CNWRA 96-002

GROUND MAGNETIC SURVEY OF THE LITTLE CONES, CRATER FLAT, NEVADA

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

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ABSTRACT

A ground magnetic survey was made at the Little Cones, two Quaternary basaltic cinder cones in Crater Flat, located approximately 15 km southwest of the proposed high-level radioactive waste (HLW) repository site at Yucca Mountain (YM). A primary goal of this survey was to evaluate the utility of ground magnetic data for characterizing igneous intrusions and related structures at small-volume basaltic volcanoes in the YM region. This activity was undertaken because two Key Technical Uncertainties (KTUs) associated with volcanism,

- Low resolution of exploration techniques to detect and evaluate igneous features and
- Inability to characterize many igneous features and events,

will likely have a strong impact on volcanic hazard assessments made as part of the license application review. These KTUs exist because surface geological studies of volcanism provide an incomplete and necessarily biased view of the extent of igneous activity in the YM region. Application of ground magnetic methods can reduce these KTUs and thereby reduce the number of conservative assumptions necessary to meet siting criteria described in 10 CFR Part 60 122(a)(2)(ii).

A total of 2,891 ground magnetic observations were made during a 5-d sampling period in May 1995 using a proton-precession magnetometer. Based on the results of this survey, two areas were surveyed at a higher resolution in September 1995 using an optically pumped cesium-vapor magnetometer.

Three aspects of the magnetic survey were investigated in detail:

- A reversed, dipolar anomaly centered on NE Little Cone
- The subsurface extent of lava flows revealed by the magnetic map, particularly north of NE Little Cone
- An anomaly northeast of NE Little Cone that is interpreted to be related to a vent or shallow intrusion

Modeling and map filtering of a reversely magnetized dipolar anomaly at NE Little Cone indicates that this cone consists of agglutinate spatter or welded scoria deposited above the Curie-point blocking temperature, beneath a mantle of unconsolidated pyroclastic material that is likely less than 5 m thick. Such welding occurs in spatter mounds as a result of high-effusion rate of lavas and low eruption column height, different eruption characteristics than are indicated by deposits at SW Little Cone.

Lava flows do not crop out around the Little Cones except south of SW Little Cone. The presence of large-amplitude short-wavelength anomalies, however, indicates that lava flows are present around both cones, but are buried by alluvium. The high-resolution magnetic survey delineates the lava flow margin 300 m north of NE Little Cone. Modeling of this anomaly using polygonal prisms suggests that the indurated interior of the lava flow is approximately 10 m thick and is buried at a depth of 15 m. The area of the lava flow field within the survey area is approximately 1±0.1 km^2, but lava flows also extend south of the survey area. If the lava flow averages 10 m in thickness, the volume of the flow field within the

survey area is approximately 1×10^7 m^3, or about 10 times the volume of the cones. This lava flow field was not identified by earlier aeromagnetic surveys.

A negative anomaly, >1,000 nT in amplitude, is located 250 m northeast of the summit of NE Little Cone. This anomaly has a wavelength of approximately 80 m, much longer than other anomalies associated with the buried lava flow surface. An 80-m-long, 15-m-wide vertical prism having strong remanent magnetization and extending from the base of the lava flow to great depth explains this anomaly. This geometry is consistent with a shallow dike and/or buried vent. This shallow dike is located on the NE-trend of the Crater Flat cinder cone alignment. One interpretation based on these observations and models is that vents were distributed along a NE-trending zone early in the eruption, then coalesced to build the two Little Cones as the eruption progressed, feeding the extensive lava flow field about the two cones.

Results of this survey indicate that a great deal can be learned about the volume, distribution, and volcanology of cinder cones and related features in the YM region using inexpensive ground magnetic surveys. It is recommended that ground magnetic surveys be made in other areas near YM in order to bound assumptions about Plio-Quaternary volcanism used in license review.

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FIGURES

FIGURES (Cont'd)

ACKNOWLEDGMENTS

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: CNWRA-generated original data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: The EarthVision and ARC/INFO computer codes were used for analyses contained in this report. These computer codes are controlled under the CNWRA Software Configuration Procedures. This report describes the development of a computer code for calculation of magnetic anomalies due to polygonal prisms. However, the code has not been sufficiently developed to be placed under the CNWRA Configuration Management system.

1 INTRODUCTION

The proposed high-level waste (HLW) repository at Yucca Mountain (YM), Nevada, is located within a geologically active volcanic field. This volcanic field consists of eight basaltic cinder cones formed by volcanic activity within the last 1 m.y., and numerous cinder cones and lava flows formed within the last 5 m.y. (Figure 1-1) (Faulds et al., 1994; Bradshaw and Smith, 1994; Champion, 1991; Heizler et al., 1994). As is typical for volcanic fields of this kind located throughout western North America, volcanic activity in the YM region is best characterized by the formation of new basaltic volcanoes at a low recurrence rate. Recent estimates of the probability of a new basaltic cinder cone forming within the area of the proposed repository are $1\text{–}5\times10^{-4}$ for a 10,000-yr period (Crowe and Perry, 1989; Ho et al., 1991; Smith et al., 1990; Margulies et al., 1992; Connor and Hill, 1995). Although probability estimates have relatively large uncertainties and will likely be refined, current estimates are high enough to be of regulatory concern and must be addressed in performance assessment.

Estimates of the probability of volcanic disruption of the candidate repository are strongly affected by the volume, orientation, shape, and frequency of intrusions associated with volcanic events. These factors are represented by an area term included in all probability models. If, for example, volcanic events are considered to be very spatially limited phenomenon, then the probability of volcanic disruption of the candidate repository is less for a given recurrence rate than if the area affected by an individual volcanic event is large. Consequently, it is important to estimate the area impacted by individual volcanic events in the YM region in as much detail as possible. Current estimates of this area term are based on assumptions about intrusion geometries that may not be conservative (e.g., Barr et al., 1993; Lin et al., 1993; Wilson et al., 1994).

This report presents results of a ground magnetic survey made at the Little Cones, two Quaternary basaltic cinder cones located in Crater Flat approximately 15 km southwest of the proposed repository site (Figure 1-1). The goals of this survey were to:

- Evaluate the utility of ground magnetic data for characterizing intrusions and related structures at basaltic volcanoes
- Identify intrusions and related volcanic features associated with the formation of the Little Cones
- If possible, estimate the subsurface area disrupted by the Little Cones eruption

The results of this ground magnetic survey provide an indication of the utility of high-resolution ground magnetic surveys for elucidating the volcanic history of known volcanic features, such as the Little Cones. Furthermore, interpretation of the ground magnetic survey using a variety of map filtering and forward modeling techniques indicates that collection of these data is essential in order to assess the true extent of volcanism in the YM region. Results of such magnetic surveys and interpretation of these data can be used to refine estimates of area terms used in probability models for volcanic hazard assessment.

1.1 REGULATORY BASIS

Insight into the frequency, distribution, and volume of basaltic magmatism in the YM region, the repository and regional scales of volcanic effects, and the relationships between volcanism and regional

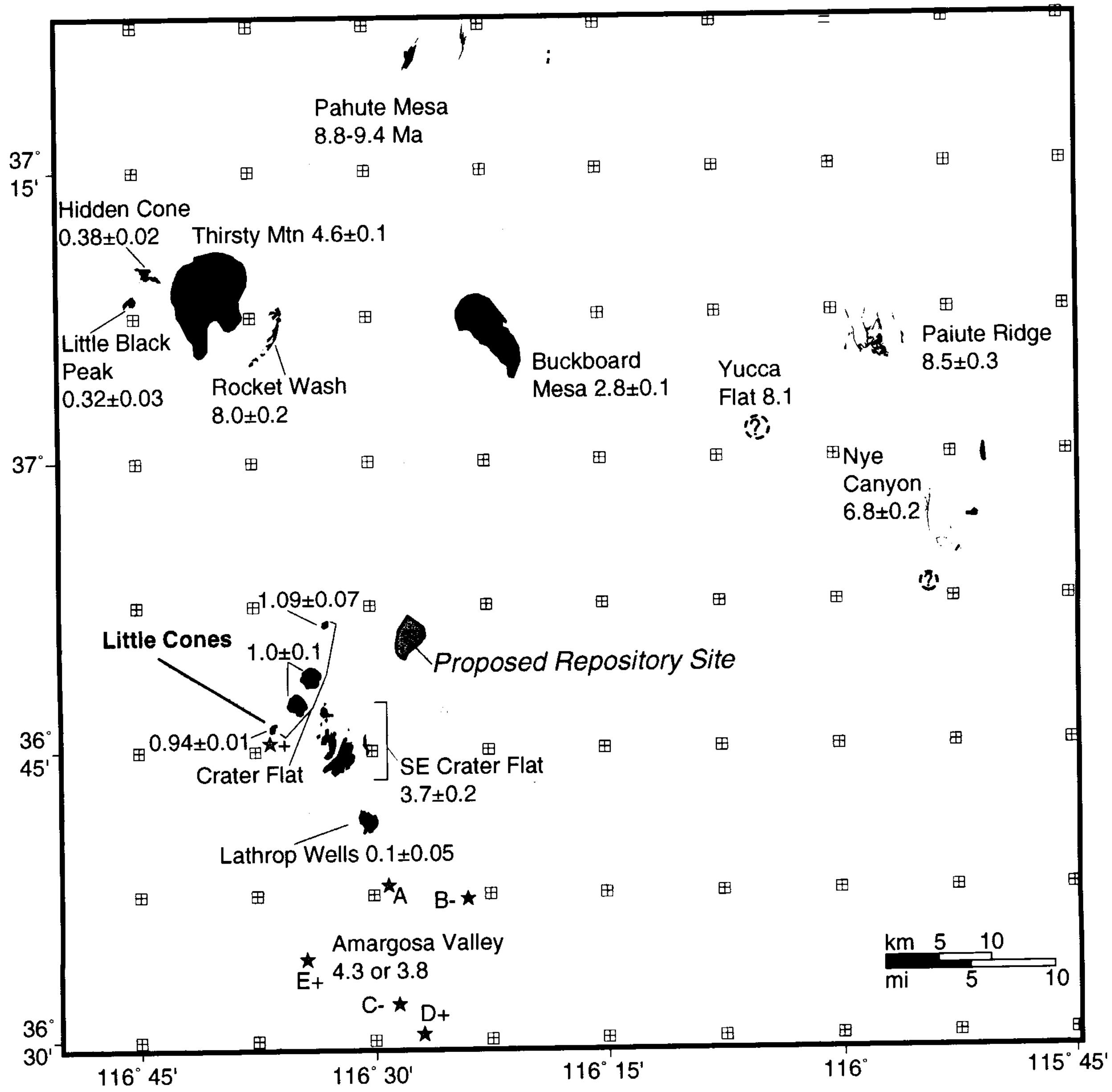

Figure 1-1. Basaltic vents, lavas, and known intrusions in the YM region younger than about 9 Ma. Geology compiled from Byers et al. (1966); Ekren et al. (1966); Carr and Quinlivan (1966); Byers and Barnes (1967); Byers and Cummings (1967); Hinrichs et al. (1967); Noble et al. (1967); Tschanz and Pampeyan (1970); Cornwall (1972); Crowe et al. (1983; 1986); Carr (1984); Swadley and Carr (1987); and Faulds et al. (1994). Locations of aeromagnetic anomalies (stars) from Kane and Bracken (1983) and Langenheim et al. (1993). Little Cones are located in southern Crater Flat. Universal Transverse Mercator projection, Nevada zone 11, NAD 1983 datum. Modified from Connor and Hill (1995).

tectonic and structural settings, form an integral part of license review. Volcanism must be reviewed in terms of site characterization as described in the License Application Review Plan (LARP). These activities include review of evidence of igneous activity as a potentially adverse condition (LARP Section 3.2.1.9), review of the impact of volcanism on groundwater movement (LARP Section 3.2.2.7), and description of overall system performance (LARP Section 6.1).

The Compliance Determination Strategy (CDS) associated with evidence of Quaternary igneous activity is of Type 5, indicating that independent research must be conducted to evaluate Key Technical Uncertainties (KTUs) associated with volcanism, and that volcanism poses a high risk to the Nuclear Regulatory Commission (NRC) of reaching unwarranted conclusions about compliance with 40 CFR Part 191 and 10 CFR Part 60.122(c)(15).

Igneous activity is considered to be a Key Technical Issue (KTI) by the NRC. The magnetic survey of the Little Cones was made to partially address several KTUs associated with this issue. These include:

- Low resolution of exploration techniques to detect and evaluate igneous features (Type 4)
- Inability to characterize many igneous features and events (Type 5)
- Probability of igneous activity and resulting disruption of the candidate repository site (Type 5)
- Consequences of igneous activity for repository performance (Type 5)

Clearly each of these KTUs cannot be resolved based on the results of a single magnetic survey. However, the techniques used in this magnetic survey of the Little Cones provide significant insight into the ways in which commonly available geophysical techniques may be used to reduce the impact of KTUs on models of the probability and consequences of igneous activity.

1.2 ORGANIZATION OF THIS REPORT

The results and geological interpretation of the ground magnetic surveys are presented in Section 2 of this report. In Section 3, the regulatory significance of the results of the field survey of Little Cones is discussed. References cited throughout the text are given in Section 4. Much of the magnetic survey results are provided in Plate 1 (inside back cover). Drift-corrected magnetic data and the results of map filtering of these data are provided in Appendix A.

2 RESULTS OF THE GROUND MAGNETIC SURVEY

The two Little Cones are small pyroclastic cones located in the southern part of Crater Flat. The Little Cones were selected for the ground magnetic survey because these cinder cones are small and are located in the most accessible part of Crater Flat, simplifying survey logistics. As few lava flows crop out around the Little Cones, it was believed that magnetic surveys of these cones would provide an opportunity to identify intrusions associated with Quaternary volcanism in Crater Flat. Lava flows associated with Red Cone and Black Cone in Crater Flat produce substantial magnetic anomalies that mask anomalies produced by intrusions.

2.1 GEOLOGY OF THE LITTLE CONES

The Little Cones are the southernmost of five Quaternary cinder cones in a 12-km-long alignment that trends north-northeast across the valley and includes Red Cone, Black Cone, and Northern Cone (Figure 2-1). This alignment is arcuate: the azimuth at the north end of the alignment, between Black Cone and Northern Cone, is approximately 025°; the azimuth at the southern end of the alignment, between the Little Cones and Red Cone, is approximately 040°.

2.1.1 Geologic Setting of the Little Cones

NE and SW Little Cones are located near the main axis of deposition in Crater Flat on a broad alluvial surface that slopes gently to the south (Figure 2-2). Faulds et al. (1994) referred to this alluvium as the Quaternary Little Cones Alluvium and described it as fan skirt and low basin remnants of Late Pleistocene to Holocene age. Faulds et al. (1994) report ^{14}C rock-varnish ages on alluvial material of this deposit of 6,645±245 and 11,135±105 yBP. Except for active washes, this alluvial surface is the youngest in Crater Flat.

No faults have been mapped on this young alluvial surface (Faulds et al., 1994). The nearest mapped fault to the Little Cones is the north-northwest-trending Bare Mountain Fault, located approximately 1.5 km west of SW Little Cone. The Bare Mountain Fault has been active since the Miocene and has accumulated more than 2 km of slip (Snyder and Carr, 1984). Trenching studies along the Bare Mountain Fault (Klinger and Anderson, 1994; Reheis, 1988) as well as analyses of the distribution of alluvial fan deposits (Ferrill et al., 1995) document Bare Mountain Fault slip in the Holocene. Slip rate on the Bare Mountain Fault is approximately 0.16 mm/yr, based on fission track analyses of apatites collected on Bare Mountain (Spivey et al., 1995). The Bare Mountain Fault dips eastward beneath Crater Flat. Assuming an average dip of 60° along the shallow portion of the Bare Mountain Fault (Ferrill et al., 1995), the fault crosses beneath the Little Cones at a depth of approximately 2.5 km, or less if the fault dip shallows over this distance. Numerous north-trending faults cut older Quaternary alluvial surfaces in western Crater Flat (Faulds et al., 1994). These mapped faults are near-vertical or are steeply dipping and do not likely project beneath the Little Cones.

