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Evaluating the Feasibility of Modeling the Subsurface Structure of Two Volcanic Units in Drill Holes UE-18r and ER-EC-2a Using Existing Magnetic Data, Nevada Test Site

By G.A. Phelps

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By G.A. Phelps[1]

Abstract

The magnetic properties of two volcanic units encountered in two drill holes, ER-EC-2a and UE18r, located in the vicinity of the Nevada Test Site, were investigated to determine if the units were significantly more magnetic than overlying units and, thus, detectable by using aeromagnetic data. Magnetic-susceptibility measurements were made on cuttings from the drill holes and were combined with published data on remanent magnetism to generate two-dimensional magnetic models, based on an interpreted geologic cross-section. The resulting magnetic anomaly calculated from the models was compared with the observed aeromagnetic anomaly and was found to differ significantly from it. Furthermore, the calculated magnetic anomalies were found to be relatively insensitive to changes in the two units of interest.

Introduction

Pahute Mesa, located in the northwest corner of the Nevada Test Site, Nye County, Nevada (fig. 1), was the location of multiple underground nuclear tests conducted by the Department of Energy from 1951 to 1992 (U.S. Department of Energy, 2000). Many of these tests were performed below the water table. The Department of Energy's Environmental Restoration Program is investigating the potential migration of radionuclides, by-products of the underground nuclear tests, through the subsurface by way of groundwater flow. Models of groundwater flow beneath Pahute Mesa and the surrounding region show subsurface water flowing south-southwest from Pahute Mesa towards Timber Mountain and the northwestern moat area of the Timber Mountain caldera complex (fig. 1).

The site of the Timber Mountain caldera complex was an eruptive center for at least two caldera-forming eruptions (Slate and others, 2000). The first eruption deposited the

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Rainier Mesa tuff, dated at 11.6 Ma (Sawyer and others, 1994), and formed the larger caldera. The second eruption deposited the Ammonia Tanks tuff, dated at 11.45 Ma (Sawyer and others, 1994), and formed a caldera nested within the first. The calderas partially filled with ash-flow tuff and collapse breccias during caldera formation. After the eruption of the Ammonia Tanks Tuff and formation of the Ammonia Tanks caldera, resurging magma domed up the central portion of the Timber Mountain caldera complex forming Timber Mountain and the surrounding caldera moat. Following the Timber Mountain eruptions, rhyolite flows and tuffs of the Beatty Wash Formation, part of the Fortymile Canyon group, filled much of the calderas, erupting from a series of local vent complexes largely within the moat of the Ammonia Tanks caldera, approximately 11.45–11.4 Ma (Slate and others, 2000; Sawyer and others, 1994). The Fortymile Canyon units in particular formed a thick and complex sequence of rhyolite lava and tuff within the caldera moat (L. Prothro, written comm., 2008). The Trail Ridge Tuff and the Pahute Mesa Tuff of the Thirsty Canyon group, associated with the eruption and collapse of the Black Mountain caldera (northwest of the Timber Mountain caldera complex) approximately 9.4-9.15 Ma, both buried the northwestern region of the moat area of the Timber Mountain caldera complex. The region surrounding the calderas is cut by north-trending normal faults that are the result of middle Miocene extension pervasive in the region.

The northern moat area of the Timber Mountain caldera complex lies just south, and slightly west, of Pahute Mesa, directly in line with the flow of groundwater out of Pahute Mesa. Models of groundwater flow are sensitive to the shape and distribution of aquifers and aquitards in the northern moat region of the Timber Mountain caldera complex (Stoller-Navarro Joint Venture, 2006, 2007, 2009). It is therefore important to map these units in the subsurface, determining their shape and extent. The complex geology of the region, with multiple eruptive volcanic centers overprinted by Miocene extensional normal faulting, often violates the common assumptions that rock units are of relatively uniform thickness and material properties and have a broad lateral extent. The available surface and limited subsurface data (drill holes UE-18r and ER-EC-2a) suggests that potentially important aquifers (welded ash-flow tuffs and rhyolitic lavas) occur in the subsurface, but their overall shape, thickness, and lateral extent is poorly constrained. Investigating methods that might help constrain the mapping of these aquifers is important for reducing the uncertainty of hydrogeologic models of the region.

Two drill holes, UE-18r and ER-EC-2a (fig. 2), penetrate a series of volcanic rocks in the northern moat area of the Timber Mountain caldera complex. While the down-hole volcanic rocks are identifiable and can be assigned to formations, at least two local members of the Beatty Wash formation encountered in the drill holes do not occur at the surface. Since these buried members are likely to be fracture-flow aquifers embedded in a nonwelded tuff aquitard, their lateral extent could have a significant effect on subsurface water flow in the area, and mapping their extent is an important constraint on hydrologic models developed for the region. However, because the units do not crop out, their extent must either be mapped indirectly or inferred using geologic reasoning.

