic gradients in Crater Flat basin (Figure 2-9) clearly obscure the anomaly characteristics of known basaltic features.

2.4 Evaluation of Identified Anomalies

The Amargosa Desert aeromagnetic survey produced the highest quality aeromagnetic data available for the Yucca Mountain region. Unfortunately, this survey was not optimized for the detection of buried, small volume basaltic features. Survey line spacings are too large and flightline altitudes are too high to permit high-confidence interpretations for presence or absence of buried basaltic features in most areas of interest.

In this section, we present an independent assessment of the anomalies identified in O'Leary, et al. (2002). A relative ranking of low-medium-high confidence is placed on the interpretations of buried basalt. A summary of this assessment is provided in Table 2-1. Table 2-1 also provides the relative confidence ranking by O'Leary, et al. (2002) that an anomaly represents buried basalt. Each expert in CRWMS M&O (1996) also provided a confidence estimate for anomalies "A–G" representing buried basalt. The average confidence ranking from CRWMS M&O (1996) also is provided in Table 2-1.

- A — Strong magnetic intensity and shape support interpretation of buried basalt with high confidence, as discussed in Langenheim (1995), Connor, et al. (1997), Magsino, et al. (1998), Connor, et al. (2000), and O'Leary, et al. (2002). On a general trend with the Quaternary Crater Flat alignment. Stratigraphically lower in alluvial section than 1 Ma basaltic lavas of Little Cones, and thus older than 1 Ma. Using an average sedimentation rate of 0.03 mm/yr [0.0012 in/yr] (Stamatakos, et al., 1997a), estimated age can range from <3.3 Ma for a modeled burial depth of <100 m [328 ft] (O'Leary, et al., 2002) to approximately 5 Ma for a modeled burial depth of approximately 150 m [492 ft] (Connor, et al., 2000).

- B — Well characterized (Langenheim, et al., 1993; Langenheim, 1995) basaltic volcanic center penetrated by two drill holes at approximately 70–160 m [230–525 ft] (Carr, et al., 1995) and dated at approximately 4 Ma with reversed polarity remanent magnetization (see NRC, 1999, Appendix A). Average sedimentation rate of 0.04 mm/yr [0.0016 in/yr] assuming 160 m [525 ft] average depth of burial (Carr, et al., 1995).

- C — Well characterized anomaly with reversed polarity remanent magnetization that can be modeled as basaltic lava approximately 200 m [656 ft] deep in Amargosa Desert alluvium (Langenheim, et al., 1993; Langenheim, 1995). High confidence in the interpretation of buried basalt. Degree of desert varnish on alluvium appears similar to alluvium overlying anomaly "B." Assuming a 0.04 mm/yr [0.0016 in/yr] sedimentation rate yields an estimated date of 5 Ma. Sedimentation rate may be higher, however, due to contributions from the ancestral Amargosa River system and thus estimated age may be younger than 5 Ma.

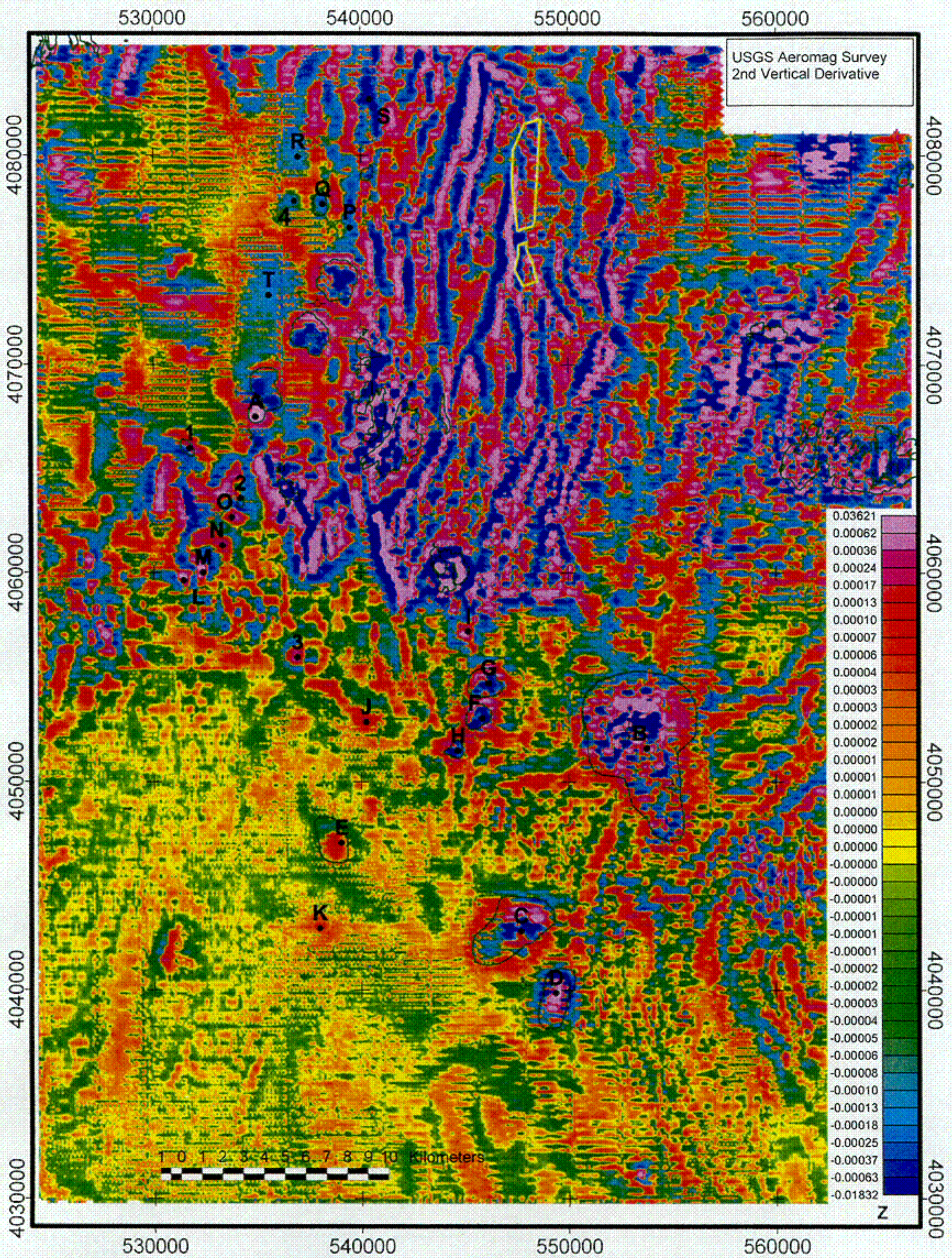

Figure 2-9. Second Derivative Map for the Yucca Mountain Region Aeromagnetic Survey (Blakely, et al., 2000). Known or Previously Inferred Basalt Outlined in Green. Anomalies With High Gradients are Accentuated With this Filtering Calculation.