Aeromagnetic anomalies have a pronounced north-trend in Crater Flat (Kane and Bracken, 1983), consistent with the presence of buried north-trending faults. The Quaternary Crater Flat cinder cone alignment is positioned at a transition from comparatively low magnetic gradients to the west and high magnetic gradients produced by shallow Miocene ignimbrites to the east (Figure 2-1). This change in magnetic gradient, combined with the north-trend of aeromagnetic anomalies and mapped structures elsewhere in the valley, suggest that basement structure may influence the position and development of

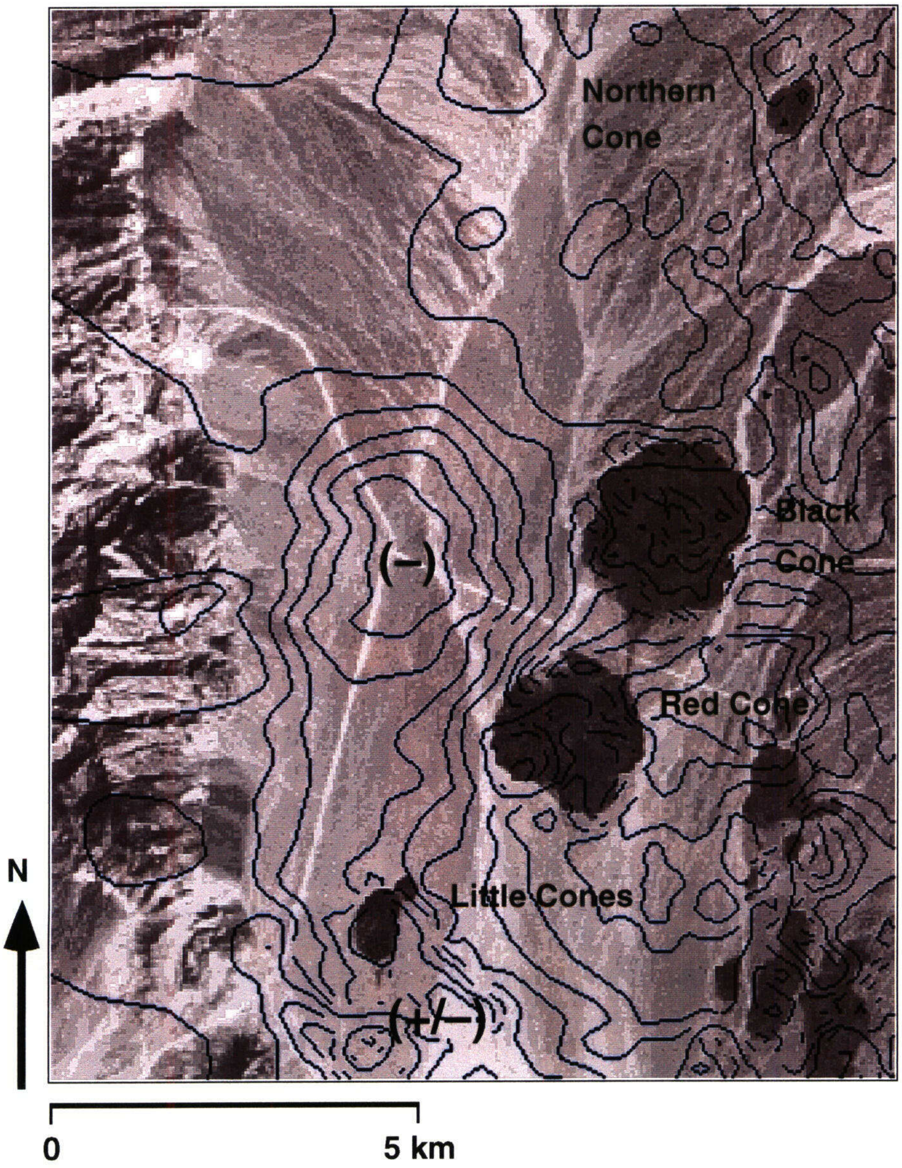

Figure 2-1. Aeromagnetic data from Kane and Bracken (1983) is superimposed on a LandSat TM Band 3 image of Crater Flat. Contour interval is 50 nT and contours are broken in areas with high magnetic gradients.

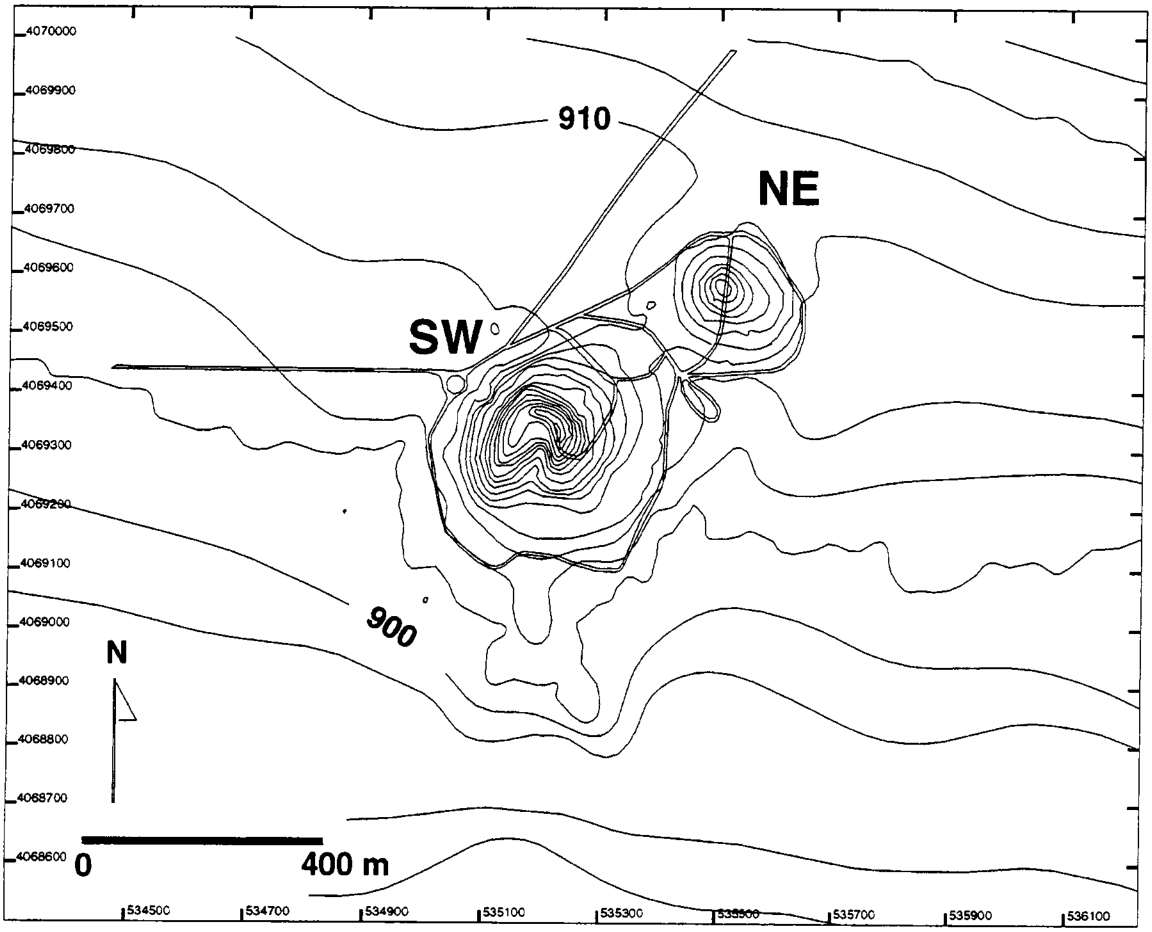

Figure 2-2. Topographic map of the NE and SW Little Cones. Topography was surveyed using plane table and alidade methods during May 1995, and referenced to U.S. Geological Survey 30-m digital elevation data. Contour interval is 2.5 m, dirt roads in the area of the two cones are indicated.

the Quaternary Crater Flat cinder cone alignment. The exact nature of this influence is not yet known and requires a more complete understanding of possible kinematic and mechanical interactions between faulting and magma ascent.

On local scales, very high gradients in the aeromagnetic data occur at Red Cone, Black Cone, and a set of Pliocene dikes, lavas, and vents in southeast Crater Flat (Figure 2-1). Small-amplitude, reversely polarized aeromagnetic anomalies are expressed at Northern Cone and SW Little Cone.

Other prominent magnetic anomalies in Crater Flat are not associated with mapped basalts. A comparatively large-amplitude anomaly is mapped south of the Little Cones. This anomaly is of unknown origin, but given its steep magnetic gradient, it is likely produced by shallow, highly magnetic rock, possibly of volcanic origin (Crowe et al., 1986). Several anomalies occur north of Black Cone, including an elongate magnetic low that is colinear with the alignment and several dipolar anomalies. These anomalies are comparable in size and amplitude to the aeromagnetic anomalies associated with SW Little Cone and Northern Cone, and may be produced by shallow dikes or buried volcanic rocks.

2.1.2 Physical Features and Age of the Little Cones

The highest points on the two cones are separated by 360 m along an azimuth of 052° (Figure 2-2). NE Little Cone is a low, undissected mound of cinders and bombs that is 230 m in diameter, 15 m in height, and 170,000 m^3 in volume. NE Little Cone is slightly elongate in an east-west direction. The western slope of the cone is the steepest; a small topographic depression occurs low on its south flank. A small outcrop of indurated lava caps NE Little Cone. SW Little Cone is larger, 24 m in height, 350 m in diameter, and 630,000 m^3 in volume (Figure 2-2). Rill development is much more pronounced on SW Little Cone compared with NE Little Cone, especially on the north and west sides of the cone. SW Little Cone is breached on its south side. The lava flow associated with this breach crops out up to 0.5 km south of the cone, but is almost completely covered by alluvial material.

SW Little Cone is quarried on its west flank. Cinder to block-sized angular pyroclasts are exposed in this quarry. Poorly developed bedding and the fragmented character of the pyroclasts indicates some downslope movement during or immediately after deposition. A lack of agglutinate or deformed pyroclastic material exposed in the quarry at SW Little Cone indicates that at least some stages of the eruption were sufficiently energetic for pyroclastic material to cool during transport within the eruption column. Agglutinate spatter occurs in patches on and around the summit of SW Little Cone.

Faulds et al. (1994) report a K-Ar date of 0.77±0.04 Ma on a plagioclase separate collected at the Little Cones. Heizler et al. (1994) dated a sample of sanidine xenocrysts from SW Little Cone at 0.94±0.01 Ma by $^{39}Ar/^{40}Ar$ step-heating. Conventional whole-rock K/Ar dates average 1.0±0.2 Ma. Basaltic rock samples collected at the two cones have reversed polarity magnetizations (Champion, 1991), which indicates the 0.94±0.01 Ma date of Heizler et al. (1994) is inaccurate by at least 0.02 Ma. D. Champion collected samples from three sites at the Little Cones for rock magnetic analysis[1]. These sites are located on the summit of NE Little Cone, SW Little Cone, and a lava outcrop south of SW Little Cone. Champion found a uniform remanent magnetization at the three sites with inclination = $-67°$ and declination = 177° (α_{95} = 6.3°). This steeper than expected inclination suggests that, despite the differences in the two numeric age determinations, the Little Cones eruption occurred over a brief period of time during the late Matuyama epoch, possibly over a short enough time-span (less than 10,000 yr) so that secular variation of the earth's magnetic field was not fully averaged to the dipole.

2.2 BACKGROUND ON THE GROUND MAGNETIC METHOD

Potential field methods are commonly used to develop a three-dimensional view of geologic structures. Identification of these structures is one of the primary goals of geophysical exploration in the YM region (Oliver et al., 1990). The principles and utility of magnetic methods for the identification of basaltic volcanic rocks in the YM region have been reviewed recently by Connor and Sanders (1994).

Magnetic methods have been among the most successful techniques for the identification of basalts in the YM region that do not crop out at the surface (Kane and Bracken, 1983; Langenheim et al., 1993; Ponce et al., 1992). Magnetic methods are particularly suited for the exploration and mapping of basaltic rock in alluvial valleys because of the high contrast in magnetic properties between basalt and alluvium. Aeromagnetic surveys in the YM region (Kane and Bracken, 1983) have led to the identification

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[1] Personal communication to J. Stamatakos, October 1995.

of five magnetic anomalies in the Amargosa (Figure 1-1) that have been attributed to the presence of buried basaltic volcanoes (Langenheim et al., 1993). Recognition of these anomalies has led to revision of estimates of the extent and recurrence rate of basaltic volcanism in the YM region (Connor and Hill, 1995), and indicates that additional ground magnetic surveys may provide additional insight into unrecognized igneous features in the region.

2.3 SURVEY DESIGN AND RESULTS

During a 5-d sampling period in May 1995, 2,891 ground magnetic observations were made using a Geometrics model G-856 proton-precession magnetometer. Survey point locations are shown in Figure 2-3. The magnetometer sensor height was 3 m above the surface. Usually, drift in the magnetic field was monitored continuously using a model G-866 base station magnetometer. Amplitude of diurnal variations in the total magnetic field were always less than 60 nT and typically less than 40 nT during the survey. Occasionally, drift was monitored by reoccupying base stations at frequent intervals (less than 15 min). All magnetic data were drift corrected based on these observations. Drift-corrected magnetic readings are listed in Appendix A.

Based on the results of this survey, two areas were surveyed at a higher spatial resolution using a Geometrics Model G-858 optically pumped cesium-vapor magnetometer (Figure 2-3). This magnetometer provides highly repeatable readings in areas of high magnetic gradient, such as those identified in the Little Cones area, and is capable of collecting data at a much greater sampling rate than proton-precession magnetometers. Sensor height for these detailed surveys was 1 m. Both the proton-precession and cesium-vapor magnetometers measure the intensity of the total magnetic field. High- and low-resolution surveys were not integrated into a single map because of differences in sensor height and survey point density.

Results of the low-resolution survey are presented on Plate 1 (inside back cover). The total magnetic field has a significant dynamic range within the survey area (> 6,000 nT), from approximately 47,000 to 53,000 nT. This dynamic range reflects the strong remanent magnetization of the Little Cones basalt.

Short-wavelength anomalies surround and extend outward from the two cones to distances of 300–600 m (Plate 1). These short-wavelength anomalies extend off the magnetic map area to the south. Short-wavelength anomalies are interpreted to be produced by lava flows that form an apron about the two cones. The survey was extended beyond these anomalies on the east, west, and north sides of the map, into the magnetically quiet alluvium. Typical horizontal gradients in the total magnetic field within this alluvium are <1 nT/m. In contrast, the magnetic gradients in the area immediately around the cones often exceed 100 nT/m.

Large-amplitude anomalies associated with the two cones dominate the magnetic map (Plate 1). A roughly north-trending negative anomaly correlates with the breach on the south side of SW Little Cone. High-amplitude anomalies extend over lava flows that crop out on the south side of the SW Little Cone, reflecting the thick, shallow lava flows in this area. A prominent dipole 300 m south of SW Little Cone is associated with a basaltic lava outcrop of this flow.

