APPENDIX I

SUMMARY OF RECENT INFORMATION RELEVANT TO DISRUPTIVE EVENTS—VOLCANISM AND SEISMICITY

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1. INTRODUCTION

This white paper contains a summary of recent test results and other additional information that are relevant to the Disruptive Events models for volcanism and seismicity that were used to support the *Yucca Mountain Science and Engineering Report* (YMS&ER) (DOE 2001a) and the *Yucca Mountain Preliminary Site Suitability Evaluation* (YMPSSE) (DOE 2001b). The U.S. Department of Energy (DOE) released these two documents for public review in May and August, respectively, of this year.

Proposed 10 CFR 963.17(b) (64 FR 67054) requires consideration of disruptive processes and events. The specified criteria related to disruptive processes and events include volcanism, seismicity, criticality, and human intrusion. *Disruptive Events Process Model Report* (CRWMS M&O 2000a) and this white paper consider only volcanic and seismic events. Criticality, which is listed as a disruptive event in proposed 10 CFR Part 963 (64 FR 67054) is addressed separately in another white paper. Human intrusion is analyzed separately from the primary total system performance assessment (TSPA), as prescribed by regulation.

This white paper focuses on additional information that became available after the analysis of volcanism and seismicity were completed to support the preparation of the YMS&ER and the YMPSSE. The summary of this recent information is being used to conduct an impact review, in accordance with AP-2.14Q, *Review of Technical Products and Data*, to determine if this additional information has any impact on the technical analyses supporting the YMS&ER and the YMPSSE. The documentation of the additional information in this white paper is an interim step and primarily used to support this impact review. This information is expected to be formally documented in subsequent Project technical reports, as appropriate.

To assist in the impact review, this white paper briefly describes the volcanism and seismicity models that were used to support the YMS&ER and the YMPSSE, provides a summary of the recent test results and other additional information, and discusses the potential implications of this more recent information on our understanding of volcanism and seismicity.

2. SUMMARY DESCRIPTION OF THE DISRUPTIVE EVENTS (VOLCANISM AND SEISMICITY)

The *Disruptive Events Process Model Report* (CRWMS M&O 2000a), rather than reflecting a formal process model, summarizes the results of eight analysis model reports (AMRs) and one calculation that together analyze the potential consequences for (1) volcanism (which includes both intrusive and extrusive occurrences); and (2) seismicity (vibratory ground motion) and associated structural deformation (fault displacement). The key points, inputs, outputs, and interrelationships of the AMRs and calculation are summarized in the tables provided in the *Disruptive Events Process Model Report* (CRWMS M&O 2000a).

This section provides a brief description of the models and approaches for volcanism and seismicity that were used to support the YMS&ER and the YMPSSE. Site characterization work, expert elicitations, technical workshops, TSPAs, and other analyses and calculations by the Yucca Mountain Site Characterization Project and other researchers contributed to developing the bases for the analysis of volcanism and seismicity for the TSPA-SR model (CRWMS M&O 2000b).

2.1 APPROACH TO VOLCANISM ANALYSIS

The approach to the volcanism analysis that supports the TSPA is a fully probabilistic treatment of consequences with volcanic eruption release and igneous intrusion groundwater release analysis included in the TSPA-SR model. For both the eruptive and intrusive disruptive events, the corresponding risk is determined by weighting the (conditional) dose with the probability of the igneous event occurring within the footprint of the potential Yucca Mountain repository. The consequence models for the two events are described in detail in *Igneous Consequence Modeling for TSPA-SR* (CRWMS M&O 2000c, Section 6). The doses are calculated in the TSPA-SR model (CRWMS M&O 2000b). Results of the TSPA-SR analyses are discussed in Section 4.3.2 of the *Yucca Mountain Science and Engineering Report* (DOE 2001a). The dose from releases due to volcanism is treated as part of the expected annual dose by combining the probability-weighted sum of the dose due to volcanic sources and the nominal dose.

Section 4.3.2.1 of the *Yucca Mountain Science and Engineering Report* (DOE 2001a) describes the DOE's approach for evaluating potential volcanic activity and addressing uncertainty. The assessment of the likelihood of volcanic activity disrupting the repository, including uncertainty considerations, is documented in *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996). The panel of experts agreed that future volcanism is more likely to occur within or near existing clusters of geologically recent volcanism than elsewhere in the Yucca Mountain region. Therefore, they considered the past 5 million years as the most appropriate time period for assessing volcanic hazard and emphasized the Crater Flat basin because of the frequency of past volcanic activity there and its proximity to the potential repository (CRWMS M&O 2000d, Sections 6.3.1.3 and 6.4). Data considered by the panel of experts are briefly summarized in Section 3.1.

The geologic conceptual model for volcanism is that dike intrusion precedes formation of an eruptive event and that all dike intrusions that reach the level in the earth's crust equivalent to the repository elevation will continue to the earth's surface and formation of a volcano will occur. The probability of an eruptive event is calculated beginning with the probability of an intrusive event; therefore, these two types of events are linked in probability analysis, with probabilities based on the findings of the probabilistic volcanic hazard analysis. The consequence analysis estimated the effects for an intrusive and an eruptive volcanic scenario. The eruptive release conceptual model in the consequence analysis (CRWMS M&O 2000c, Section 3.10.2.2) assumes that magma in the form of a dike rises to the repository level and intersects one or more emplacement drifts. One or more eruptive conduits form somewhere along the dike and feed volcanoes at the surface. Waste packages in the path of the conduit are damaged to the extent that they provide no further protection for the waste, and waste particles are entrained in the erupted material. The magma erupts at the surface of the mountain, entraining radionuclides in the ash plume, then disperses them downwind and deposits them on the ground at the location of the receptors.