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Table 2-1. Summary of Magnetic Anomalies Potentially Representing Buried Basaltic Volcanic Features in the Yucca Mountain Region							
Label	Easting	Northing	Polarity	USGS	This Rpt.	PVHA	Notes
A	534917	4067499	n	1	H	0.20	Modeled depth 100–150 m [328–492 ft]
B	553787	4051604	r	confirmed	H	0.90	Drilled depth 70 m [230 ft]
C	547688	4042829	r	1	H	0.84	Modeled depth 200 m [656 ft]
D	549365	4039859	n	1	H	0.88	Modeled depth 180 m [591 ft]
E	539038	4047061	n	2	M	0.61	Signal likely attenuated due to high survey altitude
F	545821	4053035	r	1	H	0.37	Modeled depth 250 m [820 ft]
G	546132	4054715	r	1	H	0.36	Modeled depth 150 m [492 ft]
H	544639	4051479	r	1	H	n/r	Depth likely comparable to anomaly "F"
I	545154	4057186	n	2	M	n/r	Modeled depth 250 m [820 ft]
J	540220	4052848	n	3	L	n/r	Merges with presumed bedrock anomalies
K	537980	4042954	n	3	L	n/r	Merges with bedrock outcrops
L	531446	4059631	n	3	M	n/r	Modeled depth 150 m [492 ft]
M	532380	4060005	n	3	M	n/r	Modeled depth 150 m [492 ft]
N	533313	4061312	n	3	M	n/r	Modeled depth 250 m [820 ft]
O	533779	4062664	n	3	M	n/r	Modeled depth 50 m [164 ft]
P	539474	4076558	r	4	L	n/r	Merges with presumed bedrock anomalies to N
Q	538167	4077678	r	4	M	n/r	Ground magnetic surveys increase confidence
R	536985	4079918	r	4	L	n/r	Diffuse boundary to anomaly
S	540407	4082656	r	4	tuff	n/r	Bedrock outcrop of Rainier Mesa Tuff
T	535553	4073322	r	?	L	n/r	May be channeled Rainier Mesa Tuff
1	531735	4065981	r	n/r	M	n/r	Ground magnetic survey interpretation
2	534189	4063581	r	n/r	M	n/r	Ground magnetic survey interpretation
3	536916	4055944	n	n/r	M	n/r	Aeromagnetic anomaly from body beneath Big Dune
4	536520	4077790	4	n/r	L	n/r	Aeromagnetic anomaly 2 km [1 mi] west of Q

Notes: Location coordinates in Universal Transverse Mercator meters, NAD 27, Zone 11; Polarity: n — normal, r — reversed; USGS = Confidence 1–4 from O'Leary, et al. (2002); n/r — not recognized; This Rpt. = Confidence from this report: H — high, M — medium, and L — low; PVHA (probabilistic volcanic hazards assessment) — Average confidence the anomalies represent basalt, calculated from CRWMS M&O (1996)

- D — Basaltic volcanic center with definitive anomaly and normal polarity magnetization, which can be modeled as basaltic lava approximately 180 m [591 ft] deep in alluvium (Langenheim, et al., 1993; Langenheim, 1995). At least 9 m [30 ft] of fractured basalt was penetrated between 178 m [584 ft] and the bottom of drill hole 17S/49-4a1, which is located at the western margin of anomaly "D" (Walker and Eakin, 1963; Langenheim, 1995). Degree of desert varnish on alluvium appears similar to alluvium overlying anomalies "B–C." Assuming a 0.04 mm/yr [0.0016 in/yr] sedimentation rate and 190 m [623 ft] depth of burial yields an estimated date of 5 Ma. Sedimentation rate may be higher, however, due to contributions from the ancestral Amargosa River system and thus estimated age also may be younger than 5 Ma.

- E — Aeromagnetic characterization only (Langenheim, et al., 1993) with a weak positive dipole anomaly. Shape and relative strength of anomaly provide moderate confidence for buried basalt, with magnetic signals likely attenuated by high {>500 m [1,641 ft]} altitude of the survey. Anomaly is clearly isolated with intensity greater than surrounding rock during residual (Figure 2-7), analytic signal (Figure 2-8), and second vertical derivative filtering (Figure 2-9). Overlain by alluvium from Fortymile Wash and Amargosa River, thus, age cannot be estimated without additional information on depth of potential burial and assumed sedimentation rates.

- F–H — Alignment of three well-characterized anomalies produced by reverse-polarity remanent magnetization, which can be modeled as buried basaltic volcanic centers (Langenheim, et al., 1993, Connor, et al., 1997; Magsino, et al., 1998; O'Leary, et al., 2002). High confidence in the interpretation of buried basalt. All three anomalies produce dipoles characteristic of buried basalt and are prominent features in all filtered maps. Anomaly "G" has a modeled maximum depth to burial of approximately 150 m [492 ft], increasing to 250 m [820 ft] for anomaly "F" (O'Leary, et al., 2002). Assuming sedimentation rate is comparable to anomaly "B" {i.e., 0.04 mm/yr [0.0016 in/yr]} yields an estimated age of 4 Ma for anomaly "G" and 6 Ma for anomaly "F." Sedimentation rates may be higher than for anomaly "B," due to additional deposition from the main Fortymile Wash drainage system. Anomalies "F–H" likely are equivalent ages due to characteristic size and alignment (cf. 1 Ma and 3.8 Ma Crater Flat alignments, Figure 1-1).

- I — Isolated anomaly produced by normal polarity magnetization approximately 1 km [0.6 mi] in diameter, which can be modeled as a buried basalt (Magsino, et al., 1998; O'Leary, et al., 2002). Moderate confidence in the interpretation of buried basalt. During filtering, anomaly "I" remains isolated from anomalies to the north that are likely caused by outcrops of normal polarity ignimbrite. Modeled 250 m [820 ft] depth to burial (O'Leary, et al., 2002) suggests older age than anomaly "G" assuming no post-depositional displacement from nearby Highway 95 fault (Figure 1-1). Sedimentation rate may be higher than 0.04 mm/yr [0.0016 in/yr] due to relative proximity of colluvial slopes, yielding a minimum age estimate of <6 Ma.