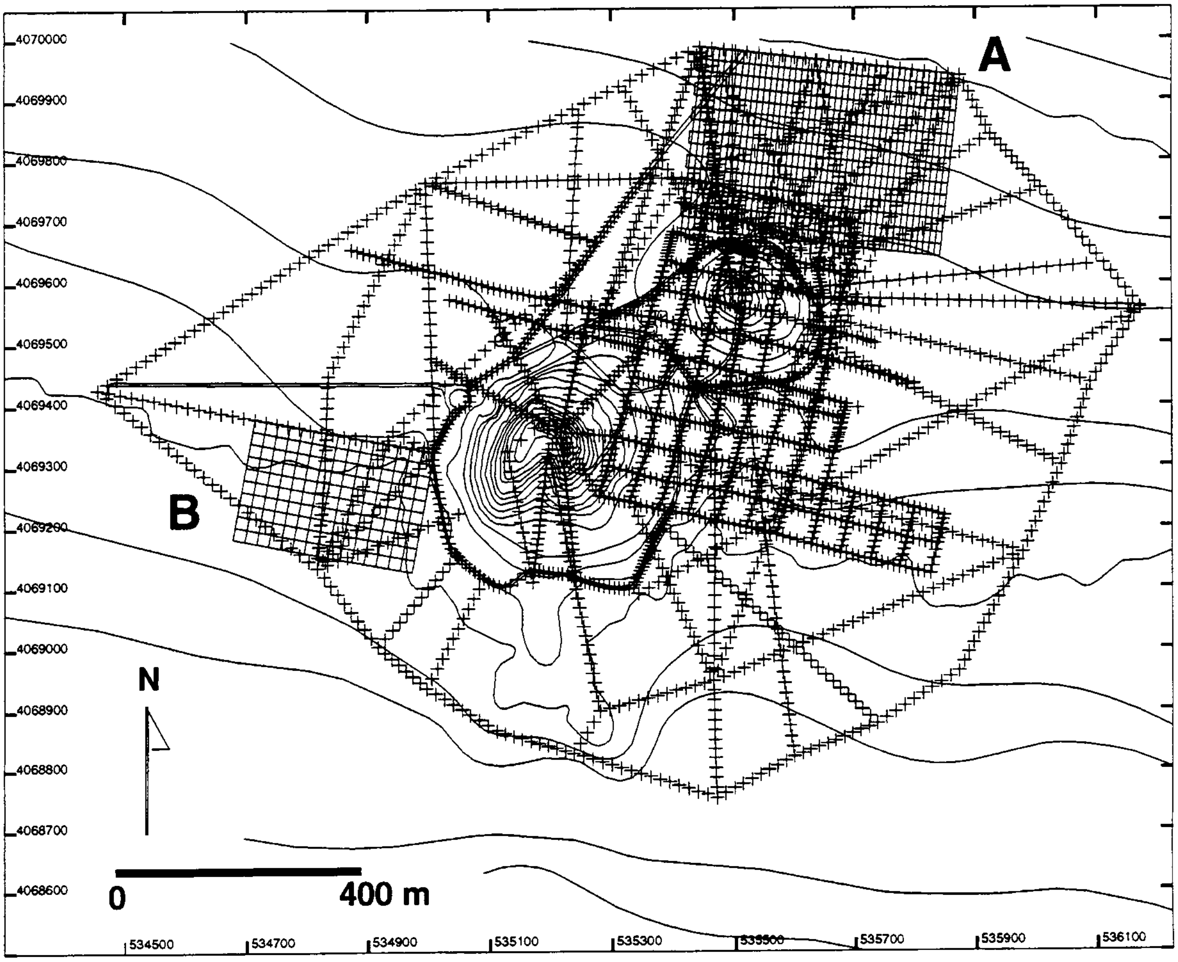

Figure 2-3. Survey point locations. Data were collected using a proton-precession magnetometer except on grids A and B, where data were collected using a cesium-vapor magnetometer.

Three aspects of the magnetic map (Plate 1) were investigated in detail. These are:

- A reversely magnetized, dipolar anomaly centered on NE Little Cone
- The areal extent of lava flows revealed by the magnetic map, particularly north of NE Little Cone
- An anomaly 250 m northeast of NE Little Cone that is interpreted to be related to a vent or shallow intrusion

2.3.1 NE Little Cone Anomaly

A large number of measurements were made on NE Little Cone with the goal of learning more about the internal cone structure. Details of the magnetic anomalies associated with NE Little Cone are shown in Figure 2-4(a). Numerous short-wavelength anomalies are prevalent on and around the cone. These anomalies often have wavelengths of less than 10 m and amplitudes of >1,000 nT. These anomalies are produced by shallow magnetized blocks. A longer-wavelength reversely magnetized dipolar anomaly is centered on the cone itself [labeled A in Figure 2-4(a)] This anomaly has an amplitude of about

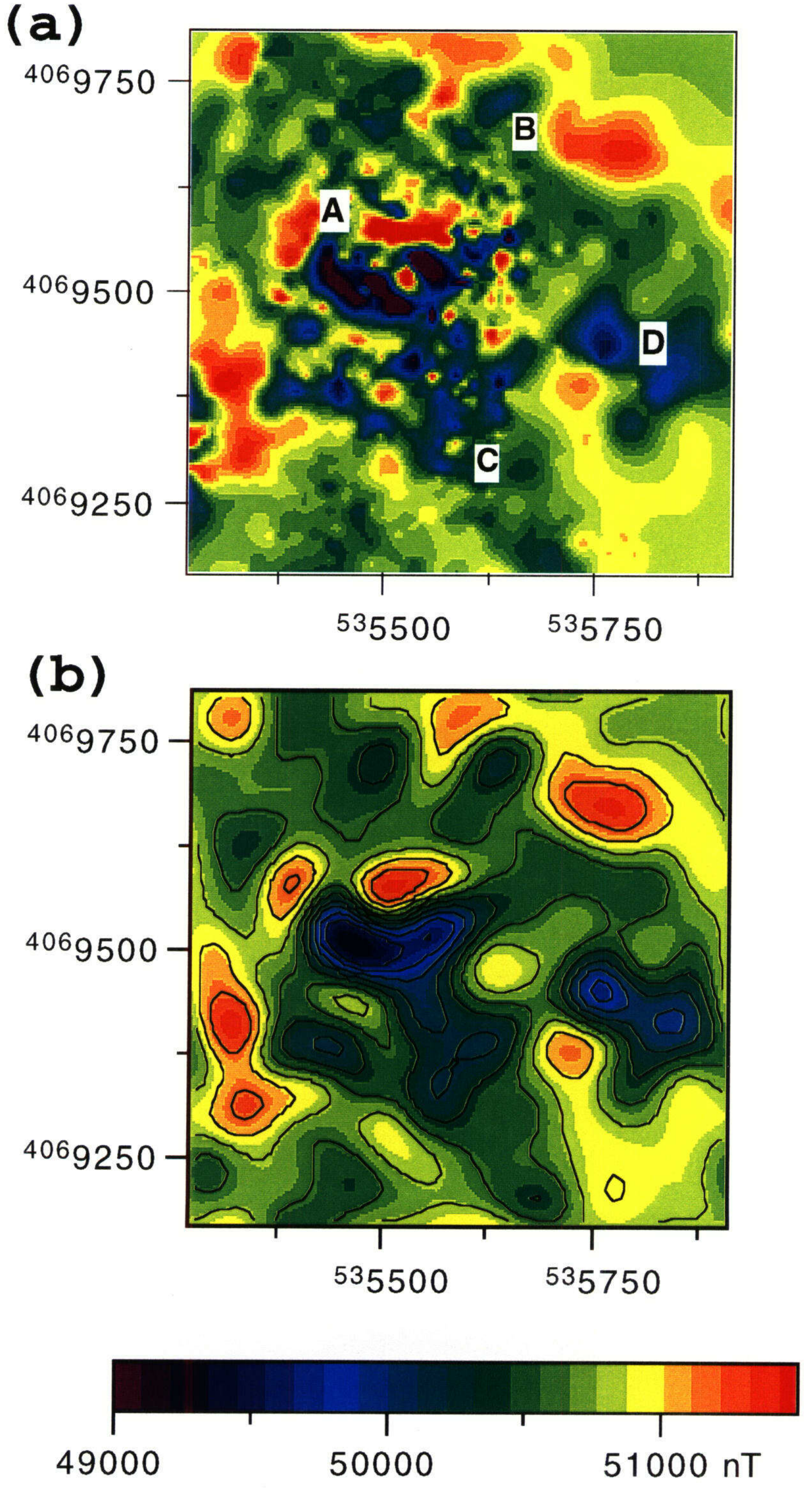

Figure 2-4. (a) Detailed map of the magnetic anomaly over NE Little Cone. A large dipolar anomaly (labeled A) occurs centered on the summit of the cone, an elongate NE-trending anomaly (labeled B) occurs NE of the cone. Negative anomalies southeast (labeled C) and east (labeled D) of the cone are interpreted to be related to shallow, massive flows. (b) Low-pass filtering of the magnetic map enhanced each of these anomalies. Contour interval (black lines) is 200 nT. Map coordinates are in meters (Universal Transverse Mercator, Nevada zone 11, Clarke 1866 projection).

3,000 nT. Three other anomalies of interest on this map are a negative anomaly (labeled B), northeast of NE Little Cone, an elongated negative anomaly (labeled C) that extends southeast of the cone, and a dipolar anomaly (labeled D) east of the cone.

The NE Little Cone map [Figure 2-4(a)] was enhanced by frequency filtering to reduce the effect of the large number of large-amplitude, short-wavelength anomalies present on the map. Map enhancement and filtering techniques are widely used to interpret aeromagnetic and ground magnetic data (e.g., Hildenbrand, 1985) and are described by Hildenbrand (1983) and Connor and Sanders (1994). In this case, a low-pass filter was used to attenuate short-wavelength anomalies. This was accomplished by interpolating observed magnetic data within the NE Little Cone area to a 64×64 grid, and filtering this grid in the frequency domain using a ramped low-pass filter. Anomalies with wavelengths greater than 50 m are passed through this filter unchanged. Anomalies with wavelengths less than 20 m are completely attenuated by the filter. Between 20 and 50 m, anomalies are attenuated using a cumulative normal distribution that provides a smooth ramp. In general, anomalies enhanced by this low-pass filter will be produced by deeper and larger magnetized bodies than anomalies that are attenuated by this filter.

The low-pass filtered map [Figure 2-4(b)] accentuates each of the magnetic anomalies [labeled A–D in Figure 2-4(a)] and reduces the effect of short-wavelength anomalies. The reversed, dipolar anomaly (labeled A) associated with the cone consists of a large negative anomaly and a smaller positive anomaly located to the north. A dipolar anomaly of this shape and amplitude is expected, given the high angle of inclination of the remanent magnetization vector (−67°), if it is related to the internal cone structure rather than surface features. Anomaly B of Figure 2-4(a) is also enhanced by the low-pass filter. This anomaly is more clearly a northeast-trending magnetic low, extending northeast of the cone. As discussed in more detail in the Section 2.3.3, this anomaly is likely produced by a buried vent or shallow dike. The filtered map shows a broad, nearly continuous magnetic low (labeled C) extending southeast from the cone for a distance of 400 m. This anomaly is interpreted to be related to a shallow lava flow. This interpretation is supported by the topography of NE Little Cone. A shallow depression in the cone is located on the southeast side of the cone, associated with the southeast trending magnetic anomaly. This depression may have been produced by incipient breaching of the cone during a late-stage effusion of lavas that flowed down the topographic gradient to the southeast. Anomaly D of Figure 2-4(a) is also a broad negative anomaly and is enhanced by the filtering process. However, sample density is relatively low in this part of the map (Figure 2-3) and, therefore, the wavelength of this anomaly is less certain. A possible interpretation of this anomaly is that it is also related to shallow lavas.

In order to further interpret anomaly A [Figure 2-4(a)], several models were constructed based on the topography of the cone and the possible structure of the cone. These models include:

- A magnetized, 20-m-diameter circular conduit that extends vertically from the surface to great depth; the cone carries a small remanent magnetization and the conduit carries a large remanent magnetization [Figure 2-5(a) and 2-5(b)]

- Uniform magnetization of the cone; most of the cone carries a high remanent magnetization beneath a mantle of unconsolidated float and scoria [Figures 2-6(a) and 2-6(b)]

- An intermediate model, in which the central part of the cone carries a high remanent magnetization and most of the volume of the cone consists of unconsolidated float and scoria [Figures 2-7(a) and 2-7(b)]

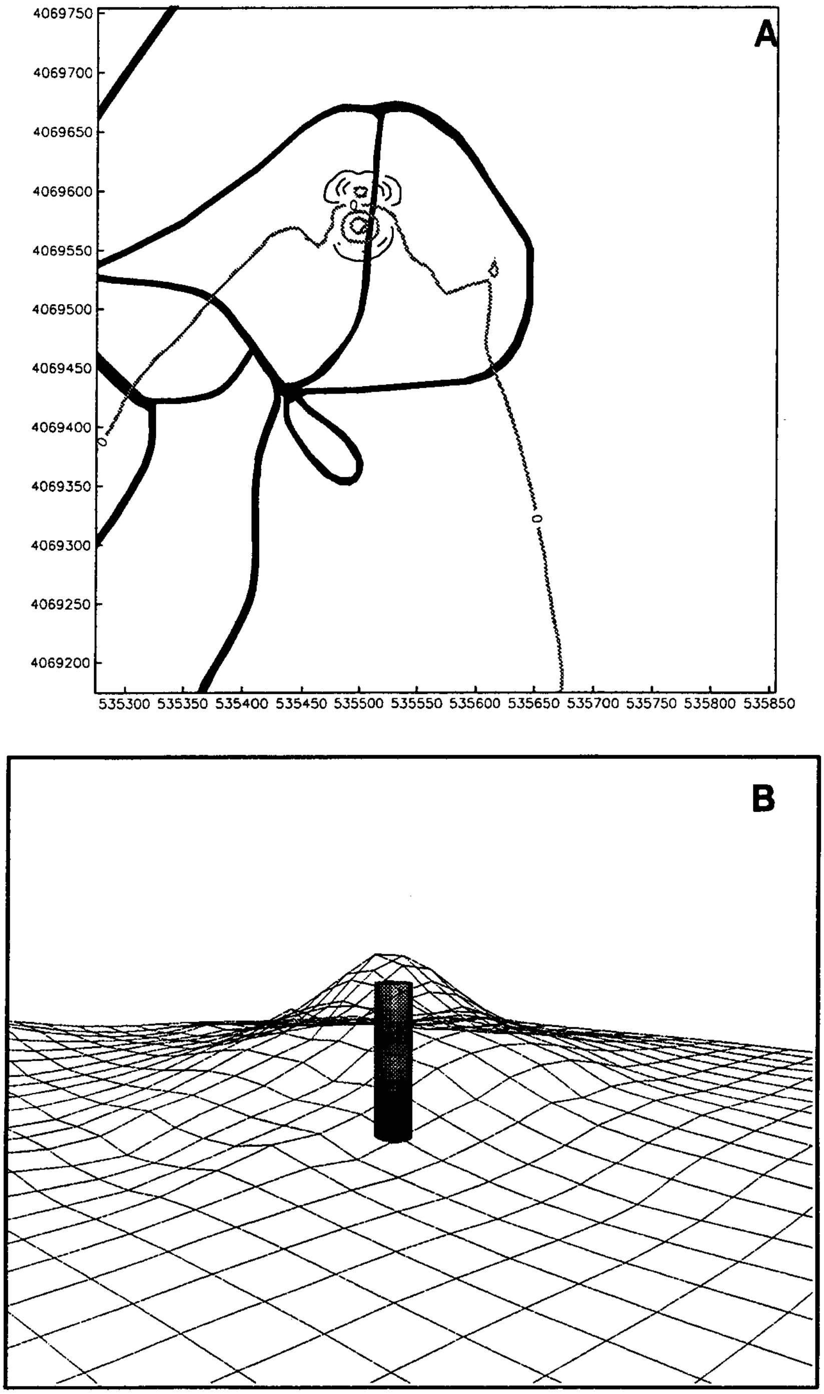

Figure 2-5. (a) Magnetic map calculated for a single magnetized vertical conduit centered on NE Little Cone on a 20-m grid. The model geometry consists of a single vertical-sided polygon extending to infinite depth. (b) Sensor height is shown by the mesh and conforms to the local topography. This model produces a magnetic anomaly that is similar in amplitude, but shorter in wavelength than the observed anomaly [Figure 2-4(a) and 2-4(b)].