The extent of the two members of the Beatty Wash formation provides important constraints on mapping the subsurface geology of the region (L. Prothro, written commun., 2008). In drill hole ER-EC-2a, an approximately 40-m-thick, partially welded tuff, which had not been mapped previously, was encountered at a depth of 830 m. In drill hole UE-18r, the top of a 200-m-thick lava flow was encountered at a depth of 122 m. Both these units are within the Beatty Wash formation. The lava flow may correlate with the lava flow exposed at the surface at the location of drill hole ER-EC-2a, 11 km to the west.

One method of indirectly mapping the magnetic units, across an east-west zone of interest extending between drill-holes ER-EC-2A and UE-18r, is modeling based on aeromagnetic data. This study investigates the feasibility of mapping the extent of two units encountered in drill holes UE-18r and ER-EC-2a, along an east-west profile connecting the drill-holes and perpendicular to the structural normal faults, by looking for changes in the local magnetic field that may be attributed to these units. Aeromagnetic data potentially can discriminate discrete bodies if the magnetic properties are distinct and separable from the surrounding rock. Demonstrating the efficacy of aeromagnetic data in this particular case would provide another tool for mapping similar subsurface geologic units in other parts of the moat.

Data

An aeromagnetic survey over the Timber Mountain region, which includes the northern moat area of the Timber Mountain caldera complex, was flown in 1967 (Kane and others, 1981). This survey was flown at a height above ground of 122 m, with an east-west oriented line spacing of 400 m; therefore, magnetic bodies shallower than approximately 800 m below the instrument will be poorly resolved in the north-south direction, owing to aliasing in the power spectrum at high wave numbers. Along individual flight lines in the east-west direction, a much finer resolution is possible because of the high density of information along the flight lines. Figure 2 shows the shaded relief topography and the unfiltered aeromagnetic data for the study area.

The moat area of the Timber Mountain caldera complex is filled with volcanic rocks derived from the Thirsty Canyon group, Beatty Wash formation, and the Timber Mountain group. Drill holes UE-18r, with a total depth of 1,525 m, and ER-EC-2a, with a total depth of 1,461 m, encountered volcanic rocks throughout the entire section. ER-EC-2a bottomed in tuffs from the Ammonia Tanks formation, and UE-18r bottomed in tuffs from the Rainier Mesa formation, both of the Timber Mountain group.

The total magnetization of a given volcanic unit is measurable and can be used to model the shapes of magnetic bodies in the subsurface, assuming the induced and remanent magnetic properties can be treated as homogeneous within a given volcanic unit. The volcanic rocks of the study area generally are very magnetic, with a significant component of remanent magnetism, and at least two of the units in the region are reversely magnetized (Hudson and others, 1994; Grauch and others, 1999; Slate and others, 2000).

Published data for the total magnetization of samples of volcanic units within the Thirsty Canyon and Timber Mountain groups and the Beatty Wash formation provide estimates for the total magnetization of volcanic units within the study area (Hudson and others, 1994; Grauch and others, 1999; Slate and others, 2000). However, the total magnetization is not necessarily uniform for a given volcanic unit, and a range of values, rather than a single value, is published. The range of total magnetization of each unit is listed in table 1. The variability of the magnetic properties of the volcanic units must be considered when modeling the shapes of these units in the subsurface.

The volume susceptibility for each unit was measured on available samples from both drill holes, ER-EC-2a and UE-18r (fig. 3; appendix I). The measurements were made with a hand-held KT-6 susceptibility meter. Cuttings were the only material available, so the susceptibility was measured by placing the meter against the sand- to gravel-sized cutting fragments, which are contained in small cardboard boxes approximately 5x5x12 cm in dimension, each representing intervals of 10 ft. Five to six measurements were made on each sample. Since the measurements were made using cuttings, the readings are probably biased low by a factor of 2 or 3 (Phelps and others, 2004). Taking the bias into account, the susceptibility measurements ranged from approximately 1 to 3 x 10^{-3} SI. This is consistent with the magnetic susceptibilities for rhyolites in the vicinity of the Nevada Test Site measured by Bath (1968). Figure 3 shows the measured magnetic susceptibilities and elevation, symbolized by rock unit.

Methods

A forward modeling approach was used to estimate the anomalies that could be caused by various units in the study area. The volcanic units of the Forty Mile Canyon group and younger are likely shallower than about 700-m depth and, therefore, would be poorly modeled in the north-south direction because 400-m line spacing is too coarse to resolve them. The units, therefore, need to be modeled east-west in the direction of the individual flight lines. If the contribution to the calculated magnetic anomaly from surrounding volcanic units is larger than the contribution from the volcanic unit of interest, then it will be difficult to model the unit of interest because changes in the shape of the other volcanic units will have greater influence on the modeled magnetization.

The induced magnetism does not contribute significantly to the total magnetization of the two volcanic rocks units in question, which is in agreement with the previous results of Bath (1968). The shape and magnitude of the calculated anomaly is primarily controlled by the remanent magnetism and shape of the volcanic units.