- J — Isolated anomaly with normal-polarity magnetization identified only through aeromagnetic data (O'Leary, et al., 2002). If the anomaly does represent buried basalt, the intensity of the anomaly is low compared to other anomalies overflown with similar survey altitudes. Analytic signal is only slightly greater than surrounding rock (Figure 2-8). Broadly defined anomaly appears to merge with surrounding normal polarity anomalies in residual (Figure 2-7) and second vertical derivative filtered maps (Figure 2-9). Thus, anomaly "J" may represent relatively deeply buried basalt with low confidence (i.e., O'Leary, et al., 2002), or faulted blocks of welded ignimbrite. Based on the lack of a well-defined magnetic signature, we interpret the presence of buried basalt with low confidence.

- K — Broad, relatively isolated anomaly with normal-polarity magnetization identified only through aeromagnetic data (O'Leary, et al., 2002). Amplitude of the magnetic signal may be attenuated due to the high altitude {>750 m [2,461 ft]} of survey measurements. Anomaly "K" appears to merge with surrounding rock in residual filtered maps (Figure 2-7) but remains discernable in analytic signal (Figure 2-8) and second vertical derivative filtered maps (Figure 2-9). Outcrops of pre-Crater Flat Group (i.e., older than 13.5 Ma) tuffaceous sediments (Swadley and Carr, 1987) occur on the southern sector of the anomaly, suggesting anomaly may be related to shallowly buried bedrock rather than buried basalt. Diffuse boundary lacks steep magnetic gradients characteristic of most other anomalies, giving low confidence to the interpretation of buried basalt.

- L–O — Series of four high amplitude anomalies with normal-polarity magnetization located on a 4-km [2-mi]-long, northeast-trending alignment that intersects anomaly "2." Aeromagnetic anomalies can be modeled as buried basaltic volcanic centers for all four anomalies (O'Leary, et al., 2002). Anomalies retain distinctive characteristics during filtering. Moderate confidence in the interpretation of buried basalt. Sedimentation rates poorly constrained in this area. U.S. Borax monitoring well ASH-B is located within several kilometers of these anomalies. This drill hole penetrated 225 m [738 ft] of alluvium before encountering welded tuffs likely associated with the 11 Ma Rainbow Mountain Formation[2] (Maldonado, 1990). These stratigraphic relationships suggest an average sedimentation rate of 0.02 mm/yr, [0.0008 in/yr] comparable to rates in the Crater Flat basin. Modeled depths to burial of 50–250 m [164–820 ft] (O'Leary, et al., 2002) thus suggest an age range of approximately 3–12.5 Ma, although basaltic lavas must be younger than the likely basement of 11.45 ± 0.03 Ma Ammonia Tanks Tuff.

- P — Irregular anomaly with reversed-polarity magnetization along a possible northwest-trending alignment consisting of anomalies "P–R." Moderately strong magnetic signals (Figure 2-8) merge with similar strength analytic signal to north. Changes in anomaly shape in residual (Figure 2-7) and second vertical derivative filtered maps (Figure 2-9) suggest this anomaly may represent the southern extent of a generally north-trending bedrock feature. Similar features, however, are rare elsewhere on the anomaly maps. Low confidence that this anomaly represents buried basalt.

- Q — Isolated anomaly with reversed-polarity magnetization investigated with ground magnetic surveys (i.e., southwest northern cone of Magsino, et al., 1998). Strength of magnetic signal equivalent to anomalies "P" and "R," however, anomaly "Q" retains characteristic form in filtered maps. Dipole character may be obscured by magnetic anomaly of underlying tuffs or thinning of buried basalt to the northwest (e.g., Magsino, et al., 1998). Alluvium overlying causative body contains large amounts of tuff blocks, which increases the magnetic noise in the anomaly signal. Moderate

[2]Schier, B., Personal Communication. 1995.

confidence on the interpretation of buried basalt based on anomaly shape and relative intensity.

- R — Isolated anomaly with reversed-polarity magnetization along a possible northwest-trending alignment of anomalies "P–R." Relatively high survey altitude {i.e., 450 m [1,476 ft]} may have attenuated anomaly "R" relative to anomaly "P." Abuts a strong magnetic high on the northeastern sector, which may obscure anomaly shape and character. Magnetic signals appear isolated from adjacent bedrock as a discrete anomaly (Figure 2-8), although boundaries of anomaly are only broadly defined (Figures 2-7 and 2-9). Low confidence in interpretation of buried basalt due to shape and relatively small gradients.

- S — Strong, elongated, anomaly with reversed-polarity magnetization that corresponds to a mapped outcrop of reversed polarity 11.6 Ma Rainier Mesa Tuff (Frizzell and Shulters, 1990; Slate, et al., 2000). All evidence indicates that the anomaly is caused by Rainier Mesa Tuff and is not related to buried basalt.

- T — Irregular, 7-km [4.3-mi]-long anomaly with reversed-polarity magnetization in western Crater Flat. Anomaly amplitude may be attenuated by high altitude {>600 m [1,969 ft]} of survey measurements. Anomaly is interpreted as buried basaltic lavas of possible Miocene age (Langenheim, 1995; Fridrich, 1999; O'Leary, et al., 2002). Edges of anomaly are at least 1 km [0.6 mi] west of 11 Ma basaltic lavas in drill hole VH-2 (e.g., Carr and Parrish, 1985). Anomaly also does not correspond to eastern extent of buried basaltic lavas imaged seismically (Brocher, et al., 1998) between Little Cones and drill hole VH-1 (Figure 2-1). If anomaly "T" represents buried basalt, magnetic characteristics may be obscured by strongly magnetized rocks underlying the basalt (e.g., O'Leary, et al., 2002). Alternatively, the anomaly can be modeled as a relatively thick section of reversely magnetized Rainier Mesa Tuff that filled a north-trending topographic low next to the Bare Mountain fault zone (Stamatakos, et al., 2000). Low confidence in interpretation of buried basalt due to low intensity and lack of correlation between anomaly boundary and basalt in drill hole VH-2.

- 1 — Elongated anomaly with reversed-polarity magnetization identified by ground magnetic surveys in the Steve's Pass area (Magsino, et al., 1998). Amplitude of magnetic signals is consistent with buried basalt having a relatively strong remanent magnetization (Figure 2-8). Shape of anomaly may reflect disruption by nearby Carrara fault (Stamatakos, et al., 1997b; Slemmons, 1997; Slate, et al., 2000). High confidence in interpretation of buried basalt based on anomaly amplitude and morphology. Poorly resolved in aeromagnetic data, as discussed in previous sections of this report.