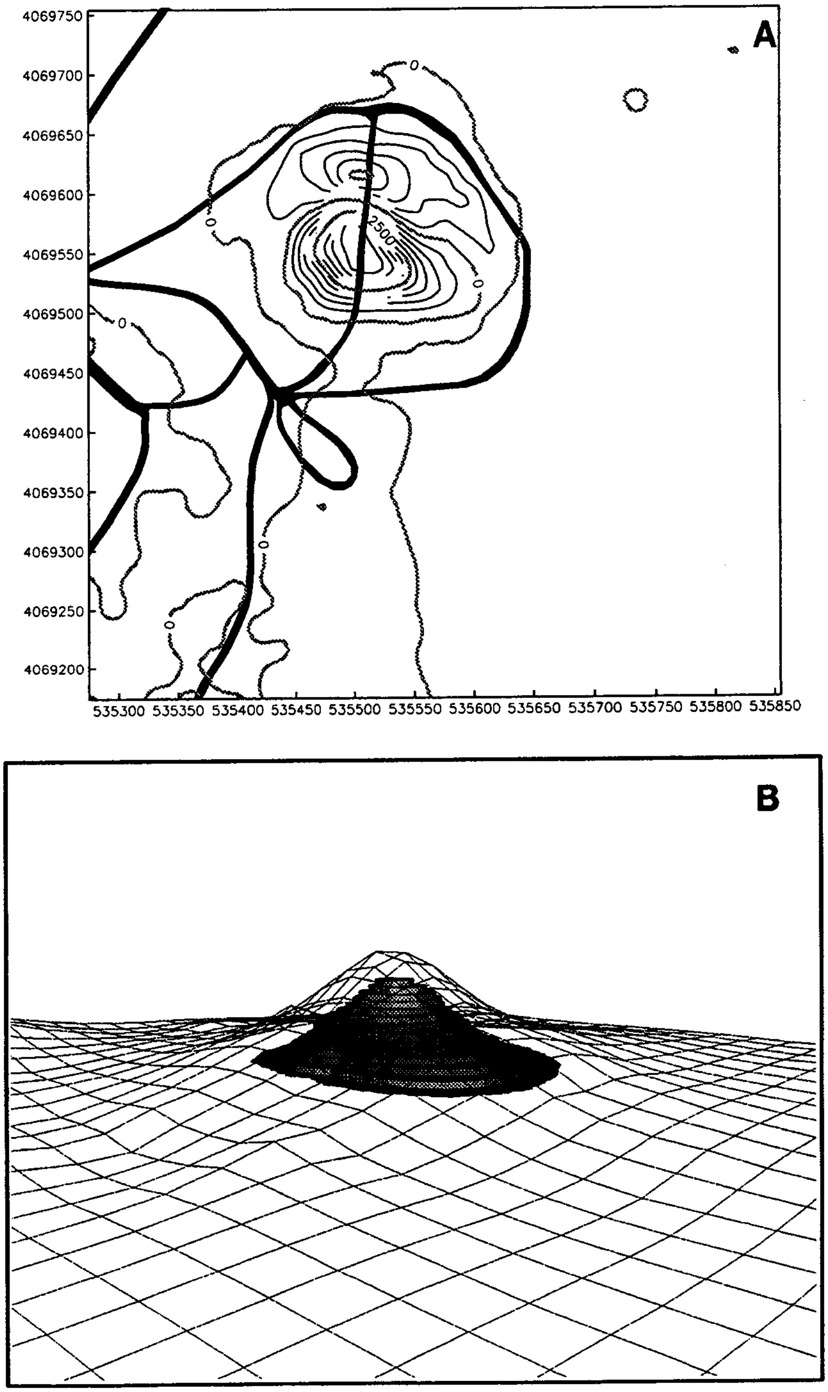

Figure 2-6. (a) Magnetic map calculated on a 20-m grid assuming that NE Little Cone is a uniformly magnetized body, carrying a high remanent magnetization except for a thin carapace of rubbly surface material. (b) The model geometry consists of multiple vertical-sided polygons that follow topography. Sensor height is shown by the mesh and conforms to topography.

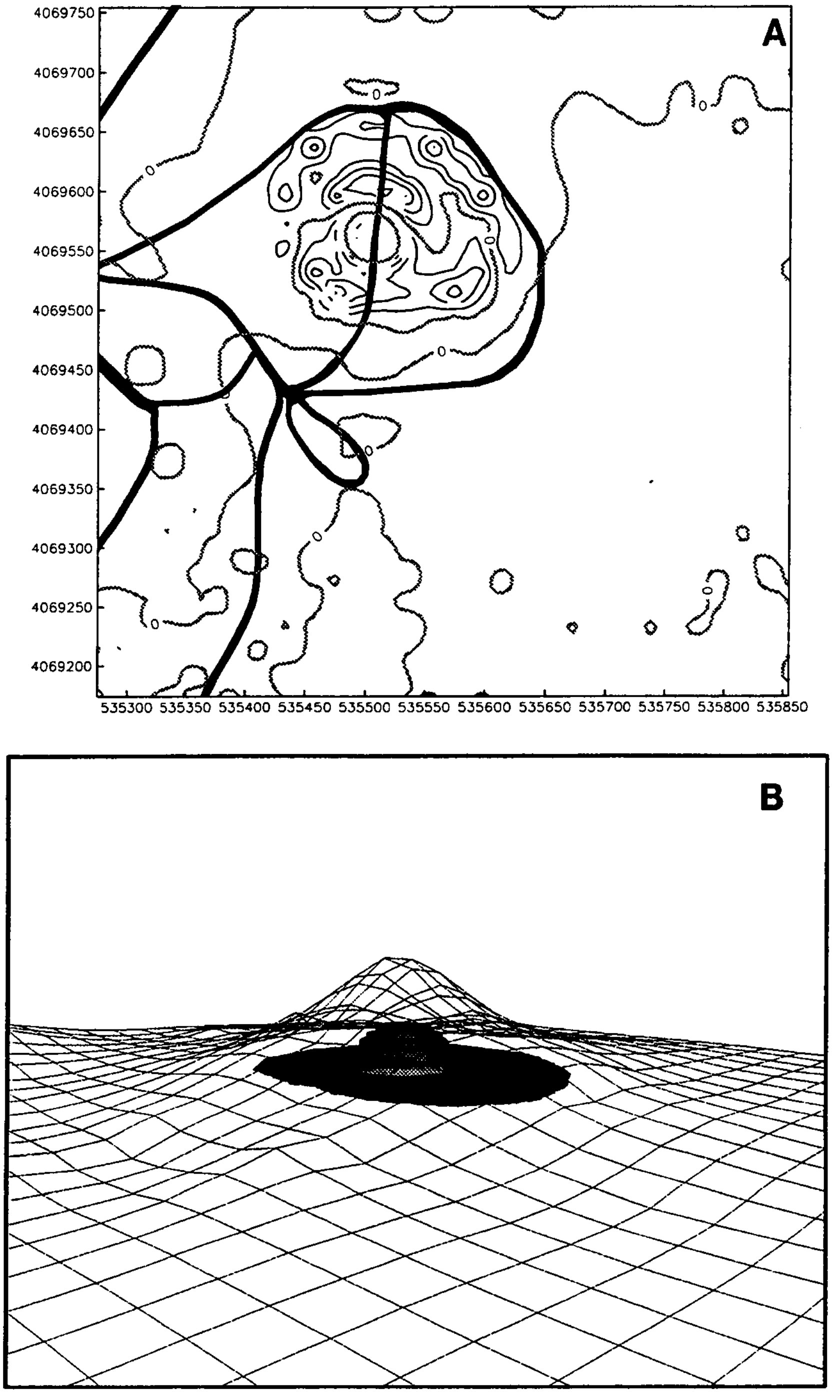

Figure 2-7. (a) Magnetic map calculated on a 20-m grid assuming that NE Little Cone consists of a small, early-formed spatter mound that carries a high remanent magnetization and a thick carapace of unconsolidated rock that carries a low remanent magnetization. The model geometry consists of multiple vertical-sided polygons of varying thickness. (b) Sensor height is shown by the mesh and conforms to topography.

In each of these models, the geometry is approximated by vertical-sided polygons and the magnetic anomaly associated with the geometries is calculated based on the algorithm of Plouff (1976). The magnetic anomaly is calculated at points on a 20-m grid and at elevations corresponding to the sensor height for the proton-precession magnetometer survey, 3 m above the topographic surface.

These three model geometries correspond to volcanological models for the origin of NE Little Cone. In the simple conduit model, it is assumed that the cone consists of scoria and blocks that carry low bulk remanent magnetization. Of course, individual blocks of basalt carry high remanent magnetization. However, if the blocks and scoria are cooled below their Curie-blocking temperatures before deposition, vectors of the remanent magnetization will not be consistently oriented between blocks, cumulatively leading to a low bulk remanent magnetization for the cone. Randomized vectors of magnetization of blocks and other pyroclasts will occur in pyroclastic eruptions in which the column height is high enough, or the accumulation rate is low enough, so that welding or rheomorphism of pyroclasts does not occur. The central conduit is assumed to consist of massive basalt. A 20-m-diameter conduit is used. Even with this large diameter, the resulting magnetic anomaly is small and has a short wavelength [Figure 2-5(a)] relative to the observed anomaly [Figures 2-4(a) and 2-4(b)].

In contrast, a uniformly magnetized cone with a strong remanence produces a large-amplitude, long-wavelength anomaly [Figure 2-6(a)]. This calculated anomaly is similar in wavelength but larger in amplitude than the observed anomaly [Figures 2-4(a) and 2-4(b)]. In this model, a thin (≈1 m) weakly magnetized mantle of unconsolidated material covers a massive cone interior. Such a geometry is produced if the cone consists of welded pyroclasts or agglutinated spatter, deposited at temperatures above the Curie-blocking temperatures for this basalt. The mantle may be produced by later, more energetic activity and/or cone degradation.

The third model [Figures 2-7(a) and 2-7(b)] consists of a thick mantle of pyroclastic material that constitutes much of the volume of the cone. A small, 10-m-high and 30-m-diameter spatter mound carries a high bulk remanent magnetization at the center of the cone. This spatter mound overlies a lava flow that extends outward radially under the weakly magnetized pyroclastic material that mantles the spatter mound. The resulting magnetic map [Figure 2-7(a)] is more complicated than the others, but does produce an anomaly that is slightly shorter in wavelength and smaller in amplitude than the observed anomaly [Figure 2-4(a) and 2-4(b)].

Based on these calculated magnetic maps, it is concluded that NE Little Cone consists of highly magnetized rock beneath a relatively thin mantle of weakly magnetized rock. Overall, the second model [Figures 2-6(a) and 2-6(b)] fit the observed anomaly best, although the weakly magnetized mantle may be thicker than 1 m. High bulk remanent magnetization of the cone indicates the presence of agglutinate spatter or welded scoria deposited above the Curie-point blocking temperature, beneath a mantle of unconsolidated pyroclastic material that is likely less than 5 m thick. Such spatter mounds are common and often form early in basaltic cinder cone eruptions (e.g., Tokerev, 1983). The magnetic anomalies associated with the NE Little Cone are not consistent with intrusion geometries, such as a large central conduit. Magnetic anomalies associated with intrusions that fed the NE Little Cone are masked by anomalies produced by extrusive material that comprises the cone itself.

2.3.2 Extent of Lava Flows

Possibly the most surprising result of the ground magnetic surveys is recognition of the extent of the lava flow field surrounding the Little Cones. Lava flows do not crop out around the Little Cones except south of SW Little Cone, yet it is clear from the extent of short-wavelength anomalies that lava flows are present around both cones. Three lines of investigation help clarify the nature and distribution of flows around the cones: (i) a high-resolution cesium-vapor magnetometer survey made north of NE Little Cone; (ii) models of these high-resolution magnetic data; and (iii) a filtered map that shows the distribution of short-wavelength, large-amplitude anomalies, constructed using the low-resolution proton-precession magnetometer data.

The character of the lava flow and its margin is best elucidated by the high-resolution survey north of NE Little Cone [Figure 2-8(a) and 2-8(b)]. This survey shows the complex surface of the lava flow in detail. The high-resolution magnetic map [Figure 2-8(a)] was actually made in two surveys. The first survey consisted of 43 north-south trending lines spaced at 10-m intervals. The second survey consisted of east-west trending lines spaced at 20-m intervals. Even very short-wavelength anomalies correlate between these surveys, indicating a high degree of precision in the locations, amplitudes, and wavelengths of anomalies was achieved.

The most prominent anomaly on this map [Figure 2-8(a)] is a +500 nT anomaly that forms an arcuate band across the survey area. The wavelength of this anomaly is approximately 100 m. The anomaly separates the magnetically quiet alluvium to the north from the complex, large-amplitude, short-wavelength anomalies produced by the shallow lava flow surface in the southern portion of the map area. This type of long-wavelength, positive, total magnetic field anomaly is exactly what is expected at the northern margin of a thin, reversely magnetized horizontal sheet, such as lava flow.

Additional perspective on the complex anomalies mapped on the lava flow surface is provided by viewing the total magnetic field data as a shaded relief map, illuminated from a sun-angle of 45° above the horizon and from the north [Figure 2-8(b)]. This sun-angle enhances east- trending features on the flow surface. Although the anomalies produced by the rubbly flow-top are complex, the shaded relief map suggests a lobate character of anomalies on the flow-top. In this case, the lobate character of the magnetic anomalies suggests flow from the south (i.e., the NE Little Cone vent).

Data collected along four survey lines using the cesium-vapor magnetometer were modeled using a three-dimensional algorithm first developed by Plouff (1976). Figure 2-9 shows the positions of these lines within the survey area and the magnetic data along these lines are shown in profile in Figures 2-10 through 2-13. The lava flow was modeled as two vertical-sided polygons that extend well beyond the map area to the south and west. The polygons are assumed to carry remanent magnetizations similar to those measured by Champion (1991). In all the models, the inclination and declination of the remanent magnetization vectors were held constant at $I = -67°$ and $D = 177°$. Champion (1991) determined the magnitude of remanent magnetization, J, to be between 7.5 and 15 Am^{-1} for Crater Flat basalts. The models shown here use $J = 20\ \mathrm{Am}^{-1}$. Using $J = 20\ \mathrm{Am}^{-1}$, the modeled lava flows tend to be thinner than is the case using lower values of J. However, it was found that the steep gradients observed on the map and profiles is better modeled using a higher remanent magnetization. $J = 20\ \mathrm{Am}^{-1}$ is reasonable, given the range of basaltic rock magnetic properties observed in Crater Flat. The lava flows are assumed to have a low susceptibility compared to remanent magnetization. In this case, a susceptibility of 0.063 SI (0.005 emu) was used.

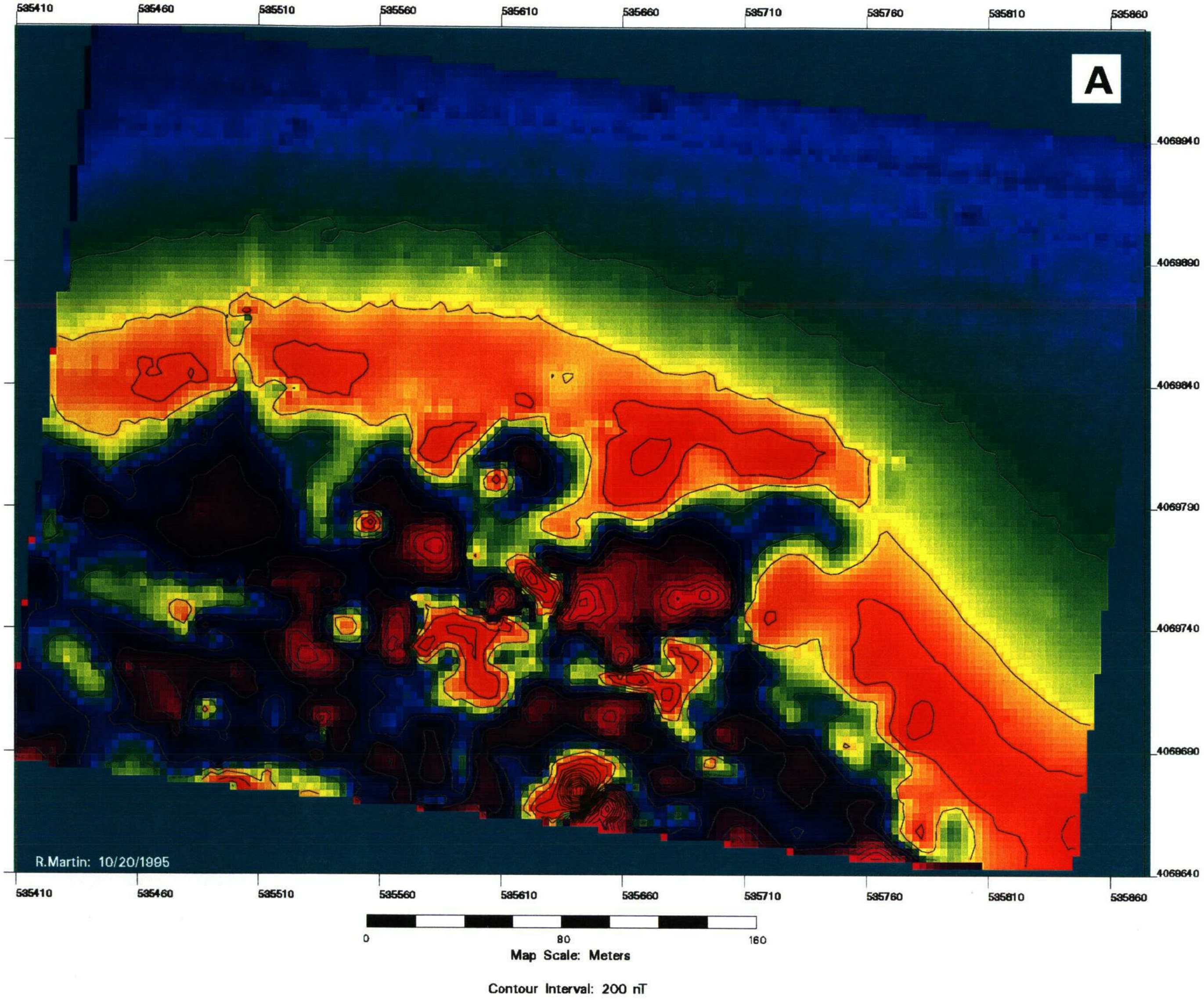

Figure 2–8(a). High–resolution, cesium–vapor magnetic survey north of NE Little Cone. Survey grid is shown in Figure 2–3. Map is contoured using a 200nT and colored using an equal area histogram stretch algorithm.