Figure 4 shows an idealized cross-section through drill holes ER-EC-2a and UE-18r (geology from L. Prothro, written commun., 2008). The magnetization of each unit was assigned using the values shown in parentheses in table 1. Because a range of values exists, values were chosen to maximize the magnetic anomaly generated by the two volcanic rock units in question. This represents a ―best case" scenario for detecting the two volcanic rock units. Models that include the effect of the induced magnetization do not change the calculated magnetic profile shown in figure 4 by more than the width of the line. Where data on the orientation of the remanent magnetization vector were not available, the orientation of the present day field was used. Following the approximation proposed by Bath (1968), if the remanent magnetization vector is within 25 degrees of the present day vector, the error of the calculated magnetic fields is less than 10 percent, which is acceptable for this modeling effort.

Table 1. Magnetization used in the cross-sectional models in figure 4. Grey cells highlight units of interest. Numbers in parentheses are the remanent magnetization values (in degrees) used for the models shown in figure 4.

Geologic Unit	Cross-section unit	Remanent magnetization magnitude [A/m]*	Inclination*	Declination*
Thirsty Canyon tuff (Ttt, Ttp, Ttr, Tt)	Ttp	0.5-1.5 *(0.5)*	-8	170
Beatty Wash formation (Tfbw)	Tfbw welded	0.5-1.5 *(1.5)*	60	14
(Tfbw, Tfb, Tf)	Tfb non-welded	0.5-1.5 *(0.5)*	60	14
(Tfb welded)	Tfb	0.5-1.5 *(1.5)*	60	14
Ammonia Tanks tuff (Tma, Tm)	Tma	>1.5 *(1.5)*	63	3
(Tmat)	Tmat	>1.5 *(1.5)*	63	3
Rainier Mesa tuff (Tmr)	Tmr	>0.5 *(1.5)*	-50	175

* from Hudson and others, 1994; Grauch and others, 1999; and Slate and others, 2000.

Discussion

The profiles in figure 4 demonstrate two key points. First, given the assigned magnetizations, there could be a small, but noticeable, change in the observed aeromagnetic anomaly due to a change in the shape of the Beatty Wash formation lava flow (―Tfbw” in fig. 4, top), or the Beatty Wash formation welded tuff encountered in drill hole ER-EC-2a (―Tfb welded” in fig. 4, bottom). Second, the interpretive geologic cross-section and the values used for the magnetism of volcanic rocks do not match the observed aeromagnetic anomaly, indicating that the geologic structure below the surface is more complex than is shown in the interpretive cross-section. While the calculated anomaly matches the observed anomaly in a gross sense (the calculated anomaly decreases from west to east across the cross-section), individual anomalies on the order of a few kilometers in wavelength are not matched. The observed aeromagnetic anomaly has higher amplitude features, indicating abrupt changes in magnetization below the surface. This could be due to some combination of several factors: an initially heterogeneous distribution of magnetic minerals in the tuffs and lavas, laterally irregular deposition (for example, tuffs filling canyons), hydrothermal alteration, faulting, or a significant difference in the modeled versus actual remanent magnetization. The model is sensitive to the values used for remanent magnetization. Values of remanent magnetization two to four times the size of those used in the model (3-6 A/m) produce anomalies of roughly the same amplitude as anomalies seen in the observed data. Such high values have been measured in tuffs from the Yucca Mountain area (Schlinger and others, 1991) and so are not unreasonable. Improved characterization of the magnetic properties of the rock units in the study area would help constrain at least one of the factors contributing to uncertainty in the model.

The largest positive magnetic anomalies in figure 2 are trending approximately east, indicating that north is the optimal direction for modeling magnetic bodies in cross-section within the study area, perpendicular to the direction of the modeled cross-section. However, modeling in a northerly direction does not help determine the east-west dimensions of the rock units in question.

The modeling indicates that the structure shown in the cross-section in figure 4 lacks sufficient detail to explain the fluctuations in the observed magnetic anomaly, and that fault offsets, or other methods of producing truncated units, are greater than depicted. Additionally, uncertainty in the magnetization, particularly the remanent magnetization, adds to the uncertainty in the calculated magnetic anomaly. Both of these factors conflate, overshadowing the relatively minor changes in the magnetic anomaly caused by modifying the shapes of the two Fortymile Canyon units. An improved understanding of the remanent magnetization and geology, including mineralogy, faulting, and hydrothermal alteration, would constrain the model depicted such that the two Fortymile Canyon units could be modeled with increased certainty. If geologic uncertainty in any such model remains high, however, it is unlikely that magnetic data will be effective in delimiting the extent of these units.