- 2 — Short wavelength anomaly with reversed-polarity magnetization identified by ground magnetic surveys in the Steve's Pass area (Magsino, et al., 1998). Strength of magnetic signal {peak-to-peak amplitude of 1700 nT [0.017 Gauss]} is consistent with buried basalt having relatively strong remanent magnetization. Not resolvable in aeromagnetic data. High confidence in interpretation of buried basalt based on ground magnetic mapping of the dipolar anomaly with a steep magnetic gradient.

- 3 — Isolated anomaly with normal-polarity magnetization identified through aeromagnetic survey data (Blakely, et al., 2000). Strength of magnetic signal

(Figure 2-8) and relatively consistent form in residual (Figure 2-7) and second vertical derivative maps (Figure 2-9) are consistent with the interpretation of buried basalt. Moderate confidence in interpretation, although the anomaly also could represent a block of welded tuff displaced by nearby faults. Location directly beneath the Big Dune sand dunes leads to the speculation that outcrops of the causative body may have formed traps for eolian sediments that form the dunes.

- 4 — Isolated anomaly with reversed-polarity magnetization located approximately 2 km [1 mi] west of anomaly "Q." Relatively high survey altitude {i.e., 5,000 m [16,405 ft]} may have attenuated anomaly "4" relative to anomaly "Q." Magnetic signals appear isolated from adjacent bedrock as a discrete anomaly (Figure 2-8), with relatively well-defined boundaries (Figures 2-7 and 2-9). Low confidence in interpretation of buried basalt due to relatively small gradients.

- Jackass Flat — A complex series of highly intense magnetic anomalies (Figure 2-8) that occur directly southwest of Miocene basalt outcrops in Jackass Flat. These anomalies are in the transition zone between the north-trending "Gravity fault" that defines the eastern boundary of the Crater Flat basin, and northeast-trending Mine Mountain faults (e.g., Slate, et al., 2000). Although the overall pattern of the anomalies appears to represent faulted ignimbrite deposits in a relay structure, several areas have prominent high-intensity anomalies that are accentuated in the second vertical derivative map (Figure 2-9). These areas may represent buried basalt, with the anomalies partially obscured by faulted bedrock ignimbrite. The structural complexities of the relay structure could have favored the localization of basaltic magma here. We suggest that this area has the highest likelihood of containing additional buried basaltic features east of the proposed repository site.

2.5 Evaluation of Known Basaltic Volcanoes

A straightforward method to evaluate the resolution limits of the aeromagnetic survey is to determine how well the survey detects known basaltic volcanoes. As discussed in previous sections of this report, approximately half of the known basaltic volcanoes in the Yucca Mountain region do not appear resolvable in the unfiltered aeromagnetic data (Figure 2-2). Applying standard filters to these data, however, could enhance the anomalies caused by known basaltic volcanoes. This section determines if the application of analytical filters enhances the detection limits of the Yucca Mountain region aeromagnetic survey.

Using the same relative criteria to interpret the aeromagnetic anomalies, we would have high confidence in the interpretation of basalt from these aeromagnetic data for only Black Cone and perhaps Lathrop Wells volcano. Basaltic rocks could be interpreted with moderate confidence for Red Cone and perhaps Little Cones based on the relative strength of the analytic signal (Figure 2-8) and second vertical derivative filtered maps (Figure 2-9). These Quaternary-age basalts, however, have a high remanent magnetization of 10–20 A/m [0.13–0.25 Oe] (e.g., Langenheim, 1995; Stamatakos, et al., 1997a). Other basalts in the Yucca Mountain region may have remanent magnetizations on order of 1 A/m [0.01 Oe] (e.g., O'Leary, et al., 2002). Based on observed aeromagnetic anomalies and associated filtered maps, however, we would assign low confidence to interpretations of basalt at Northern Cone, Pliocene Crater Flat, the shallow basalt located along the Yucca Mountain-Crater Flat seismic line (reflector "H," Brocher, et al., 1998), or the Miocene volcanic center in southern Crater Flat. As expected (e.g., Connor and Sanders, 1994), small but important dikes located at the headwalls of Solitario Canyon (e.g., Day, et al., 1998) or extending from the Miocene volcanic center in southern Crater Flat also are undetectable with the aeromagnetic survey technique. In essence, more than half of the known basaltic features in the Crater Flat basin cannot be resolved by the existing aeromagnetic data and standard analytical filtering techniques. These low resolution limits suggest that some relevant basaltic volcanoes may remain undetected in the Crater Flat basin. In other words, we presently lack a technical basis to refute the hypothesis that additional basaltic volcanoes may be present but undetected within the Crater Flat basin. In the following sections we provide results of a scoping calculation to address the potential implication of present but undetected volcanoes. To evaluate the potential significance of this uncertainty, we must first estimate how many volcanoes could reasonably be present but undetected within this area.

2.6 Method for Estimating Number of Present but Undetected Volcanoes

Estimating the number of basaltic volcanoes that could remain present but undetected within the Crater Flat basin is a highly subjective exercise. One approach is to use data from analogous Western Great Basin volcanic fields (e.g., Connor and Hill, 1994) to derive spatial densities of basaltic volcanoes. Using these spatial densities, we then can estimate the number of additional volcanoes that could be present but undetected in the Crater Flat basin in order to match the spatial density in analogous volcanic fields. This approach provides a transparent basis to evaluate the effects of uncertainty on probability and risk calculations. We recognize that other approaches to estimating this uncertainty may also be valid. We provide this approach as an example methodology.

Using data summarized in Connor and Hill (1994), spatial densities of Western Great Basin basaltic volcanic fields are approximately one volcano per 4 km^2 [1.5 mi^2] {i.e., 1v/4 km^2 [1v/1.5 mi^2]} in the Plio-Quaternary Cima volcanic field, 1v/16 km^2 [6.2 mi^2] in the Quaternary Big Pine volcanic field, 1v/6 km^2 [1v/2.3 mi^2] in the Quaternary Lunar Crater volcanic field, and 1v/8 km^2 [1v/3.1mi^2] in the Neogene Pancake Range volcanic field. The analog systems produced these spatial densities of volcanoes through 1 to 4 million years of activity. Although the Yucca Mountain region basaltic system has been active for 11 million years, this activity appears more episodic than continuous (e.g., Vaniman, et al., 1982; CRWMS M&O, 1996, 2000a; Smith, et al., 2002). Thus, comparable duration episodes of basaltic activity in the Yucca Mountain region could reasonably produce spatial densities of volcanoes that are comparable to the analog volcanic fields.