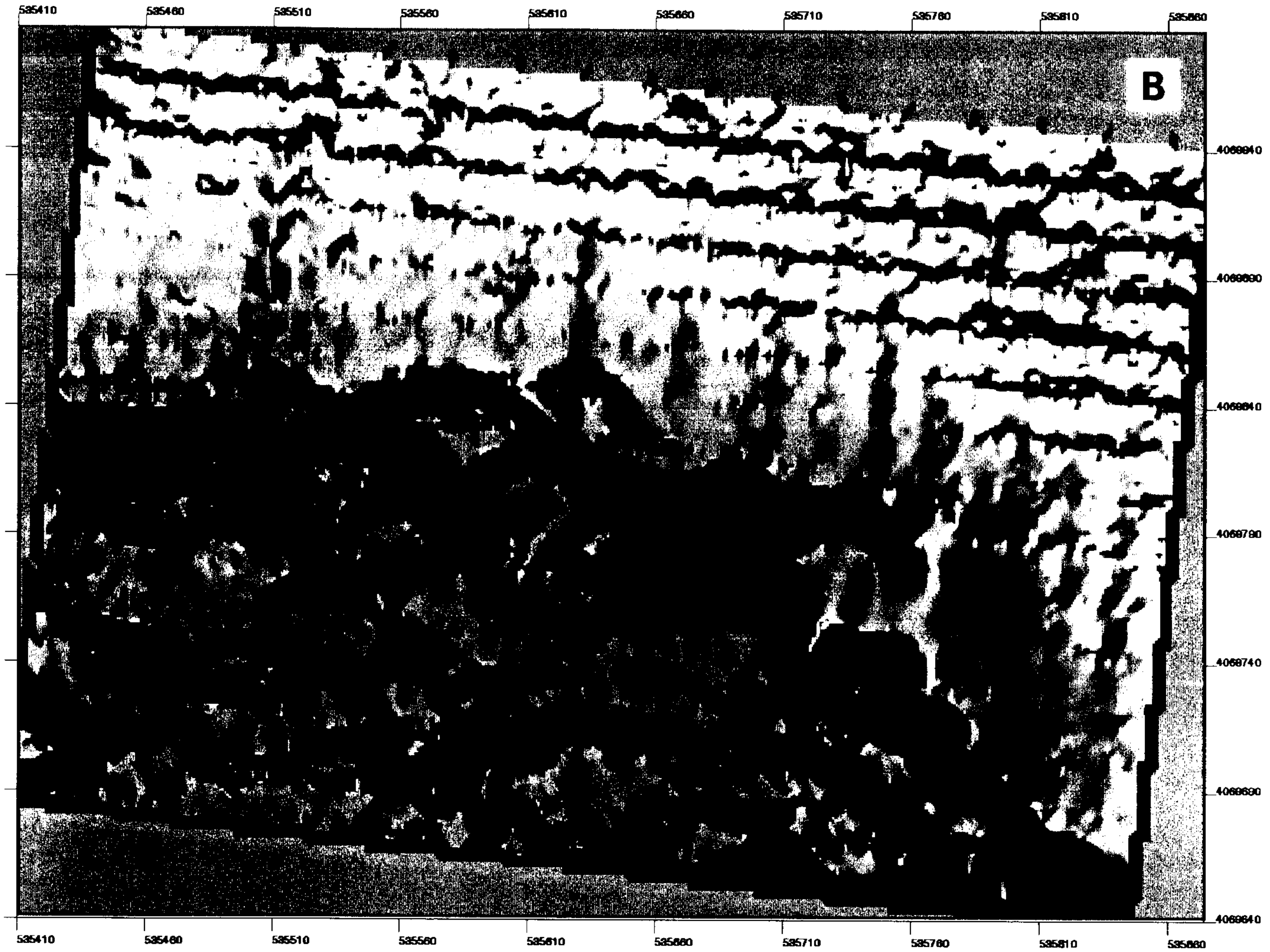

Figure 2–8(b). Shaded relief map of the high–resolution magnetic survey north of NE Little Cone. Magnetic anomalies are illuminated from the north by a light source 45 above the horizon. East–West–trending lobate structures on the lava flow surface are enhanced.

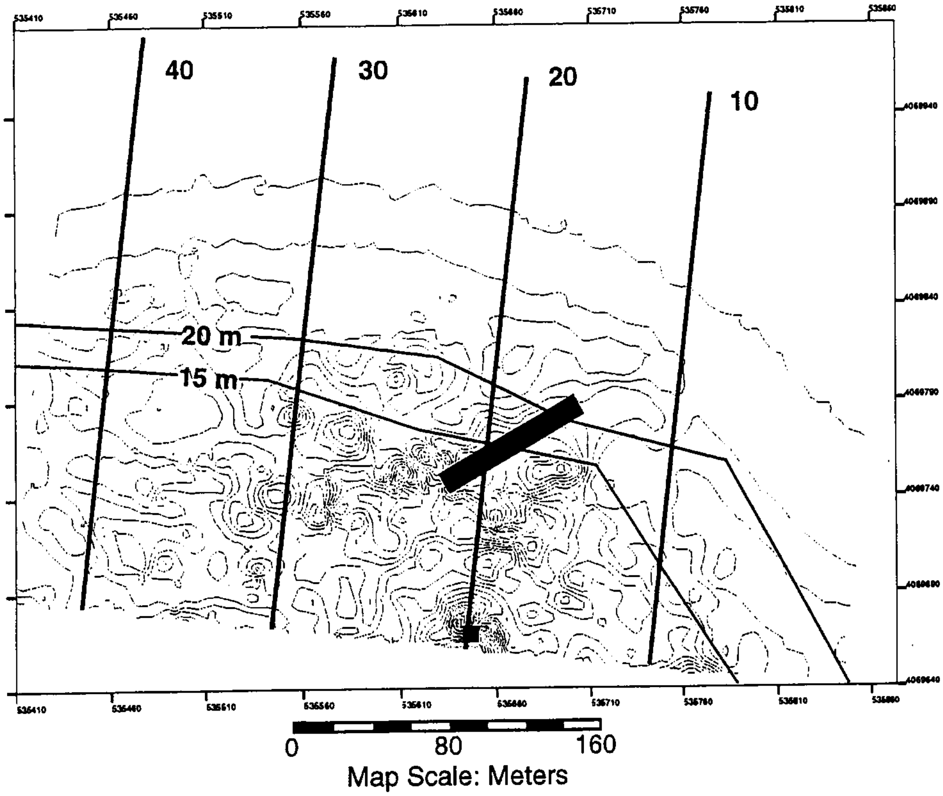

Figure 2-9. Model geometries for the high-resolution survey north of NE Little Cone. Two polygons are used to model the lava flow; each is 5 m thick and the tops of the polygons are at depths of 15 and 20 m beneath the surface. The two polygons extend far beyond the map area to the west and south. Four survey lines were modeled in detail – labeled 10-40. Line 20 was modeled using additional polygons shown as solid boxes. Magnetic data are contoured using a 200 nT contour interval.

The modeled lava flow geometry is shown in map view in Figure 2-9 and in cross section in Figure 2-14. Vertical-sided polygons are used to represent the indurated, massive flow interior. This part of the lava flow cooled *in situ* to produce a uniform vector of remanent magnetization. Blocky material caps the massive flow interior. This material represents the rubbly flow-top which formed as the exterior part of the flow cooled, solidified, and broke up as the flow continued to move. Each block in this flow-top carries a remanent magnetization similar to that of the lava flow interior, locked in as the block cooled through its Curie temperature. Remanent magnetization vectors are additive and, because individual blocks are rotated, the net remanent magnetization of the rubbly flow-top is low. Nonetheless, large, shallow blocks within this carapace produce large-amplitude, short-wavelength and somewhat lobate anomalies of the type seen on the high-resolution map [Figures 2-8(a) and 2-8(b)]. No attempt was made to model these very short-wavelength anomalies. Two vertical-sided polygons are used to represent the change in thickness of the lava flow at its margin.

The magnetic field anomaly produced by this model geometry captures the amplitude of the long-wavelength anomaly associated with the flow margin in each map profile. For the calculated magnetic anomalies in Figures 2-10 through 2-13, the top of the massive flow interior is assumed to be 15 m beneath the surface and 10 m thick. Experimentation indicates that this massive flow interior is not likely greater than 20 m in total thickness and the top of the massive interior is not likely deeper than 20 m. The thickness of the rubbly flow-top may be quite variable and is poorly constrained by the magnetic data.

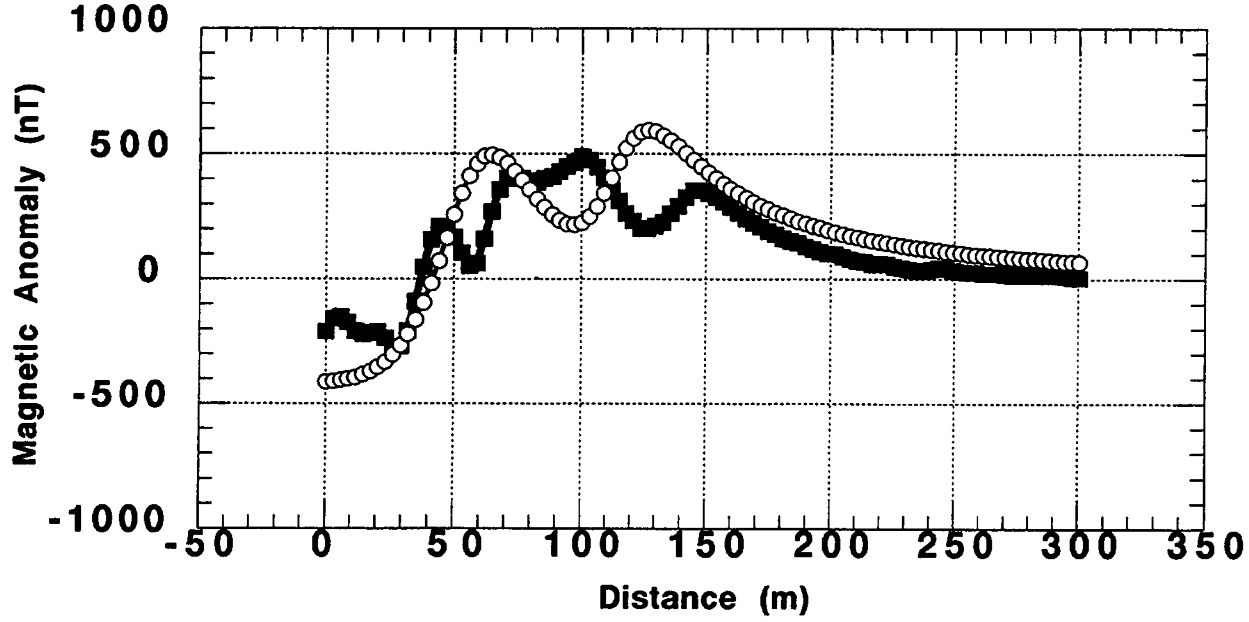

Figure 2-10. Observed magnetic anomaly along line 10 is shown by solid squares and calculated magnetic anomaly is shown by open circles. Distance is indicated from the southern end of the line and survey line trends NNE (Figure 2-9).

The high-resolution survey and modeling of these data indicate that the lava flow field extends approximately 300 m north of NE Little Cone. The extent of lava flows around the two cones can be determined using the low-resolution survey data. Magnetic data collected across the entire area (Plate 1) were filtered using a high-pass filter on a line-by-line basis. In this case, a ramped high-pass filter was used, passing anomalies with wavelengths shorter than 10 m unchanged, and completely attenuating anomalies with wavelengths greater than 40 m. The root-mean-square of the derivative of this map shows the locations of short-wavelength anomalies in the survey area (Figure 2-15).

The most prominent areas of short-wavelength anomalies are on the south side of SW Little Cone where lavas occasionally crop out, south and east of NE Little Cone, and to a lesser extent north and west of NE Little Cone. Sources of these anomalies must be highly magnetized rocks close to the surface, as magnetic anomalies associated with the cones themselves cannot produce high-frequency anomalies hundreds of meters away from the base of the cones.

The location of the flow margin was estimated throughout the survey area based on the extent of anomalies using Figure 2-15 and Plate 1, together with models of the flow margin on the north side of the cone (Figure 2-9). The low-resolution survey encompassed and extended beyond these anomalies everywhere except on the south side of the cones, where lava flows clearly extend beyond the map area. The approximate flow margin is shown in Figure 2-16. The area within the outlined flow margin

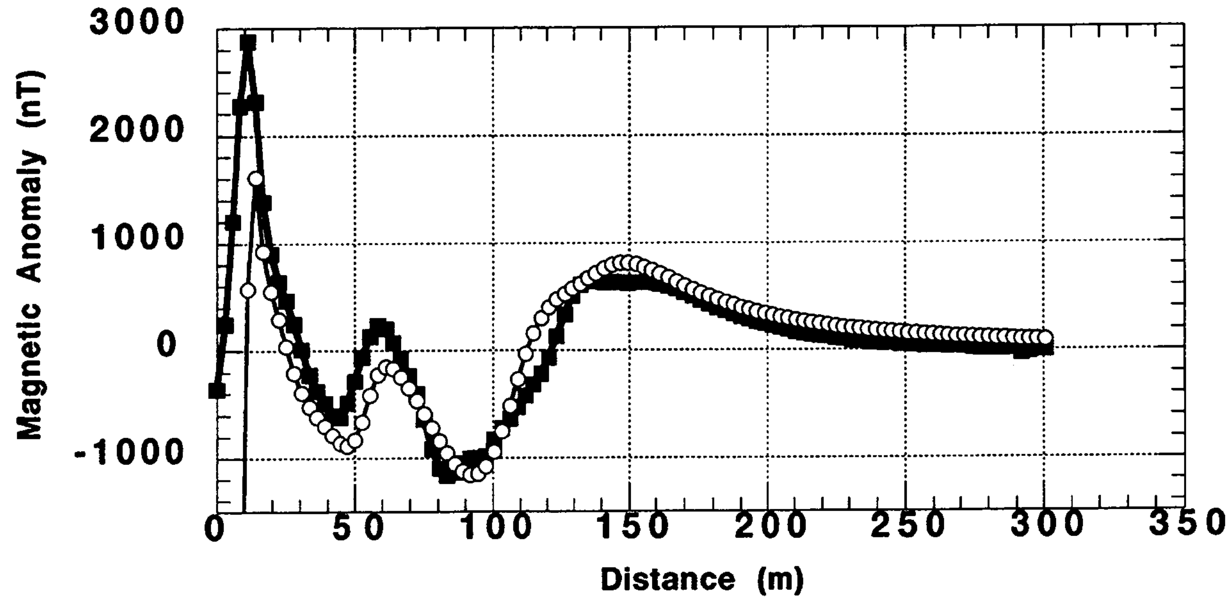

Figure 2-11. Observed magnetic anomaly along line 20 is shown by solid squares and calculated magnetic anomaly is shown by open circles. Distance is indicated from the southern end of the line and the survey line trends NNE. The magnetic model includes both the flow margin and two polygons representing magnetized rock beneath the flow and a smaller magnetized body on top of the flow (Figure 2-9).

(Figure 2-16) is 970,000 m^2. Given the uncertainty in locating the flow margin in low-resolution survey areas, the area of the flow field within the survey area is taken to be 1±0.1 km^2. If the lava flow averages 10 m in thickness, the volume of the flow field within the survey area is approximately 1×10^7 m^3, or about 10 times the volume of the cones.

Unfortunately, it is uncertain how far the lava flow field extends south the Little Cones and, therefore, an eruptive volume cannot be calculated. Based on the known distribution of flows and the extent of outcrops south of the SW Little Cone, the eruptive volume is >0.01 km^3, much greater than the 0.0008 km^3 represented by the cones. In comparison, the volume of the exposed lava flow field at Black Cone, including the cinder cone, is approximately 0.07 km^3.