Conclusion

To address the question of whether or not existing aeromagnetic data and data available on the magnetization of the volcanic rocks in the vicinity of drill holes ER-EC-2a and UE-18r could help define the subsurface structure of two volcanic units within the Beatty Wash formation of the Fortymile Canyon group, a model was constructed by using a geologic cross-section and published magnetization values. The model explored the maximum magnetization contrast between these two units and the surrounding units and examined the effect of changing the shape of each unit on the calculated magnetic anomaly. This result was compared to the observed aeromagnetic anomaly to determine if the changes were significant enough to be detected. Although the changes in the calculated magnetic anomaly would cause changes that in theory could be detected, the mismatch between the calculated magnetic anomaly and the observed aeromagnetic anomaly is substantial, indicating that the interpretive geologic cross-section and magnetization data is insufficient to model the subsurface geology. The variations in the calculated magnetic anomaly caused by changing the shape of the two units in question was far less than the changes in structural representation of the geology needed for the geology within the model to be consistent with the observed aeromagnetic anomaly. Thus in order for the observed aeromagnetic anomaly to be used to model the two units in question, the structure and magnetization of the other subsurface volcanic units must be better understood.

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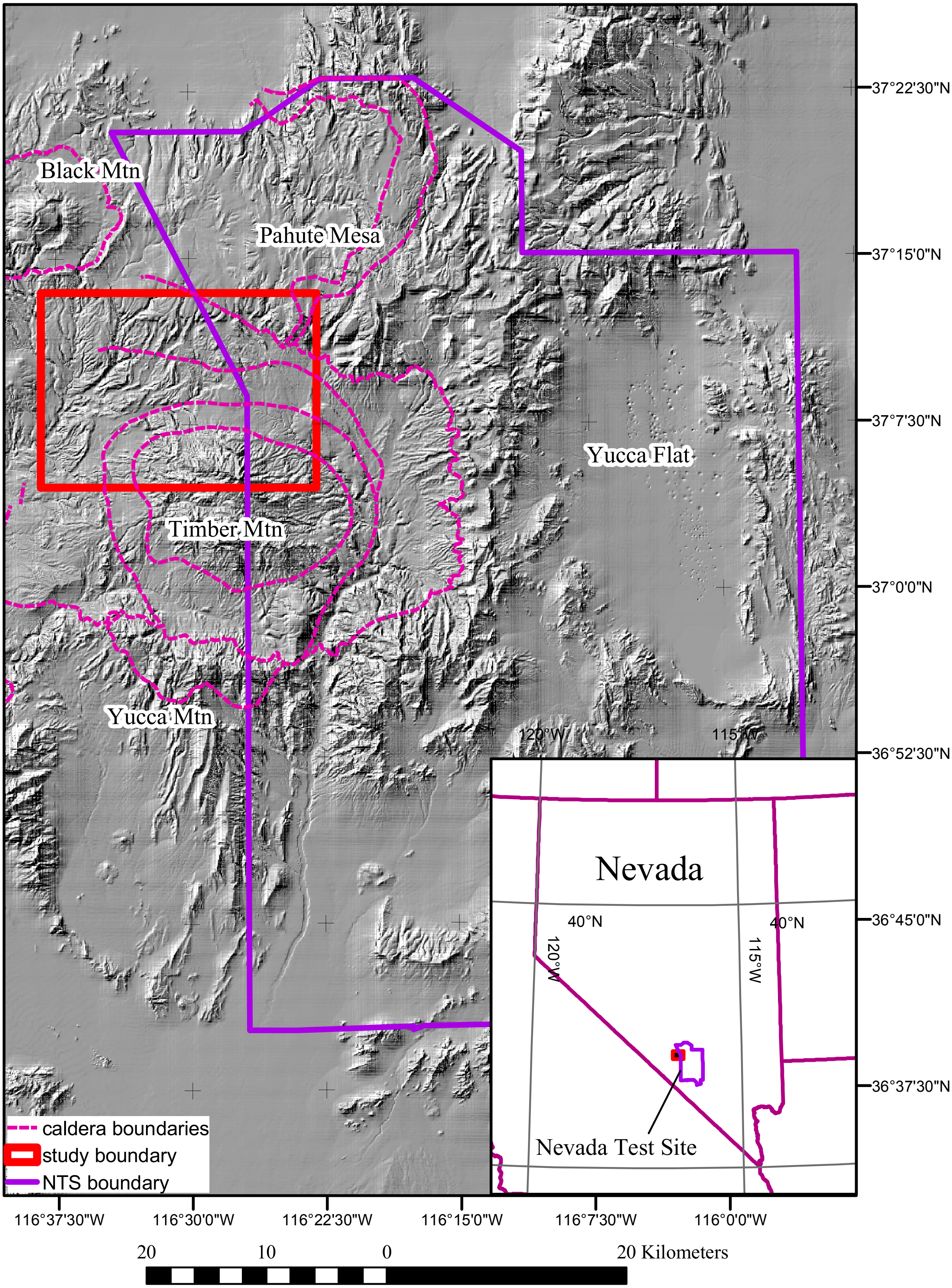

Figure 1. Shaded-relief map of the northern Nevada Test Site. Topography simplified from U.S. Geological Survey seamless National Elevation Dataset.