For comparison to the analog volcanic fields, we calculate that the entire 1,013 km^2 [391 mi^2] Crater Flat basin (Figure 2-10) has a spatial density of 1v/38 km^2 [1v/15 mi^2] represented by ten volcanic events and seventeen high-to-medium confidence magnetic anomalies. This spatial density of volcanoes in the Crater Flat basin is two-to-ten times lower than observed in other analogous Western Great Basin volcanic fields. Two alternative hypotheses are proposed to explain this low spatial density.

In the first hypothesis, Crater Flat basin is considered to represent the lower endmember of the range of spatial densities in Western Great Basin basaltic volcanic fields. This hypothesis does not require the presence of any additional undetected basaltic volcanoes in the Crater Flat

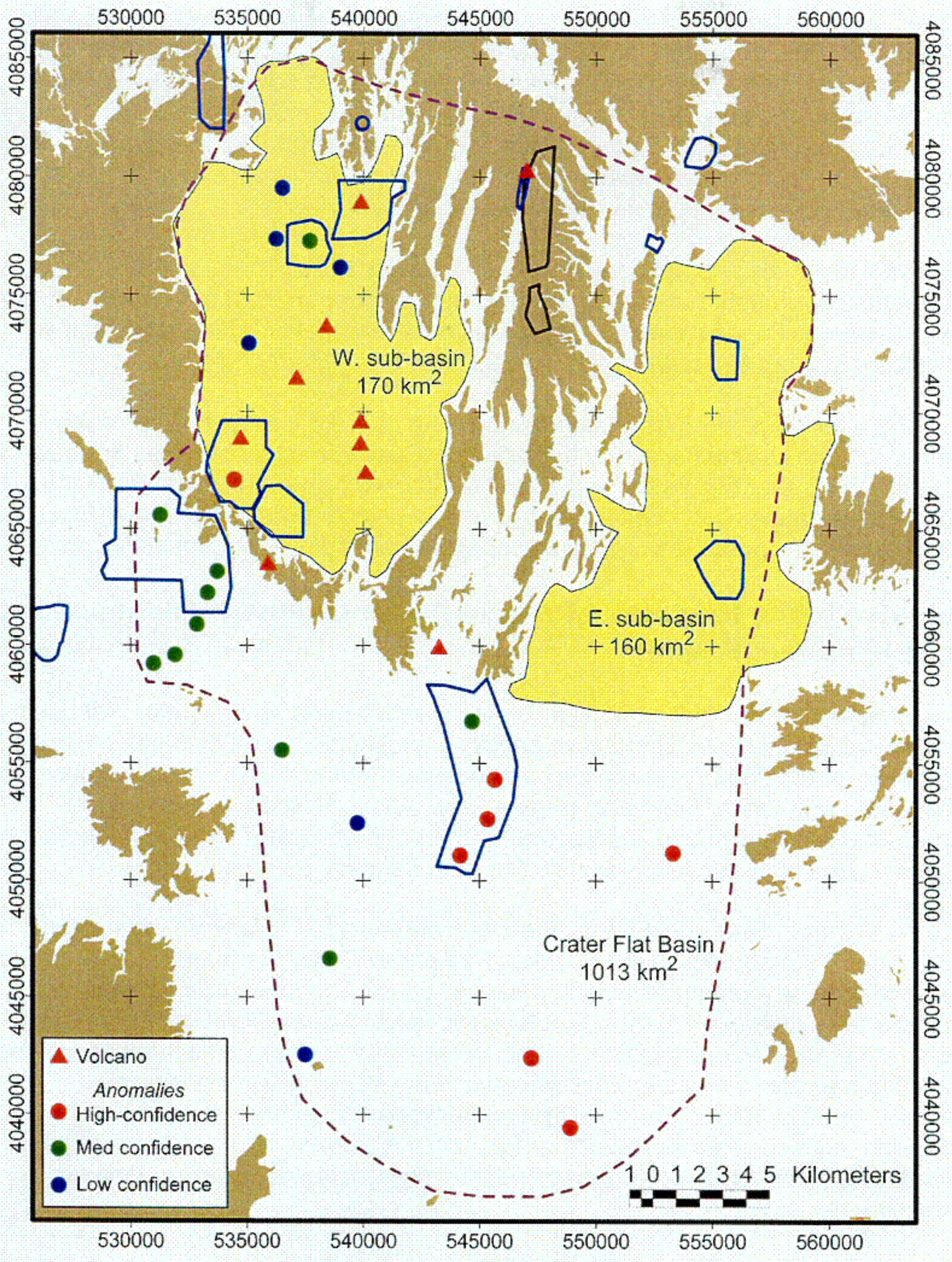

Figure 2-10. Extent of the Crater Flat Structural Basin Subjectively Outlined Based on Gravity Gradients (e.g., Figure 2-3) and Extent of <11 Ma basalt. Shaded Sub-Basins Defined by General Extent of Quaternary Alluvium that Could Possibly Conceal Buried Basaltic Volcanic Features. Confidence Levels for Interpreted Magnetic Anomalies (e.g., Figure 2-2) Shown in Colors, Bedrock Outcrops from Slate, et al. (2000), and CNWRA Ground Magnetic Survey Areas (Magsino, et al., 1998) Outlined in Blue.

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basin. Basaltic volcanism in the Crater Flat basin is long lived, relative to other analogous Western Great Basin basaltic volcanic fields (Vaniman, et al., 1982; Connor and Hill, 1994; Smith, et al., 2002). Although petrogenetic models have not been developed to explain this long duration of activity, we speculate that relatively low rates of crustal extension in the Crater Flat basin (e.g., Connor, et al., 2000) could result in relatively low rates of magma production and ascent. Thus, the relatively low spatial densities of volcanoes in the Crater Flat basin could be consistent with a long-duration, low-volume basaltic volcanic field.

In the alternative hypothesis, the apparent low spatial density of volcanoes in Crater Flat basin is too small because of present but undetected volcanoes. Support from this hypothesis comes from comparison with analogous Western Great Basin volcanic fields, which have spatial densities of volcanoes from two-to-ten times greater than in the Crater Flat basin.

We currently lack a technical basis to distinguish between these alternative hypotheses. Because we cannot rule out the possibility that additional basaltic volcanoes may be present but undetected within the Crater Flat basin, in the next section we provide an estimate of the number of basaltic volcanoes that could be buried and undetected within the Crater Flat basin. This estimate is then considered in the potential effects of uncertainty on probability models.