2.3.3 Anomaly Northeast of NE Little Cone

Not all of the magnetic field variation identified in the high-resolution survey north of NE Little Cone is easily explained by the lava flow model. In particular, a negative anomaly, greater than 2,000 nT in amplitude, is located near the edge of the flow in the central part of the map area [Figure 2-8(a)]. This anomaly has a wavelength of approximately 80 m, much longer than other anomalies that are more readily associated with the lava flow surface.

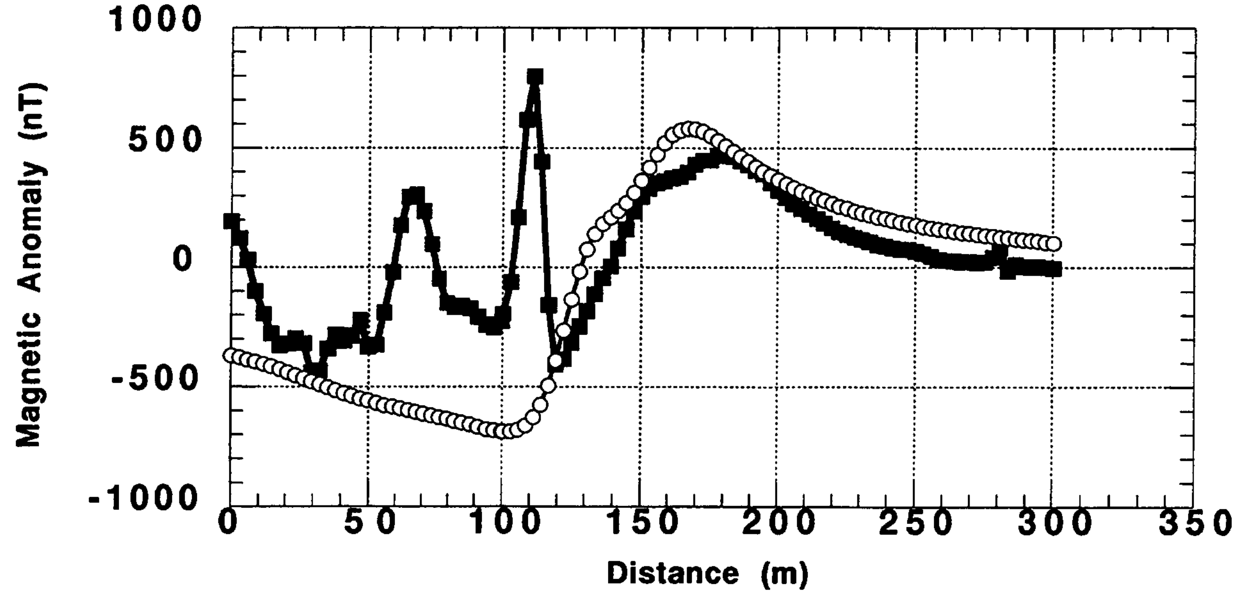

Figure 2-12. Observed magnetic anomaly along line 30 is shown by solid squares and calculated magnetic anomaly is shown by open circles. Distance is indicated from the southern end of the line and survey line trends NNE (Figure 2-9).

The shape of this anomaly is best revealed by filtering the magnetic data using a low-pass filter. Anomalies with wavelengths less than 40 m were completely attenuated by the low-pass filter. The filter ramped-up using a cumulative normal distribution between wavelengths of 40 and 80 m, and anomalies with wavelengths greater than 80 m passed through the filter unchanged. The resulting map [Figure 2-17(a)] shows that the anomaly is enhanced by this filtering process, and therefore is not likely associated with variation on the flow-top that produces large-amplitude, but short-wavelength anomalies.

A vertically sided prism is used to model this anomaly. This prism is 80 m in length, 15 m wide, and extends from the base of the lava flow to a model depth 100 m below the surface. The magnetic properties of the prism are the same as those of the lava flow ($I = -67°$, $D = 177°$, $J = 20\ Am^{-1}$). The map extent of this prism is shown in Figure 2-9. The calculated anomaly resulting from this body is shown in map view in Figure 2-17(b) and the profile in Figure 2-11. Such a magnetized body explains the observed anomaly near the lava flow margin. One interpretation of this magnetized body is that it represents a shallow dike or dike zone. This intrusion likely fed a vent, given the width and depth of the modeled prism. Modeling variation in flow-top morphology did not successfully reproduce the observed magnetic anomaly.

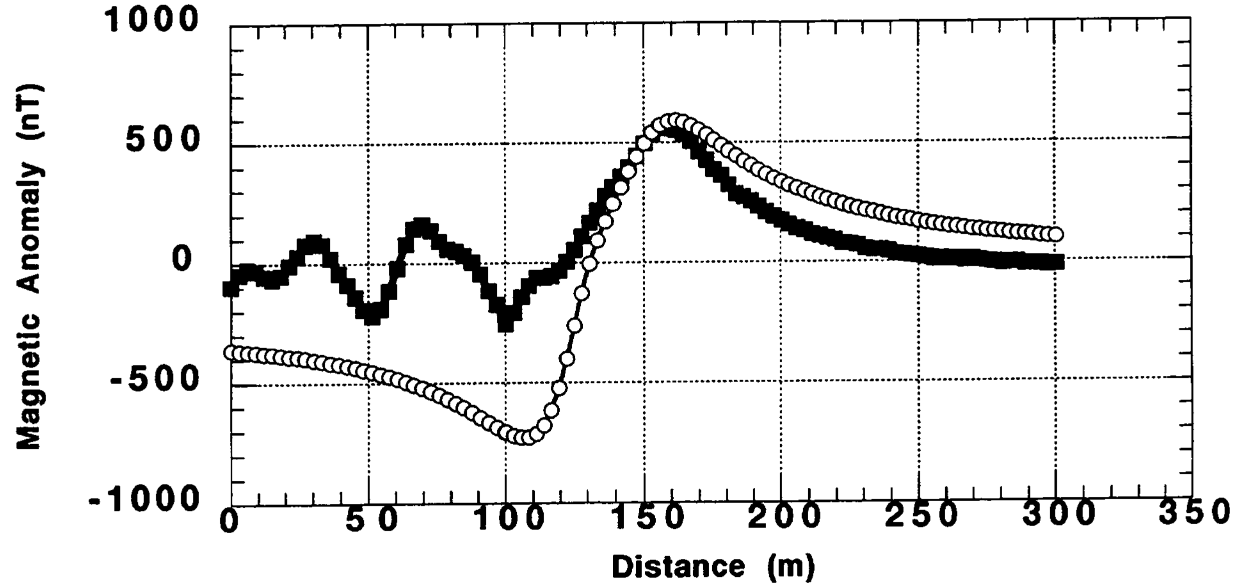

Figure 2-13. Observed magnetic anomaly along line 40 is shown by solid squares and calculated magnetic anomaly is shown by open circles. Distance is indicated from the southern end of the line and the survey line trends NNE (Figure 2-9).

2.4 DISCUSSION OF RESULTS

Like other cinder cones in the YM region, the Little Cones are surrounded by a lava flow field. Where the lava flow was modeled north of NE Little Cone, the flow is buried at a depth of approximately 5–10 m and is 10–15 m thick. The magnetic survey bounds the areal extent of these flows on all but the south side of the cones. The volume of the Little Cones eruption is an order of magnitude greater than represented by the cones themselves.

A large, >2,000 nT dipolar anomaly is located 250 m northeast of NE Little Cone along azimuth of 042° (Figure 2-16). This anomaly has a wavelength and amplitude that are too large to be associated with the lava flow-top or flow margin. A combination of map filtering and modeling indicates that a magnetized intrusion can account for the shape and dimensions of this anomaly. The modeled intrusion that extends from the base of the lava flows to great depth is 15 m wide at its top and is 80 m in length. Such a geometry is consistent with the presence of a shallow dike or dike zone.

The interpretation of this anomaly as a shallow dike and vent is consistent with the northeast trend of the Little Cones and the rest of the Quaternary Crater Flat alignment. The length of the Little Cones segment of this alignment is doubled by the presence of this vent.

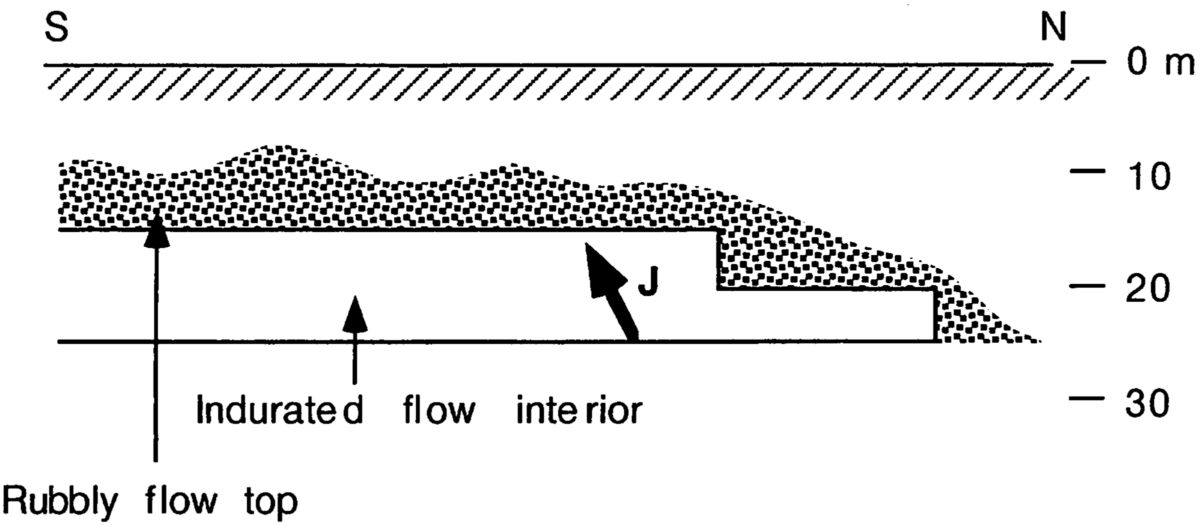

Figure 2-14. Cross-section of the polygon model used to represent the lava flow margin. The model consists of two horizontal, vertically sided polygons, each 5 m thick. The lava flow is mantled by weakly magnetized rock representing the rubbly flow-top. Short-wavelength anomalies are produced by magnetized blocks within this flow-top. The inclination of the vector of remanent magnetization is indicated by vector J.

The volcanological history of the Little Cones has been augmented by the magnetic survey in several ways:

- The volume of Little Cones magmatism is much greater than is represented by surface deposits and the cones are surrounded by a lava flow field
- NE Little Cone is interpreted to consist of a spatter mound mantled by a weakly magnetized, unconsolidated layer of pyroclastic material; the presence of this spatter mound suggests a high magma flow-rate and low-energy eruption, consistent with the presence of the surrounding lava flow field
- The anomaly northeast of NE Little Cone indicates that eruptive activity in the area may have been distributed among several vents at the outset of the eruption, then localized at the two Little Cones in a manner consistent with observations made at historically active cones.

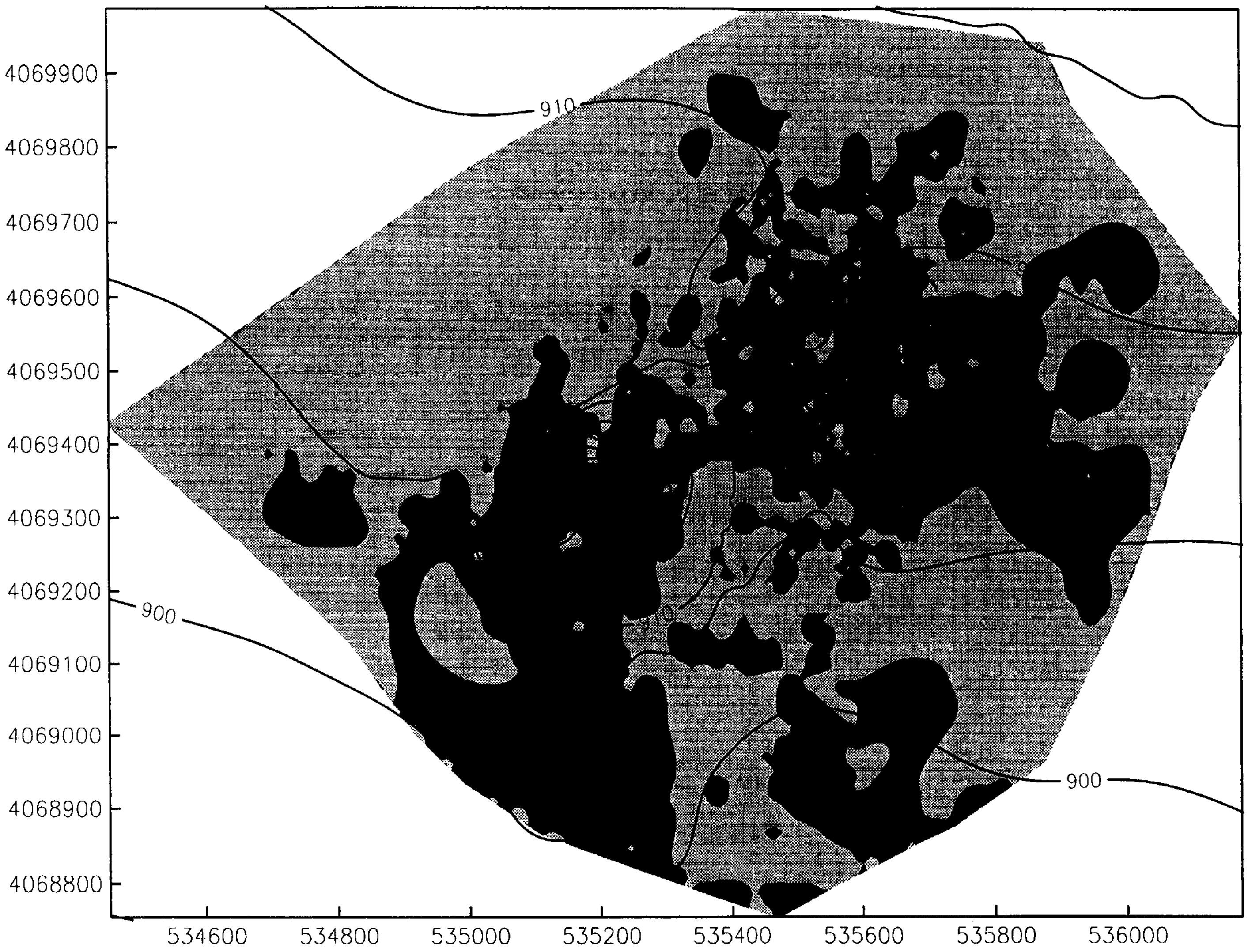

Figure 2-15. Distribution of short-wavelength anomalies in the Little Cones map area is indicated by dark shading. Anomalies are shaded by high-pass filtering original magnetic data, and calculating the root-mean-square of the derivative of this map. Short-wavelength anomalies indicate the distribution of shallow lava flow surfaces, rubbly flow-tops, and cone material.