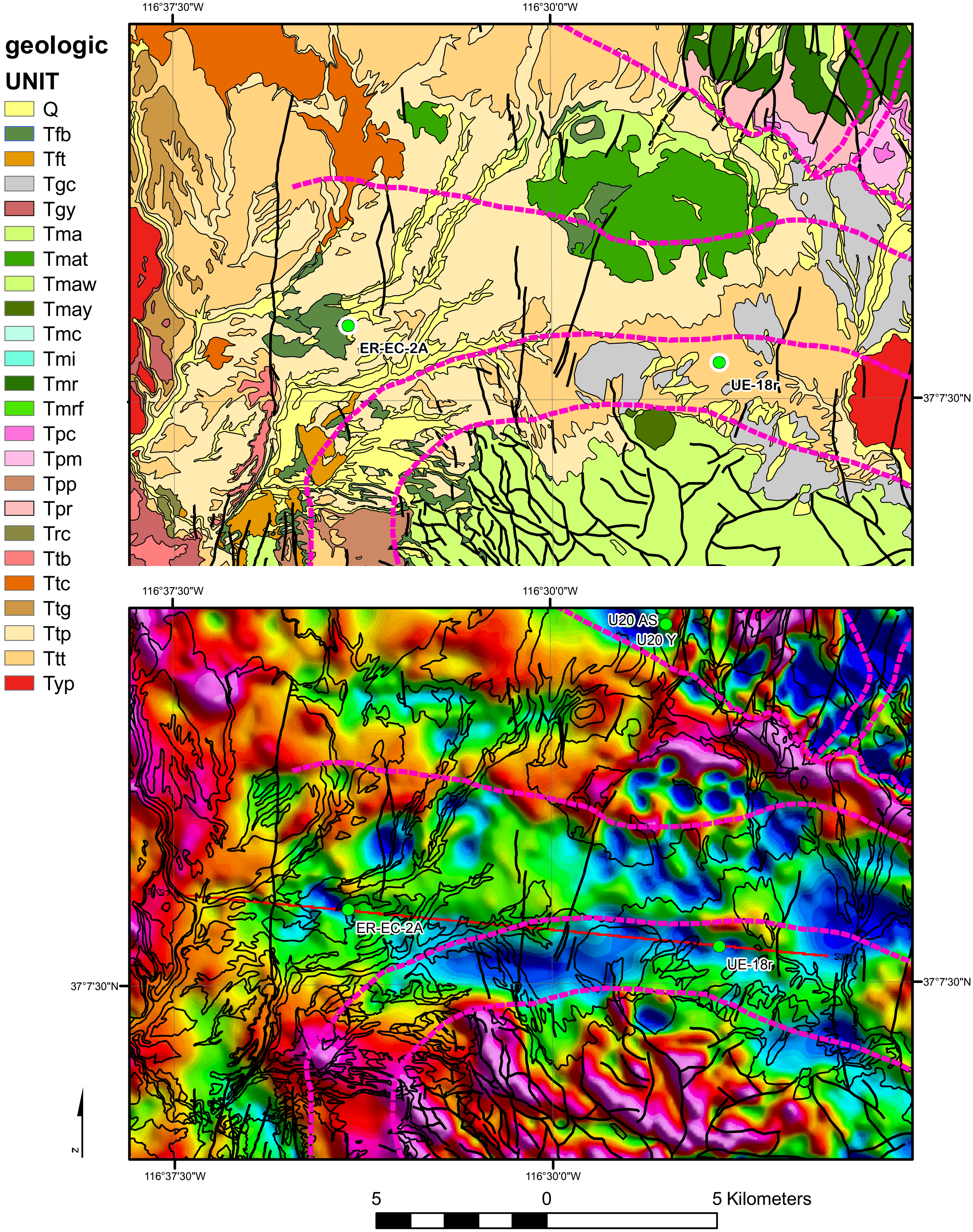

Figure 2. Top - Geologic map of the study area (Slate and others, 2000); thick black lines, faults; thin black lines, contacts; dashed pink lines, caldera boundaries; green dots, drill holes. Bottom – Filtered observed aeromagnetic anomaly, warm colors are positive, cool colors are negative, red line shows the cross-section line of figure 4.