2.7 Estimates of the Number of Present but Undetected Volcanoes in the Yucca Mountain Region

The detection of basaltic volcanoes potentially buried in many parts of the Crater Flat basin is difficult due to the high amplitude, short wavelength anomalies produced by faulted Miocene tuffs (e.g., O'Leary, et al., 2002). Terrain avoidance further attenuated the aeromagnetic signal for much of the survey in Crater Flat basin (Figure 2-1). As discussed previously, approximately half of the known basaltic features in the northern Crater Flat basin cannot be detected using the existing Yucca Mountain region aeromagnetic data.

In contrast to the northern Crater Flat basin, the relatively low amplitude, long wavelength anomalies produced from bedrock in the southern half of the Crater Flat basin (i.e., Amargosa Desert) appear to provide a reasonable background to detect anomalies characteristic of shallowly buried basalt. Although there are no basaltic volcanoes exposed in the Amargosa Desert, ground magnetic surveys (Magsino, et al., 1998) have detected additional anomalies characteristic of buried basalt that were not detected in the Yucca Mountain region aeromagnetic survey. The lack of good calibration between known basaltic volcanoes and aeromagnetic anomalies throughout the Crater Flat basin indicates that in addition to the identified anomalies, more basaltic volcanoes could be present but undetected beneath alluvium in the Crater Flat basin.

The northern part of the Crater Flat basin can be divided into western and eastern alluvial sub-basins, which are separated by bedrock exposures of Yucca Mountain (Figure 2-10). These sub-basins contain tens-to-hundreds of meters thicknesses of alluvium, which could contain buried basaltic volcanoes. We recognize that the spatial density of volcanoes could be nonuniform within a sub-basin (e.g., Connor and Hill, 1995), but have no available technical basis to constrain spatio-temporal clustering of hypothesized events. We thus assume spatial densities are uniform within a sub-basin.

The western sub-basin has an area of 170 km^2 [65 mi^2], 20 km^2 [7.7 mi^2] of which has been characterized by ground magnetic surveys. The remaining 150 km^2 [58 mi^2] area in the western sub-basin contains eight volcanic events, by defining events as a single vent, localized vent complex (i.e., Pliocene Crater Flat represents three events, Little Cones is one event), or high-confidence magnetic anomaly. These eight volcanic events represent a spatial density of 1v/21 km^2 [1v/8.1mi^2] within the western sub-basin.

We can use the spatial densities of analog volcanic fields to estimate the possible number of buried but undetected volcanoes within a sub-basin. If we assume the western Crater Flat sub-basin should have a uniform but high spatial density of 1v/4 km^2 [1v/1.5mi^2], this 150 km^2 [58 mi^2] area should contain a total of thirty-eight volcanoes. Because eight volcanoes are known in the western sub-basin, thirty additional volcanoes would have to be buried in this sub-basin to create a spatial density of 1v/4 km^2 [1v/1.5 mi^2]. In contrast, assuming a lower spatial density of 1v/16 km^2 [1v/6.2 mi^2] (i.e., analogous to Big Pine volcanic field) would suggest only one to two additional volcanoes would be present but undetected within the western Crater Flat sub-basin. Thus, analog data suggest that one to thirty additional volcanoes could be present but undetected within the western Crater Flat sub-basin.

Although the eastern Crater Flat sub-basin (Figure 2-10) lacks surface expression of any Plio-Quaternary basaltic volcanism, this part of the Crater Flat basin is characterized by extensively faulted Miocene tuffs with complex aeromagnetic anomaly patterns. Because the degree of magnetic "noise" is comparable to that observed in the western sub-basin, additional basaltic volcanoes could be present but undetected within the eastern sub-basin.

Past patterns of recognized activity within the Crater Flat basin, however, show overall west-to-east decreases in volcano recurrence (e.g., Connor and Hill, 1995). Estimates of present but undetected events in the eastern basin thus should use assumed spatial densities that are lower than used for the western sub-basin. The 170 km^2 [66 mi^2] eastern sub-basin has 6 km^2 [2.3 mi^2] characterized by ground magnetic surveys (Figure 2-10).

Using a spatial density of 1v/16 km^2 [1v/6.2 mi^2], ten volcanoes could be present but undetected in the eastern basin. If we assume the eastern Crater Flat sub-basin should have a uniform but high spatial density of 1v/16 km^2 [1v/6.2 mi^2], this 164 km^2 [63 mi^2] area should contain a total of ten volcanoes. Decreasing the spatial density by an order of magnitude, which is comparable to the decrease in overall recurrence between the western and eastern sub-basins (e.g., Connor, et al., 2000), suggests one additional volcano might be present but undetected in the eastern sub-basin.

In conclusion, if we assume the spatial density of volcanoes in the Crater Flat basin should be analogous to analogous Western Great Basin volcanic fields (i.e., Smith, et al., 2002), one to thirty additional volcanoes could be present but undetected within the basin. Conversely, the relatively low observed spatial density of volcanoes within the Crater Flat basin may indeed represent the low end of a range of spatial densities for Western Great Basin volcanic fields. In this case, there is no requirement for any additional present but undetected volcanoes within the basin. Currently, there is no technical basis to distinguish between these alternative hypotheses. Additional information, such as forward modeling of aeromagnetic survey data to quantify detection limits, is needed to test these alternative hypotheses further.

2.8 Potential Effects on Probability Models

Probability models for future volcanic eruptions in the Yucca Mountain region depend on the timing and location of past igneous events to define recurrence rates (e.g., Crowe, et al., 1982; Ho, 1991; Connor and Hill, 1995; CRWMS M&O, 1996; Ho and Smith, 1998; Connor, et al., 2000; CRWMS M&O, 2000a). These models generally assume that volcano recurrence rates are steady and that past patterns of activity constrain future recurrence rates. Uncertainties in the age and location of past volcanic activity directly affect the uncertainty in probability calculations. Probability model uncertainties also arise due to complexities in the definition of an igneous event, times of interest, and possible incorporation of geologic processes into numerical models (e.g., NRC, 1999). Uncertainties in current probability calculations are largely driven by epistemic uncertainty in the modeling approach, rather than aleatory uncertainty in model parameters such as age and location (e.g., CRWMS M&O, 1996; Ho and Smith, 1997; Connor, et al., 2000).

A substantial number of uncharacterized volcanoes in the Yucca Mountain region could affect probability models in several ways, depending on the presumed ages of these volcanoes. The volcano ages could be uniformly distributed through time, indicating a steady recurrence rate rather than episodic recurrence averaged over a long interval of time (e.g., CRWMS M&O, 2000a). Conversely, these uncharacterized events may have all occurred at the same time, perhaps coincident with a recognized episode of activity. Recurrence rates could increase significantly if the uncharacterized events clustered in time. The uncharacterized volcanoes could also represent new episodes or compositional types, reflecting important changes in the basaltic magma system (e.g., Smith, et al., 2002). These uncertainties could directly affect the technical basis used to construct the probability models, or suggest that the models could not accurately forecast the timing and location of future basaltic activity (e.g., Condit and Connor, 1996). Without direct age determinations and geochemical analyses, it is impossible to evaluate all the potential effects of uncharacterized volcanoes on current probability models accurately.