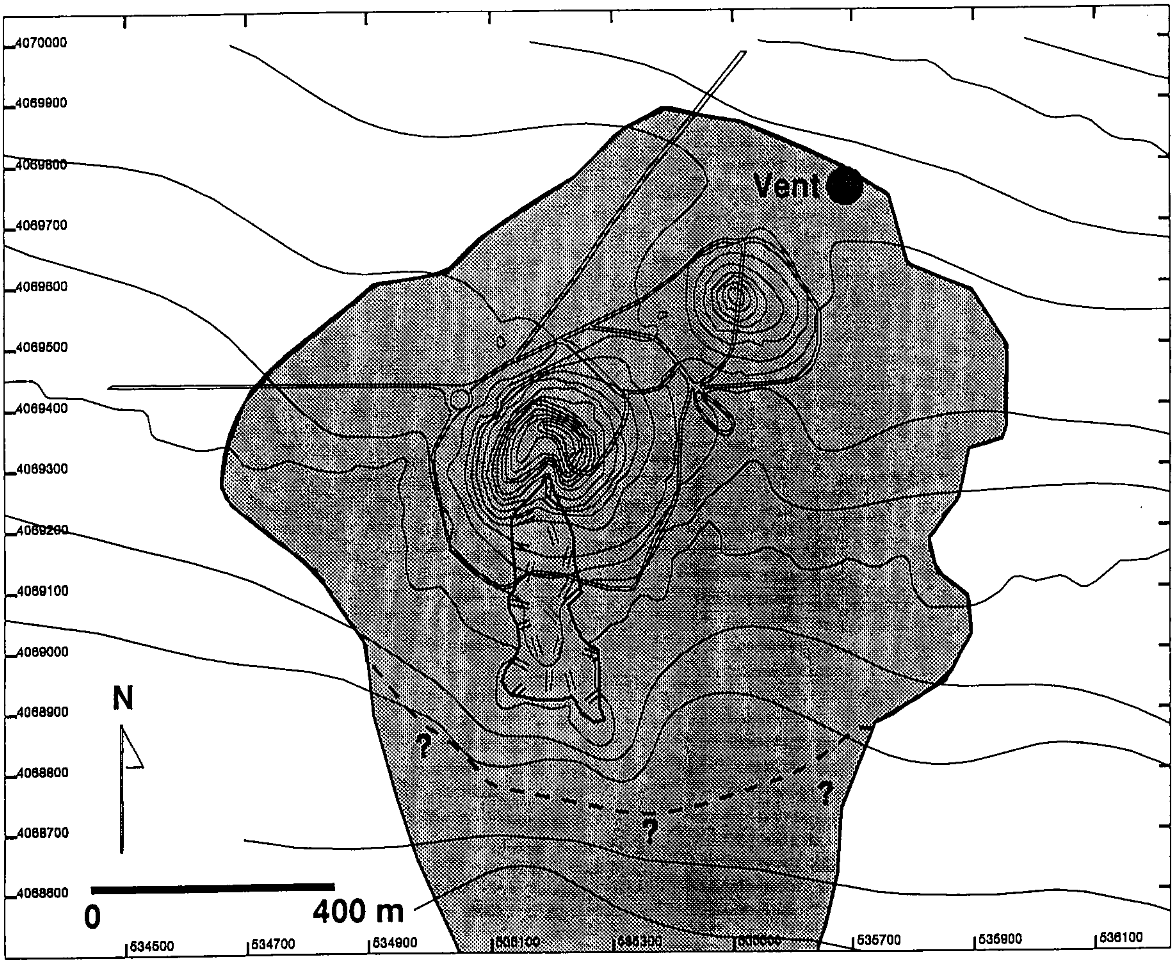

Figure 2-16. The extent of buried lava flows in the survey area is indicated by shading, based on interpretation of magnetic data presented on Plate 1, modeling, and map enhancement. Buried lava flows extend beyond the survey area, south of the queried, dashed line, but an unknown distance. Position of a possible buried vent northeast of NE Little Cone is also indicated. Lava flows crop out only in the area extending approximately 300 m south of SW Little Cone, shown by hatchured pattern.

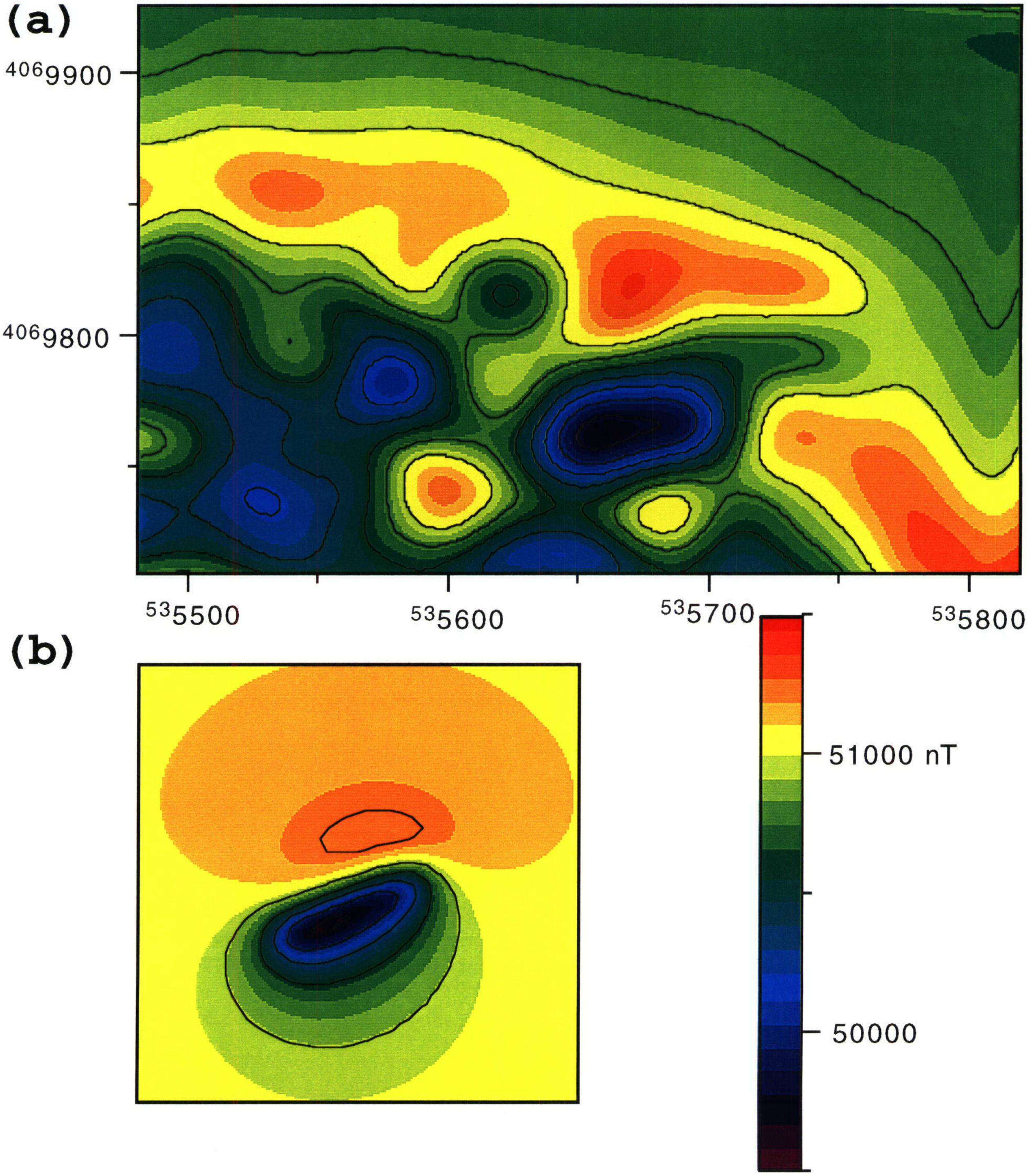

Figure 2-17. (a) Low-pass filtered magnetic map of the high-resolution survey area north of NE Little Cone, and (b) calculated magnetic anomaly using a vertical-sided polygon extending from the base of the lava flow to great depth. See Figure 2-9 for model geometry and Figure 2-11 for fit between model geometry and observed magnetic data.

3 SUMMARY

One of the primary goals of this magnetic survey was to evaluate the utility of ground magnetic data for characterizing igneous intrusions and related structures at small-volume basaltic volcanoes in the YM region. This activity was undertaken because two KTUs associated with volcanism:

- Low resolution of exploration techniques to detect and evaluate igneous features and

- Inability to characterize many igneous features and events

will likely have a strong impact on assessment of volcanism studies and hazard assessments as part of license evaluation. These KTUs exist because surface geological studies of volcanism provide an incomplete and necessarily biased view of the extent of igneous activity in the YM region (Trapp and Justus, 1992). If investigations do not provide additional insight into the extent of igneous activity, then conservative assumptions are required to compensate for lack of investigation in order to fulfill the siting criteria described in 60.122(a)(2)(ii). Thus, current probability models based on the frequency of volcanic events (e.g., Connor and Hill, 1995; Crowe et al., 1995) are biased toward lower probabilities for igneous activity in the YM region and therefore do not meet the siting criteria of 60.122(a)(2)(ii). Furthermore, the area disrupted by volcanic activity may be underestimated without the application of geophysical methods. Conversely, assumptions about the volume of undetected igneous activity can be overly conservative, resulting in estimates of probability of volcanic disruption that are higher than warranted by the geology of the region. Geophysical investigations provide the empirical evidence required to formulate realistic and conservative volcanic hazard models that do meet siting criteria.

Trapp and Justus (1992) point out that site investigations should seek a balance between the intensity of geophysical investigations and the assumptions made in volcano probability models. Ground magnetic surveys made at the Little Cones are one example of the type of investigation that can bound the extent of igneous activity near YM. The volcanological history of the Little Cones has been augmented by the magnetic survey in several ways:

- The volume of Little Cones magmatism is much greater than is represented by surface deposits and the cones are surrounded by a lava flow field.

- NE Little Cone is interpreted to consist of a spatter mound mantled by a weakly magnetized, unconsolidated layer of pyroclastic material, indicating that the early-stage of cone building activity was highly effusive.

- The interpretation that the magnetic anomaly northeast of NE Little Cone represents a vent or shallow dike suggests that eruptive activity in the area may have been distributed among several vents distributed over at least 600 m at the outset of the eruption and in an orientation consistent with the orientation of the entire Quaternary Crater Flat alignment. The eruption then localized at the two Little Cones.

- Shallow dikes do not extend northeast of the survey area, based on the low magnetic gradients observed in that area.

Thus, volcanological information, required to evaluate compliance with siting criteria, was revealed using low-cost ground magnetic surveys. Selective investigations at other volcanoes in the area, such as Northern Cone, would likely improve the basis for assumptions made in volcanic hazard assessment.

Insight into intrusion geometry was hampered at the Little Cones by the presence of the lava flow field discovered in the course of the survey. The magnetization of these lava flows prevented detection of intrusions associated with the cones. The area impacted by shallow intrusions will likely be best revealed by a combination of mapping and geophysical investigations at eroded alignments, such as the Pliocene Basalt of Crater Flat.

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APPENDIX A

TABLE OF MAGNETIC SURVEY DATA

This table gives the Universal Transverse Mercator (UTM) coordinates and drift-corrected magnetic readings made at survey points on and around the Little Cones (Plate 1). UTM coordinates are reported to the nearest meter and magnetic readings to the nearest nanoTesla. Data were filtered using a Fast Fourier Transform (FFT) and high-pass filter. The FFT derivative indicates areas of large-amplitude, short-wavelength anomalies. This filtering was done on a line-by-line basis and recontoured (Figure 2-15). In some cases the FFT filter could not be applied (blank) and the derivative could not be determined (nd) because of the few data on some lines.

ID #	UTM East (m)	UTM North (m)	Total Magnetic Field Drift Corrected (nT)	FFT Filtered Data (nT)	FFT Derivative Data (nT)
0	535415	4069772	50480		nd
1	535361	4069544	50578	-30	451
2	535375	4069590	50714	47	72
3	535375	4069590	50714	427	116
4	535385	4069588	50783	457	233
5	535394	4069586	50970	697	4224
6	535404	4069585	51172	652	3675
7	535413	4069583	51160	756	1061
8	535423	4069581	51210	570	6161
9	535432	4069579	51663	533	6792
10	535441	4069576	50768	234	5227
11	535451	4069574	49764	163	1183
12	535460	4069572	48957	-105	1524
13	535469	4069570	49736	-127	8918
14	535477	4069568	51099	-227	9822
15	535485	4069566	51084	-197	6492
16	535493	4069564	49610	-127	1238
17	535501	4069562	49025	-88	1613
18	535509	4069560	50321	39	3967
19	535517	4069558	50917	-1	1779
20	535526	4069557	50999	95	1517
21	535535	4069555	50621	-152	1826
22	535544	4069554	50029	-86	4151
23	535553	4069553	49810	-574	3090
24	535562	4069552	50341	-509	1541
25	535575	4069547	48906	-1034	6371
26	535589	4069542	48501	-971	7787
27	535602	4069537	49236	-1210	5258
28	535616	4069532	49431	-1140	9250
29	535624	4069530	48967	-969	3994
30	535633	4069527	49058	-834	1834
31	535642	4069525	49714	-473	1885
32	535651	4069523	50290	-215	1303

ID #	UTM East (m)	UTM North (m)	Total Magnetic Field Drift Corrected (nT)	FFT Filtered Data (nT)	FFT Derivative Data (nT)
1439	534954	4069334	50481	-104	538
1440	534972	4069331	50223	-139	4016
1441	534991	4069327	50681	-32	3950
1442	535009	4069324	50824	18	1123
1443	534817	4069135	50764	131	167
1444	534803	4069147	50688	40	148
1445	534789	4069158	50547	191	14
1446	534774	4069170	50428	-85	113
1447	534760	4069182	50423	-133	129
1448	534745	4069194	50402	-202	117
1449	534731	4069205	50395	-179	106
1450	534716	4069217	50319	-130	711
1451	534702	4069229	50398	-63	149
1452	534687	4069240	50794	140	59
1453	534673	4069252	50883	208	273
1454	534658	4069264	50820	263	788
1455	534644	4069276	50772	235	31
1456	534629	4069287	50737	185	27
1457	534615	4069299	50673	124	3
1458	534600	4069311	50646	105	15
1459	534586	4069323	50623	-35	8
1460	534571	4069334	50617	57	5
1461	534557	4069346	50603	43	1
1462	534542	4069358	50608	41	3
1463	534528	4069369	50600	34	1
1464	534513	4069381	50585	24	2
1465	534499	4069393	50580	23	0
1466	534484	4069405	50584	25	0
1467	534470	4069416	50582	16	3
1468	534455	4069428	50594	25	2
1469	534830	4069296	50451	-283	1159
1470	534995	4069765	50645	48	2
1471	534835	4069449	50557		nd

33	535660	4069521	50709	0	1102	1472	534844	4069465	50546	-39	6
34	535669	4069518	50899	350	5245	1473	534852	4069482	50569	3	18
35	535678	4069516	50533	287	1663	1474	534861	4069499	50595	33	9
36	535687	4069514	51330	617	1668	1475	534869	4069515	50779	213	9
37	535696	4069511	50785	395	1156	1476	534878	4069532	50854	260	14
38	535705	4069509	50599	610	1207	1477	534886	4069549	51028	396	119
39	535713	4069507	50679	380	383	1478	534894	4069565	51005	375	9
40	535720	4069505	50746	489	2723	1479	534903	4069582	50916	343	108
41	535727	4069502	50764	276	1656	1480	534911	4069599	50830	280	59
42	535733	4069500	50877	349	1656	1481	534920	4069615	50797	220	62
43	535375	4069590	50714		nd	1482	534928	4069632	50737	157	2
44	535389	4069638	50628		nd	1483	534936	4069649	50710	132	1
45	535414	4069731	50796		nd	1484	534945	4069665	50686	107	1
46	535441	4069670	50820	57	8115	1485	534953	4069682	50679	93	1
47	535464	4069762	50548	-211	4022	1486	534962	4069699	50667	74	4
48	535441	4069670	50812	-133	1085	1487	534970	4069715	50656	72	4
49	535423	4069581	51207	381	1759	1488	534978	4069732	50653	69	2
50	535469	4069570	49730	-887	5894	1489	534987	4069749	50647	52	6
51	535517	4069558	50905	-570	6987	1490	534995	4069765	50645	-4	1
52	535497	4069581	50834	123	5419	1491	535007	4069761	50649	-18	7
53	535875	4069939	50700	85	48	1492	535019	4069757	50658	-20	7
54	535866	4069921	50690	-35	48	1493	535032	4069753	50660	-13	0
55	535857	4069903	50698	7	152	1494	535044	4069748	50676	0	0
56	535848	4069885	50702	-33	214	1495	535056	4069744	50693	17	6
57	535840	4069867	50714	-53	288	1496	535068	4069740	50699	37	14
58	535831	4069849	50742	46	487	1497	535080	4069735	50726	50	14
59	535822	4069831	50741	-2	267	1498	535092	4069731	50745	83	16
60	535813	4069813	50759	165	50	1499	535104	4069727	50767	109	9
61	535805	4069795	50786	174	116	1500	535116	4069723	50810	170	75
62	535796	4069777	50821	285	734	1501	535128	4069718	50885	176	23
63	535787	4069759	50871	364	433	1502	535140	4069714	50944	143	1107
64	535778	4069741	50952	344	1143	1503	535152	4069710	50834	88	810
65	535770	4069723	51088	446	145	1504	535165	4069705	50541	-113	336
66	535761	4069705	51310	398	3167	1505	535177	4069701	50408	-172	671
67	535752	4069687	51263	380	711	1506	535189	4069697	50311	-346	681