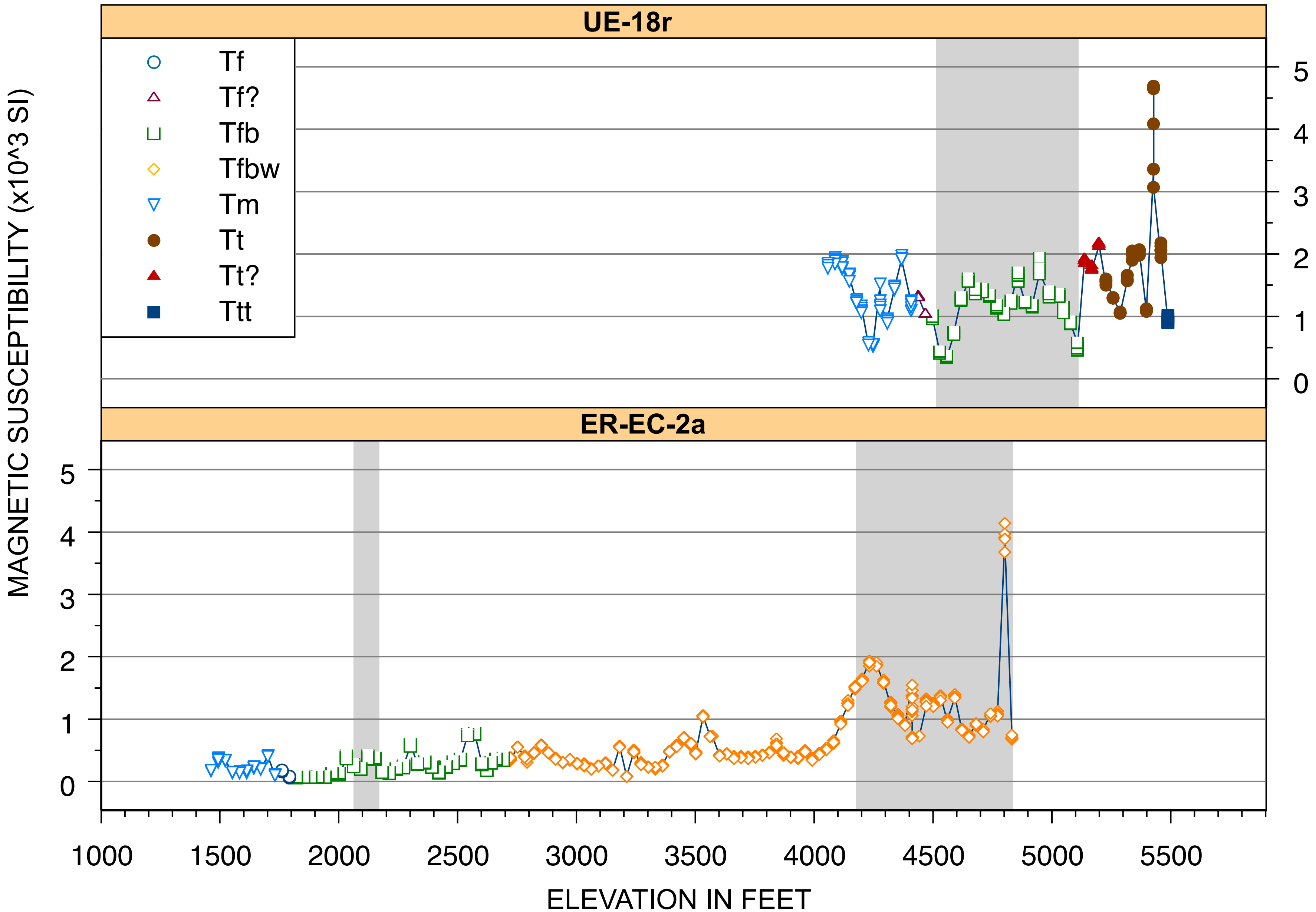

Figure 3. Magnetic-susceptibility measurements for drill holes UE-18r and ER-EC-2a, symbolized by stratigraphic unit. Gray shading indicates sub-units of interest discussed in text and shown in figure 4. All measurements are shown (multiple measurements are shown for each elevation).