Nevertheless, we propose several alternative hypotheses regarding the potential age and character of likely buried basalts represented by the high to medium confidence magnetic anomalies. We then can use these age hypotheses to estimate the potential effects on recurrence rates within the framework of current probability models. Because many of the current probability models are dependent on the location and the timing of past volcanic events, a more thorough evaluation of potential effects will require extensive calculations.

Of the twenty anomalies identified in O'Leary, et al. (2002), seven were characterized as buried basaltic volcanoes at the time of the DOE probabilistic volcanic hazards assessment (CRWMS M&O, 1996). Of these seven, three anomalies ("A, F, G") were given low likelihood by most DOE experts as representing buried basalt (Table 2-1). Defining igneous events as individual volcanoes generally yielded thirteen-to-fifteen Plio-Quaternary events within the Crater Flat basin, including the seven buried volcanoes (CRWMS M&O, 1996). Defining events as alignments of similar age volcanoes generally resulted in five-to-nine events. Although many DOE probabilistic volcanic hazards assessment experts used a subset of these data to define volcanic source zones or recurrence rates, approximately five-to-fifteen igneous events could have been used in the DOE probabilistic volcanic hazards assessment for the Crater Flat basin.

Thirteen additional anomalies were identified by O'Leary, et al. (2002) after the DOE probabilistic volcanic hazards assessment. Seven of these anomalies have moderate to high confidence for being caused by buried basaltic volcanoes. In addition, three additional magnetic anomalies are discussed herein, which also have moderate confidence for being caused by buried basaltic volcanoes (Table 2-1). These ten anomalies may represent ten individual buried basaltic volcanoes, or six-to-eight events of aligned volcanoes. The post-probabilistic volcanic hazards assessment aeromagnetic and ground magnetic surveys thus may represent six to ten igneous events, which would approximately double the number of igneous events evaluated in the DOE probabilistic volcanic hazards assessment (CRWMS M&O, 1996).

Each of the ten experts in CRWMS M&O (1996) used different combinations of event counts, source zones, and time intervals to define a range of recurrence parameters, which are not explicitly quantified in CRWMS M&O (1996). Assuming the ten magnetic anomalies represent buried basaltic volcanoes, there are three primary hypotheses that bound the possible effects volcano age on DOE probability models:

- These ten volcanoes might represent eruptions older than about 5 Ma. The DOE panel did not consider volcanoes older than 5 Ma in most probability models, thus, there would be no impact on current DOE models for this age hypothesis. However, there is no technical basis to conclude that any of these anomalies represent basalt older than 5 Ma, and it is impossible to predict how the presence of ten additional >5 Ma volcanoes would have influenced DOE model development.

- These ten volcanoes may have formed at uniform rates between about 2 Ma and 5 Ma. This hypothesis would increase volcano recurrence rates by approximately three volcanic events/million years (3 v/my), essentially doubling the estimated range of 1–3 v/my used in CRWMS M&O (1996).

- These ten volcanoes may have formed in a single episode of intense activity, comparable to other Western Great Basin volcanic fields (e.g., Foland and Bergman, 1992; Yogodzinski, et al., 1996). Assuming the age of this activity was 4 Ma, these ten events would combine with the four-to-ten recognized Pliocene events to give volcanic recurrence rates of 14–20 v/my. This hypothesis thus could result in an approximate order of magnitude increases in the volcanic recurrence rates used in CRWMS M&O (1996).

Without accurate age information on the potential buried basalts, the effect on strictly temporal (as opposed to spatio-temporal) recurrence could range from negligible (e.g., Bechtel SAIC Company, LLC, 2001) to an order of magnitude increase in DOE probability models. The effect this uncertainty in recurrence rate has on DOE probability values, however, must be calculated directly from the individual expert's probability models. Changes in recurrence rate may not affect DOE spatio-temporal probability models linearly, as the location as well as the timing of past volcanic events controls the probability calculation.

Volcanic recurrence rates used in Connor and Hill (1995), NRC (1999), and Connor, et al. (2000) generally range from 1–10 v/my, although rates as high as 12 v/my were occasionally used. These recurrence rates apply to events defined as individual volcanoes, volcanic clusters, and volcanic alignments. The same three alternative age hypothesis can be applied to these models:

- Assuming the buried volcanoes represented eruptions >5 Ma, there would be only minor effects on probability calculations due to the generally low weight given to older volcanoes in the spatio-temporal models.

- Distributing ten additional volcanoes between 2–5 Ma would add 3 v/my to typical Plio-Quaternary recurrence rates of 3–5 v/my, potentially doubling the average recurrence rate.

- Adding ten 4 Ma volcanoes to a Pliocene recurrence rate of 5 v/my could triple the temporal recurrence rate to 15 v/my.

Changes in recurrence rate may not affect these spatio-temporal probability models linearly (e.g., Connor and Hill, 1995; Connor, et al., 2000). The effects these recurrence rate uncertainties have on these probability models also will need to be calculated directly, using alternative hypotheses for both the ages and locations of buried volcanoes. In the absence of detailed calculations, we can conclude only that temporal recurrence rate may be uncertain to a factor of one to ten. This uncertainty may, but is not required to, affect probability models by a similar factor.

Several additional points must be considered in assessing the potential effects of additional uncharacterized volcanoes on probability models. First, the proposed repository designs used to support the DOE site recommendation (e.g., Bechtel SAIC Company, LLC, 2001) increase the repository footprint area southwards by a factor of 1.3 relative to calculations in CRWMS M&O (1996, 2000a) and Connor, et al. (2000). This increase should result in a proportional increase in the probability of igneous events intersecting the proposed repository. Uncertainties in volcanic recurrence rates should be scaled upwards due to this proposed increase in repository area. Second, the preceding analyses have not considered any potential effects from additional volcanoes that could remain present but undetected in the Crater Flat basin. Although one hypothesis is that there are no present but undetected volcanoes in this basin, an alternative and equally valid hypothesis is that there could be on order of ten additional undetected volcanoes within the Crater Flat basin. Additional work is necessary to evaluate these hypotheses, and provide a defensible technical basis for uncertainty analyses and licensing decisions.