68	535744	4069669	51080	302	1824	1507	535201	4069693	50387	-277	16
69	535735	4069651	50397	-63	1565	1508	535213	4069688	50271	-299	853
70	535726	4069633	50580	137	389	1509	535225	4069684	50480	-187	858
71	535717	4069615	50586	-250	1093	1510	535237	4069680	50746	10	267
72	535709	4069598	50297		nd	1511	535249	4069676	50749	80	269
73	535514	4069591	52029	405	2099	1512	535261	4069671	50845	118	191
74	535530	4069601	51904	618	2099	1513	535273	4069667	51102	274	1581
75	535546	4069611	49921	-309	1198	1514	534995	4069765	50657	-36	3
76	535563	4069621	51061	473	1720	1515	535415	4069772	50451	-196	699
77	535579	4069631	50531	-494	2712	1516	535398	4069772	50712	-62	332
78	535596	4069641	50810	134	550	1517	535381	4069772	50737	-97	295
79	535612	4069651	50410	-483	1849	1518	535365	4069771	50611	-115	55
80	535628	4069661	51210	-95	1010	1519	535348	4069771	50783	28	98
81	535645	4069671	50803	-153	9717	1520	535331	4069771	50816	18	61
82	535661	4069681	50530	-187	749	1521	535314	4069771	50804	100	13
83	535678	4069691	50813	-6	1065	1522	535297	4069770	50871	164	48
84	535694	4069701	50595	-71	1994	1523	535281	4069770	51008	210	15
85	535710	4069712	50719	17	696	1524	535264	4069770	51018	217	112
86	535727	4069722	50971	12	947	1525	535247	4069769	51013	254	3
87	535743	4069732	51158	121	1079	1526	535230	4069769	50932	183	21
88	535760	4069742	51150	106	114	1527	535213	4069769	50854	117	22
89	535776	4069752	50978	108	1655	1528	535197	4069769	50798	70	38
90	535792	4069762	50876	128	734	1529	535180	4069768	50760	-10	35
91	535809	4069772	50822	19	523	1530	535163	4069768	50741	-44	44
92	535825	4069782	50785	17	287	1531	535146	4069768	50716	-37	0
93	535842	4069792	50767	-99	499	1532	535130	4069768	50706	-48	1
94	535858	4069802	50750	-185	254	1533	535113	4069767	50693	-59	22
95	535874	4069812	50736	-148	236	1534	535096	4069767	50682	-55	21
96	535891	4069822	50733	-216	348	1535	535079	4069767	50677	-85	38
97	535907	4069832	50722	-127	351	1536	535062	4069766	50674	-109	36
98	535924	4069842	50727	-74	209	1537	535046	4069766	50672	-93	0
99	535497	4069581	50847	52	698	1538	535029	4069766	50635	-114	21
100	535496	4069591	50761	154	698	1539	535012	4069766	50659	-78	5
101	535495	4069601	50558	90	4028	1541	534959	4069374	50527	-233	187
102	535493	4069611	51064	235	2416	1542	534975	4069389	50355	-291	421

103	535492	4069621	50910	81	19	1543	534992	4069403	50556	-175	436
104	535491	4069630	50934	161	1318	1544	535009	4069418	50594	-153	2
105	535489	4069640	50883	-80	7069	1545	535026	4069433	50641	-87	6
106	535488	4069650	50530	-47	6815	1546	535043	4069447	50926	170	4
107	535487	4069660	49991	-268	1680	1547	535059	4069462	50867	136	8
108	535486	4069670	50417	-213	1762	1548	535076	4069476	51111	294	284
109	535484	4069680	50465	-274	55	1549	535093	4069491	51076	276	108
110	535483	4069690	50322	-214	1819	1550	535110	4069506	50840	191	240
111	535482	4069700	50595	-185	1198	1551	535126	4069520	50921	217	355
112	535480	4069710	50803	-166	7331	1552	535143	4069535	50975	173	125
113	535479	4069720	50592	-212	6782	1553	535160	4069550	50872	132	191
114	535478	4069730	50436	-221	1432	1554	535177	4069564	50771	93	194
115	535476	4069740	50242	-283	2401	1555	535194	4069579	50878	165	157
116	535475	4069749	50182	-280	2370	1556	535210	4069593	50904	150	29
117	535474	4069759	50368	-211	3770	1557	535227	4069608	50948	151	153
118	535472	4069769	50555	-193	633	1558	535244	4069623	50976	183	24
119	535471	4069779	50783	-72	2541	1559	535282	4068899	51010		nd
120	535470	4069789	50787	-71	138	1560	535279	4068914	49870	-181	2263
121	535469	4069799	50714	-49	2457	1561	535276	4068930	49546	-214	3645
122	535467	4069809	50574	-69	506	1562	535273	4068945	51008	414	4297
123	535466	4069819	50476	-87	1279	1563	535270	4068960	51113	-245	2581
124	535465	4069829	50432	-78	1513	1564	535267	4068976	51795	740	3211
125	535463	4069839	50558	-5	1528	1565	535264	4068991	49552	-84	3030
126	535462	4069849	50763	61	1370	1566	535261	4069006	50226	254	1845
127	535461	4069858	50923	187	256	1567	535258	4069022	51756	453	3383
128	535459	4069868	51023	256	417	1568	535255	4069037	51014	239	1107
129	535458	4069878	51090	315	150	1569	535252	4069052	50730	485	4972
130	535457	4069888	51071	328	493	1570	535249	4069068	50921	392	4
131	535456	4069898	50988	293	352	1571	535246	4069083	50773	244	970
132	535454	4069908	50908	262	115	1572	535243	4069098	50681	279	668
133	535453	4069918	50849	195	54	1573	535240	4069114	50826	370	270
134	535452	4069928	50815	161	1	1574	535237	4069129	50946	397	29
135	535450	4069938	50777	115	40	1575	535234	4069144	50973	440	905
136	535449	4069948	50752	88	7	1576	535231	4069159	51083	677	1663
137	535448	4069958	50754	70	32	1577	535228	4069175	50957	633	1169

138	535446	4069968	50724	45	3
139	535445	4069977	50720	36	0
140	535444	4069987	50706	18	3
141	535444	4069987	50705	-27	9
142	535463	4069985	50673	-47	7
143	535483	4069983	50677	-50	2
144	535503	4069981	50680	-54	1
145	535522	4069979	50682	-55	0
146	535542	4069976	50695	-43	1
147	535561	4069974	50690	-45	0
148	535581	4069972	50700	-32	1
149	535600	4069970	50692	-37	1
150	535620	4069968	50696	-36	0
151	535640	4069965	50701	-33	0
152	535659	4069963	50689	-43	0
153	535679	4069961	50700	-31	0
154	535698	4069959	50694	-40	1
155	535718	4069956	50716	-22	1
156	535737	4069954	50707	-29	0
157	535757	4069952	50709	-20	1
158	535777	4069950	50699	-27	2
159	535796	4069948	50707	-24	1
160	535816	4069945	50710	-28	1
161	535835	4069943	50713	-26	2
162	535855	4069941	50707	-24	1
163	535875	4069939	50707	-21	1
164	535875	4069939	50707	-24	201
165	535860	4069925	50705	18	84
166	535846	4069911	50712	2	10
167	535831	4069898	50717	4	54
168	535816	4069884	50737	133	92
169	535802	4069870	50741	119	658
170	535787	4069856	50764	223	28
171	535773	4069842	50803	260	561
172	535758	4069829	50905	187	1303

1578	535225	4069190	51571	895	2866
1579	535221	4069205	51435	215	2445
1580	535218	4069221	51144	-104	4443
1581	535215	4069236	49209	-647	9496
1582	535212	4069251	47740	-1383	1217
1583	535209	4069267	49958	-715	5669
1584	535206	4069282	50450	-1040	4141
1585	535203	4069297	50067	-975	6551
1586	535200	4069313	49662	-463	4423
1587	535197	4069328	48296	-1298	5429
1588	535204	4069338	50428	-86	2201
1589	535211	4069347	50567	-552	1275
1590	535217	4069356	51343	904	1942
1591	535217	4069356	51343	432	1275
1592	535171	4069110	48321	-1145	5309
1593	535196	4069360	50794	94	3213
1594	535175	4069363	49854	-310	5845
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1246	535470	4068786	50592	78	1746
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1263	535375	4069147	50903	228	202
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1265	535363	4069176	50882	113	78
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2723	535380	4069416	51205	77	3176
2724	535382	4069426	51236	117	318
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1428	534751	4069372	50676	47	198	2880	535796	4069221	50858	nd
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1430	534788	4069365	50430	-34	1525	2882	535844	4069203	51014	nd
1431	534806	4069362	50433	1	675	2883	535842	4069195	51048	nd
1432	534825	4069358	50655	-8	2363	2884	535840	4069187	51044	nd
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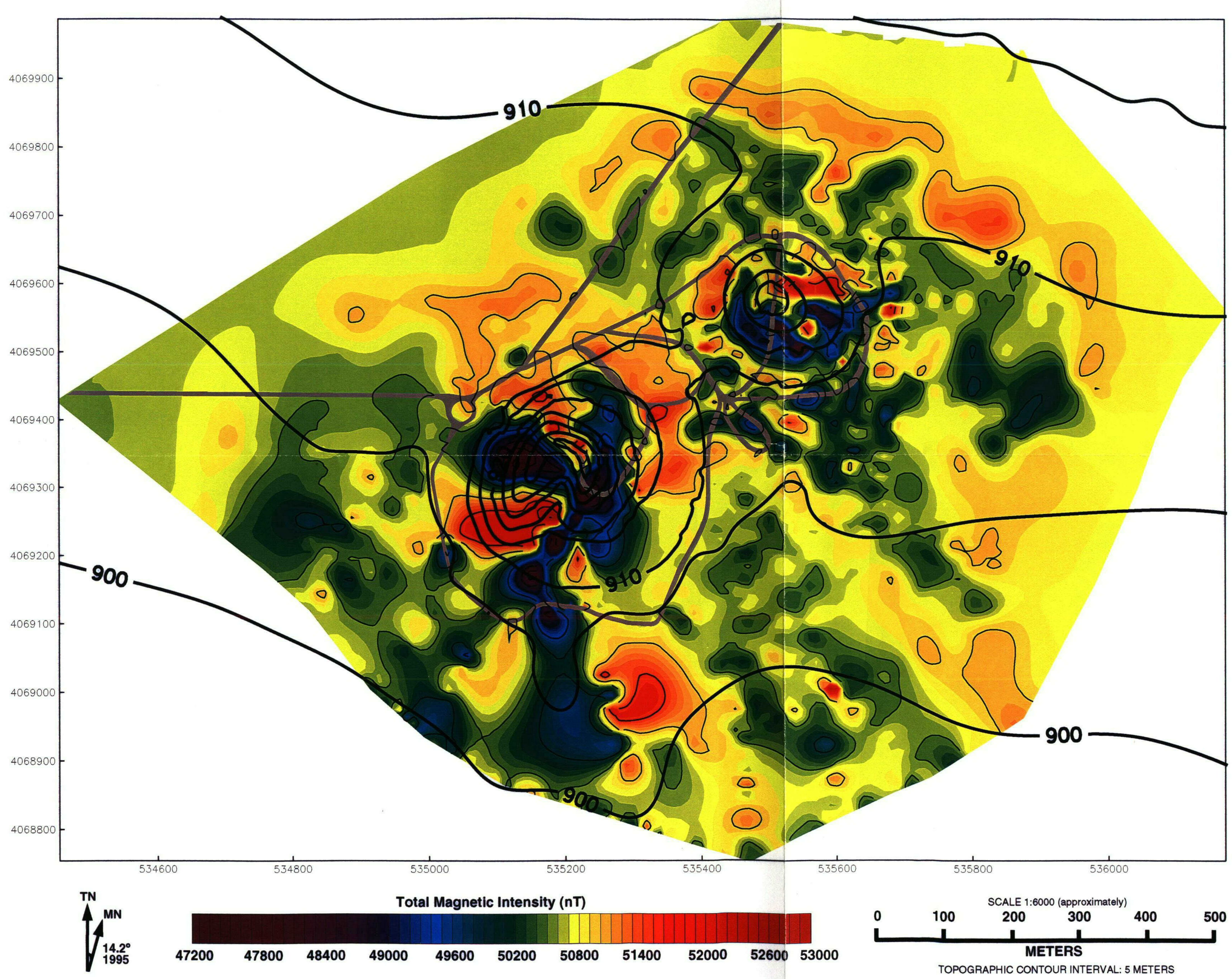
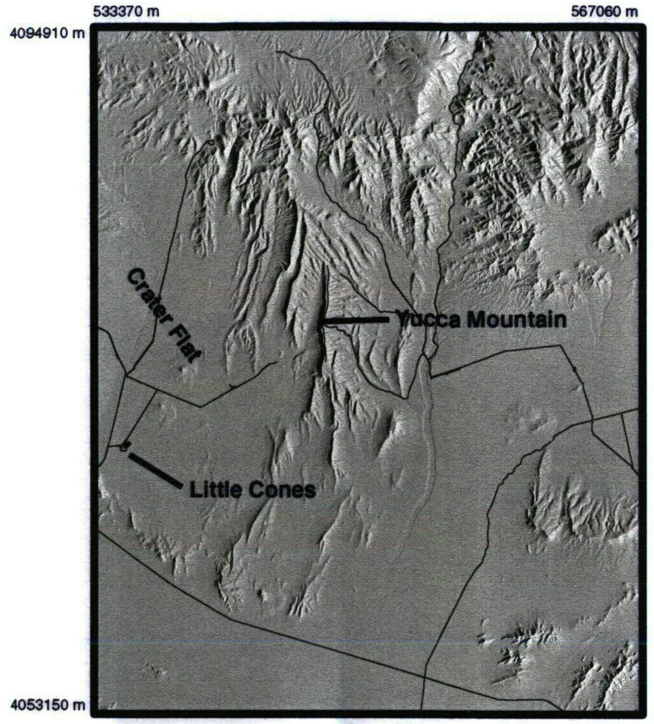
1435	534880	4069348	50522	-47	18	2887	535830	4069147	50655	nd
1436	534898	4069345	50733	-29	435	2888	535828	4069135	50526	nd
1437	534917	4069341	50765	2	8	2889	535799	4069231	50845	nd
1438	534935	4069338	50454	-73	18	2890	535786	4069182	50743	nd

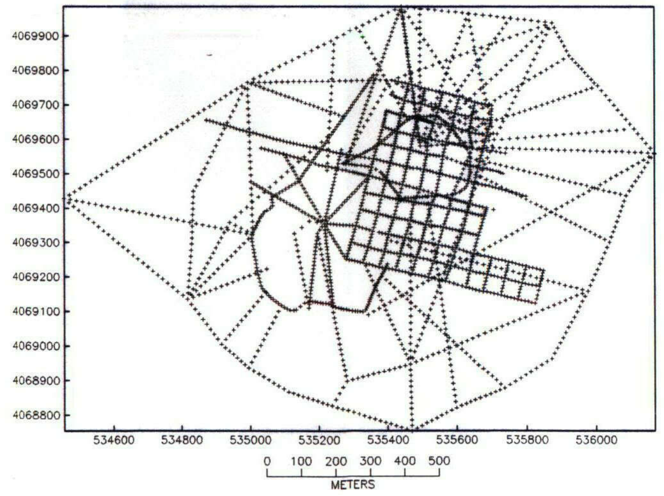
TOTAL MAGNETIC FIELD SURVEY OF THE LITTLE CONES, CRATER FLAT, NYE COUNTY, NEVADA

by Charles B. Connor, Ronald H. Martin, Peggy G. Hunka, Richard Klar, John Stamatakos, Brent Henderson
Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute





Location Map



Survey Point Locations

Explanation

Ground magnetic survey of the Little Cones, Crater Flat, Nevada, showing intensity of the total magnetic field, based on measurements at 2,891 survey points. The total magnetic field was measured using a proto–precession magnetometer with 3 m sensor height. All magnetic data are drift corrected. International Geomagnetic Reference Field for Crater Flat is declination 14.2°, inclination 61.7°, and total intensity 50,827 nT, for January 1, 1995.

Dirt roads in the area are shown by solid gray lines. Topography was surveyed in the vicinity of the Little Cones and referenced to a U.S. Geological Survey 30 m digital elevation model (also see Crater Flat 7.5 min. quadrangle, U.S.G.S. map 36116–G5–TF–24). Map projection is UTM (m), zone 11, Clarke 1866.

This map is part of Center For Nuclear Waste Regulatory Analyses document CNWRA 96–002, Ground Magnetic Survey of the Little Cones, Crater Flat, Nevada, and was produced in cooperation with the U.S. Nuclear Regulatory Commission.

PLATE 1