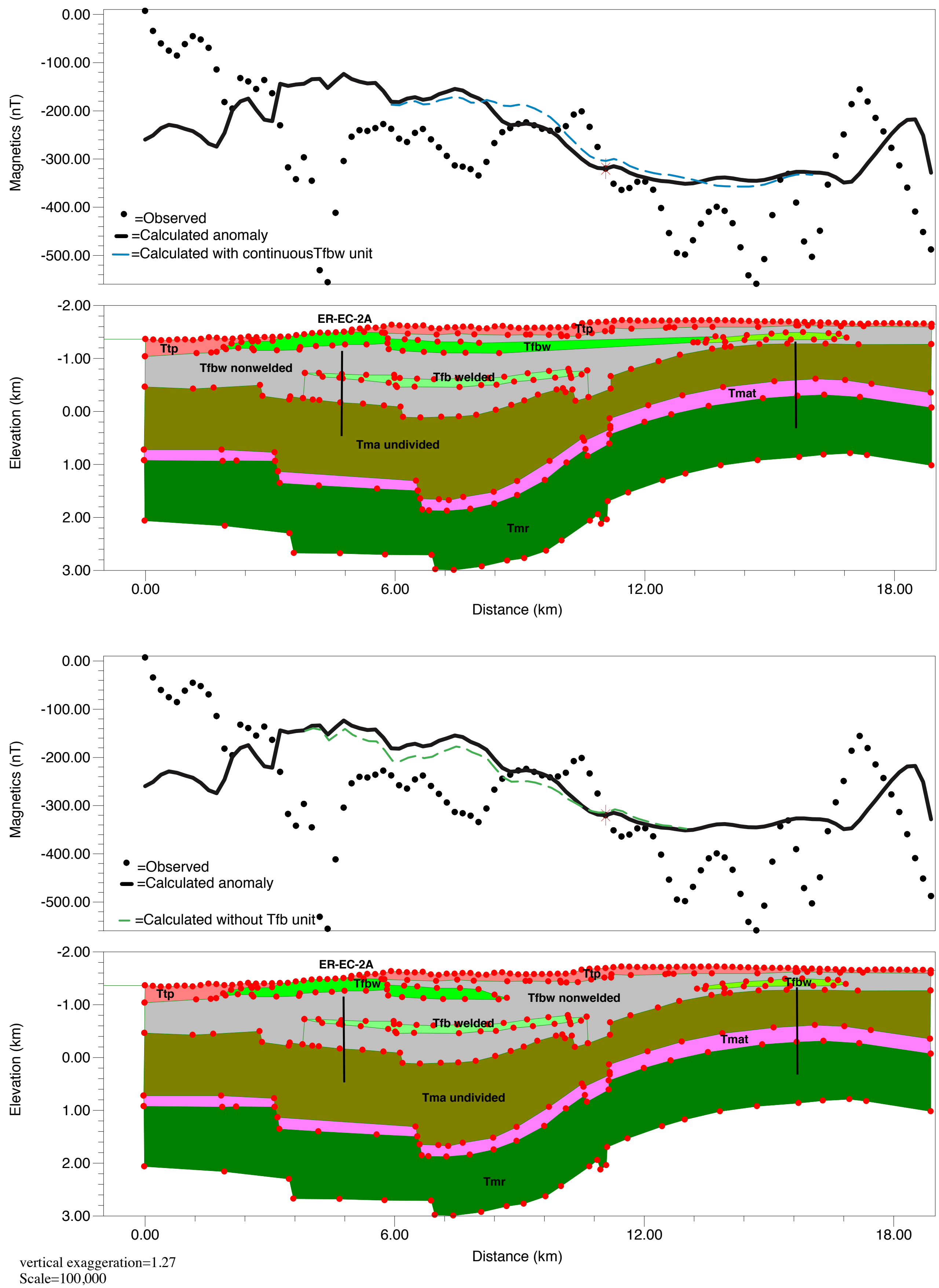

Figure 4. Observed and calculated magnetic anomalies for the near-surface units between drill holes ER-EC-2a and UE-18r. Base calculated anomaly (solid black line) follows the bottom cross-section, with the "Tfb welded" modeled as magnetic. Top – Base calculated anomaly compared with the profile that would occur if the east and west "Tfbw" units were connected (dashed line). Bottom – Base calculated anomaly compared with the profile that would occur if the unit "Tfb welded" were absent or not magnetic (dashed line).

Appendix

Magnetic susceptibility measurements made on drill-hole cuttings by using a hand-held magnetic susceptibility meter. Unit and unit descriptions are summarized from U.S. Department of Energy (2002) and L. Prothro (written commun., 2008).

drillhole	name of the drill hole
unit	geologic unit abbreviation
unitdescription	brief description of the lithology
depthtopft	depth of the top of the interval sampled, in feet
depthbotft	depth of the top of the interval sampled, in feet
susceptibility	magnetic susceptibility measurement, in 10-3 SI
susceptibility2.5x	magnetic susceptibility measurement, in 10-3 SI, multiplied by a factor of 2.5 to account for probable measurement bias

"drillhole", "unit", "unitdescription", "depthtopft", "depthbotft", "susceptibility", "susceptibility2.5x"