2.9 Is the DOE Probabilistic Volcanic Hazards Assessment Elicitation Still Useful?

Since the 1995 DOE elicitation, new models and data have been developed for the Yucca Mountain region that would likely affect an independent expert's understanding and modeling of coupled tectonic and magmatic processes. In addition to the ground magnetic and aeromagnetic surveys discussed herein, these data include:

- Detailed geologic mapping of the bedrock geology and structures at the proposed site (e.g., Day, et al., 1998) and in the northern Crater Flat basin (e.g., Carr, et al., 1996; Fridrich, et al., 1999a).

- Seismic reflection lines through Crater Flat and Yucca Mountain (Brocher, et al., 1996; 1998; Langenheim and Ponce, 1995).

- Integrated gravity maps (McCafferty and Grauch, 1997; Ponce, et al., 1999; Ponce, et al., 2001) and associated depth-to-basement interpretations.

- Integrated regional aeromagnetic surveys (McCafferty and Grauch, 1997; Ponce, 1999; Ponce and Blakely, 2001).

- Strain rate and stress distribution studies and the potential effects on volcanic recurrence rates (e.g., Minor, 1995; Morris, et al., 1996; Minor, et al., 1997; Bennett, et al., 1997; Wernicke, et al., 1998; Savage, et al., 1998, 2001; Connor, et al., 1999; Fridrich, et al., 1999b; Pezzopane, et al., 1999; Ferrill, et al., 1999a).

- Tectonic models for the Yucca Mountain region (e.g., O'Leary, 1996; Serpa and Pavlis, 1996; Ferrill, et al., 1996, 1997; Schweickert and Lahren, 1997; Hoisch, et al., 1997; Stamatakos, et al., 1997b; Slemmons, 1997; CRWMS M&O, 1998; Stamatakos and Ferrill, 1998; Ferrill, et al, 1998; Stamatakos, et al., 1998; Fridrich, 1999; Ferrill, et al., 1999b; Connor, et al., 2000; Stamatakos, et al., 2000; Snow and Wernicke, 2000).

- Petrologic models for the development and evolution of Yucca Mountain region and potentially analogous volcanic fields in the western Great Basin (e.g., Fleck, et al., 1996; Yogodzinski, et al., 1996; Heizler, et al., 1999; Wang, et al., 2002; Smith, et al., 2002).

- Probability models for the formation of new basaltic volcanoes (Ho, 1995; Condit and Connor, 1996; Ho and Smith, 1997; Conway, et al., 1997; Ho and Smith, 1998; Connor, et al., 2000).

We cannot readily evaluate how the current uncertainties in volcanic recurrence rates expressed by the aeromagnetic data would affect probability models developed before this information was available. In addition, the scope and magnitude of the information discussed above have the potential to affect probability model development and parameter estimation for the Yucca Mountain region and the proposed repository site. Although these potential effects cannot be simply quantified, they must be addressed by the DOE in any model used to support a possible license application.

As part of the finalization of NUREG-1563 (Kotra et al., 1996), DOE noted that it was in substantial agreement with the guidance set forth in this technical position, including the provision to update elicited judgments, when warranted, based on the availability of new data or information (Op cit., p. 30). Although DOE integrated NUREG-1563 into its administrative procedures for conducting expert elicitations, it is not apparent to the staff how DOE will evaluate the new aeromagnetic survey data and other information discussed above in the context of the existing probabilistic volcanic hazards assessment, including the extent to which the original probabilistic volcanic hazards assessment authors would be involved in the decision-making concerning the potential need to update their original elicited judgments.

3 CONCLUSIONS AND RECOMMENDATIONS

Sufficient evidence exists to strongly support the hypothesis that at least ten additional basaltic volcanoes are represented by newly recognized aeromagnetic anomalies in the Yucca Mountain region. The first-order effect of these volcanoes on probability models could range from negligible, to an order of magnitude increases in volcanic recurrence rates. To address this uncertainty, we recommend that:

- The effects of multiple alternative hypotheses for the ages of these volcanoes should be quantified accurately for probability models potentially used in licensing decisions. Sedimentation rates are too variable to distinguish between buried Pliocene and Miocene age basalt reasonably.

- A technical basis should be developed by the DOE to support the interpretation that low-confidence anomalies do not represent buried basalt.

- Petrologic models should be developed for basaltic volcanism in the Crater Flat basin. These models should evaluate the geologic processes that lead to the production, accumulation, and ascent of basaltic magma in the region, and determine how these processes may influence igneous recurrence rates during the next 10,000 years.

- If the cumulative effects of age and petrogenetic uncertainty affect risk significantly, samples of the likely basalts should be obtained by the DOE, dated, and analyzed for standard elemental and isotopic composition.

- Ground magnetic surveys should be extended southwards in the Steve's Pass area to cover anomalies "L–O." These data will provide a complete, high-resolution survey of likely buried basalt overlying faulted ignimbrites. This survey will provide essential information for staff evaluation of models and data the DOE will likely develop to address fundamental uncertainties affecting the probability models.

- Additional ground magnetic surveys are needed to reduce uncertainties in the interpretation that low confidence anomalies "J," "K," and "R" likely represent bedrock features rather than buried basalt. Previous CNWRA ground magnetic surveys did not cover anomalies potentially representing buried basalt as interpreted in O'Leary, et al. (2002).

At this time, there is insufficient technical basis to conclude that no additional basaltic volcanoes could remain present but undetected within the Crater Flat basin, including areas located east of the proposed repository site. To address this uncertainty, we recommend that:

- The DOE should quantify the resolution limits of the currently available characterization methods through advanced modeling, including testing against known basaltic features in the Crater Flat basin.

- Additional site characterization activities, such as ground magnetic surveys, should be conducted in eastern Jackass Flat as the presence of Pliocene or younger buried basalt in that area would invalidate fundamental assumptions in most DOE probability models.

- A technical basis should be developed by the DOE to assess how many additional basaltic volcanoes could be present but undetected within the Crater Flat basin. If the results of this analysis indicated additional volcanoes are possible, the effects of this uncertainty should be incorporated in DOE probability models.

Since the 1995 DOE probabilistic volcanic hazards assessment elicitation, new models and data have been developed that are relevant to understanding the volcanic history of the Yucca Mountain region. The aeromagnetic data discussed in this report also represent multiple working hypotheses for basaltic volcanism in the Yucca Mountain region, each of which appears capable of influencing conceptual model development. Many of the components in the DOE probabilistic volcanic hazards assessment elicitation are subjective and open to interpretation. As such, we cannot readily evaluate the effects that this abundance of new information could have on elicited models or parameter ranges. We recommend that the DOE update the original probabilistic volcanic hazards assessment to include new information developed since the 1995 elicitation.

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