"ER-EC-2A", "Tfbw", "pumiceous lava", 60, 70, 0.69, 1.73

"ER-EC-2A", "Tfbw", "pumiceous lava", 60, 70, 0.71, 1.78

"ER-EC-2A", "Tfbw", "pumiceous lava", 60, 70, 0.68, 1.70

"ER-EC-2A", "Tfbw", "pumiceous lava", 60, 70, 0.71, 1.78

"ER-EC-2A", "Tfbw", "pumiceous lava", 60, 70, 0.75, 1.88

"ER-EC-2A", "Tfbw", "pumiceous lava", 90, 100, 3.91, 9.78

"ER-EC-2A", "Tfbw", "pumiceous lava", 90, 100, 4.14, 10.35

"ER-EC-2A", "Tfbw", "pumiceous lava", 90, 100, 3.97, 9.93

"ER-EC-2A", "Tfbw", "pumiceous lava", 90, 100, 3.68, 9.20

"ER-EC-2A", "Tfbw", "pumiceous lava", 90, 100, 3.89, 9.73

"ER-EC-2A", "Tfbw", "lava", 120, 130, 1.13, 2.83

"ER-EC-2A", "Tfbw", "lava", 120, 130, 1.08, 2.70

"ER-EC-2A", "Tfbw", "lava", 120, 130, 1.09, 2.73

"ER-EC-2A", "Tfbw", "lava", 120, 130, 1.08, 2.70

"ER-EC-2A", "Tfbw", "lava", 120, 130, 1.05, 2.63

"ER-EC-2A", "Tfbw", "lava", 150, 160, 1.06, 2.65

"ER-EC-2A", "Tfbw", "lava", 150, 160, 1.06, 2.65

"ER-EC-2A", "Tfbw", "lava", 150, 160, 1.05, 2.63

"ER-EC-2A", "Tfbw", "lava", 150, 160, 1.04, 2.60

"ER-EC-2A", "Tfbw", "lava", 150, 160, 1.05, 2.63

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"UE-18r", "Tm", "nonwelded tuff", 1250, 1260, 1.09, 2.73
"UE-18r", "Tm", "nonwelded tuff", 1250, 1260, 1.52, 3.80
"UE-18r", "Tm", "nonwelded tuff", 1280, 1290, 0.55, 1.38
"UE-18r", "Tm", "nonwelded tuff", 1280, 1290, 0.53, 1.33
"UE-18r", "Tm", "nonwelded tuff", 1280, 1290, 0.54, 1.35
"UE-18r", "Tm", "nonwelded tuff", 1280, 1290, 0.52, 1.30
"UE-18r", "Tm", "nonwelded tuff", 1280, 1290, 0.55, 1.38

"UE-18r", "Tm", "nonwelded tuff", 1300, 1310, 0.58, 1.45
"UE-18r", "Tm", "nonwelded tuff", 1300, 1310, 0.55, 1.38
"UE-18r", "Tm", "nonwelded tuff", 1300, 1310, 0.58, 1.45
"UE-18r", "Tm", "nonwelded tuff", 1300, 1310, 0.58, 1.45
"UE-18r", "Tm", "nonwelded tuff", 1300, 1310, 0.54, 1.35
"UE-18r", "Tm", "nonwelded tuff", 1330, 1340, 1.17, 2.93
"UE-18r", "Tm", "nonwelded tuff", 1330, 1340, 1.08, 2.70
"UE-18r", "Tm", "nonwelded tuff", 1330, 1340, 1.13, 2.83
"UE-18r", "Tm", "nonwelded tuff", 1330, 1340, 1.09, 2.73
"UE-18r", "Tm", "nonwelded tuff", 1330, 1340, 1.06, 2.65
"UE-18r", "Tm", "nonwelded tuff", 1350, 1360, 1.27, 3.18
"UE-18r", "Tm", "nonwelded tuff", 1350, 1360, 1.21, 3.03
"UE-18r", "Tm", "nonwelded tuff", 1350, 1360, 1.21, 3.03
"UE-18r", "Tm", "nonwelded tuff", 1350, 1360, 1.24, 3.10
"UE-18r", "Tm", "nonwelded tuff", 1350, 1360, 1.22, 3.05
"UE-18r", "Tm", "nonwelded tuff", 1380, 1390, 1.65, 4.13
"UE-18r", "Tm", "nonwelded tuff", 1380, 1390, 1.63, 4.08
"UE-18r", "Tm", "nonwelded tuff", 1380, 1390, 1.68, 4.20
"UE-18r", "Tm", "nonwelded tuff", 1380, 1390, 1.67, 4.18
"UE-18r", "Tm", "nonwelded tuff", 1380, 1390, 1.56, 3.90
"UE-18r", "Tm", "nonwelded tuff", 1410, 1420, 1.88, 4.70
"UE-18r", "Tm", "nonwelded tuff", 1410, 1420, 1.85, 4.63
"UE-18r", "Tm", "nonwelded tuff", 1410, 1420, 1.76, 4.40
"UE-18r", "Tm", "nonwelded tuff", 1410, 1420, 1.86, 4.65
"UE-18r", "Tm", "nonwelded tuff", 1410, 1420, 1.78, 4.45
"UE-18r", "Tm", "nonwelded tuff", 1440, 1450, 1.94, 4.85
"UE-18r", "Tm", "nonwelded tuff", 1440, 1450, 1.90, 4.75
"UE-18r", "Tm", "nonwelded tuff", 1440, 1450, 1.91, 4.78
"UE-18r", "Tm", "nonwelded tuff", 1440, 1450, 1.89, 4.73
"UE-18r", "Tm", "nonwelded tuff", 1440, 1450, 1.84, 4.60
"UE-18r", "Tm", "nonwelded tuff", 1470, 1480, 1.84, 4.60
"UE-18r", "Tm", "nonwelded tuff", 1470, 1480, 1.85, 4.63
"UE-18r", "Tm", "nonwelded tuff", 1470, 1480, 1.82, 4.55
"UE-18r", "Tm", "nonwelded tuff", 1470, 1480, 1.82, 4.55
"UE-18r", "Tm", "nonwelded tuff", 1470, 1480, 1.77, 4.43