The igneous intrusion groundwater transport conceptual model in the analysis (CRWMS M&O 2000c, Section 3.10.2.3) assumes that a basaltic dike intersects a section of the repository and damages the waste packages, making radionuclides available for transport in groundwater. Modeling assumptions do not include development of a conduit, as that event is modeled separately. The assumption is made that all waste package damage is by the dike intrusion. Waste packages near the point of dike intersection are assumed to be damaged to the extent that they provide no further protection for the waste. Other waste packages in the same drift, but further from the intersection, are assumed to be partially damaged but still provide some protection for the waste. Radionuclide releases from waste packages destroyed or damaged by the intrusion are then available for transport in groundwater to the receptors. The rate of transport depends on factors such as the solubility limits of the waste and the availability of water. The movements of radionuclides released by this type of an event are modeled in *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b, Section 3.10.2.3) using the same models of water flow and radionuclide transport that are used for the nominal scenario.

2.2 APPROACH TO SEISMICITY AND STRUCTURAL DEFORMATION ANALYSIS

The seismic events considered for the TSPA-SR model include vibratory ground motion and fault displacement. These effects are characterized as annual probabilities of exceeding specified levels of ground motion or fault displacement. These ground motion and fault displacement characteristics are used to develop seismic design inputs for repository structures. The TSPA-SR approach for damage from vibratory ground motions is to treat the event through uncertainty analysis of nominal performance, meaning it is treated as part of the nominal case, rather than a disruptive scenario. The effects of fault displacement are addressed with the use of set-back requirements based on the probabilistically determined maximum displacements.

The methods for performing the seismic hazard analysis are summarized in Section 4.3.2.2.2 of the *Yucca Mountain Science and Engineering Report* (DOE 2001a). The method for assessing vibratory ground motion in the seismic hazard analysis for the Yucca Mountain site implemented established methods as documented in *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (PSHA) (Wong and Stepp 1998, Sections 7.0 and 7.1). The level of ground shaking, or amplitude of ground motions, is influenced by three main elements. The first element is how the size and nature of an earthquake controls the generation of earthquake waves. The second element is the travel path of seismic waves from the source of the earthquake to a particular site. The third element is the local site condition, or the effect on seismic waves of the uppermost several hundred feet (a few hundred meters) of rock and soil. All three of these elements controlling ground motions were explicitly addressed in the Yucca Mountain seismic hazard analysis. Additional data pertaining to the third element are discussed in Section 3.3.

The method for assessing probabilistic fault displacement hazard was very similar to that for assessing vibratory ground motion hazard; it relies heavily on the detailed geologic studies of individual faults in the Yucca Mountain vicinity. The fault displacement hazard was evaluated at nine locations within the Yucca Mountain site area. These locations were selected to span the range of known faulting conditions and ranged from recognized faults to small fractures and intact rock (CRWMS M&O 2000e, Section 6.3.4).

3. SUMMARY OF RECENT TEST RESULTS AND OTHER ADDITIONAL INFORMATION

This section summarizes recent results obtained from the different field tests and other information sources that provided information relevant to enhancing understanding of volcanism and seismicity. The tests and other information sources that provided this additional information are listed below and discussed in each of the sections the follow.

1. Center for Nuclear Waste Regulatory Analysis (CNWRA)-sponsored research and analyses related to dike–drift interaction

2. Additional aeromagnetic data and interpretation

3. Collection of geotechnical data to support seismic analyses

4. Geodetic results from continuous global positioning system measurements.

Because of the recent nature of the information provided in this section, much of it is unpublished; therefore, some source references have been provided where appropriate, but others could not be provided. However, this information is currently documented in the principal investigators' scientific notebooks, if applicable, in accordance with the Project's quality assurance procedure AP-SIII.1Q, *Scientific Notebooks*.

3.1 CNWRA SPONSORED RESEARCH AND ANALYSES RELATED TO DIKE–DRIFT INTERACTION

During the Igneous Activity Management Meeting and Technical Exchange in June 2001, the NRC-funded CNWRA sponsored presentations based on two papers. The first paper, "Explosive Magma-Air Interactions by Volatile-Rich Basaltic Melts in a Dike–Drift Geometry," was prepared by Bokhove and Woods (in preparation). The paper addressed the ascent of alkali basalt magma through a dike and into a horizontal subsurface drift and, in particular, examined the consequence from magma decompression and volatile exsolution (i.e., timing and development of a shock wave and overpressure conditions).

Simplifying assumptions used in the Bokhove and Woods (in preparation) work include:

- Characteristics of the basaltic magma and the dike propagation process including pressure conditions at depth, magma-host rock density differences, density of the magma-gas mixture, and that the magma remains in chemical equilibrium with the dissolved volatile phase.

- A simplified geometry for the dike–drift system including consideration of effects in a single drift and assumed left-right symmetry in the drift. This allowed for numerical solutions for determining velocities and shockwaves based on a smooth-walled, closed-end, one-dimensional flow tube model.

Bokhove and Woods (in preparation) found that owing to the difference in density and speed of sound in the air and the magma-gas mixture, a complex series of interacting shock waves develops near the end of the tunnel, resulting in a region of maximum pressure in the drift far from the dike.

Bokhove and Woods (in preparation) do not discuss the direct application of their findings to the Yucca Mountain project. However, based on their work, a second paper, “Modeling Magma-Drift Interaction at the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada,” was prepared by Woods et al. (in preparation) to explore potential implications of dike–drift interactions. The work included consideration of the Bokhove and Woods (in preparation) findings, development of a simplified flow model, and postulation of three alternative scenarios for effects of the repository on pathway development. Woods et al. (in preparation), in developing potential flow models, specifically considered viscous and turbulent drag of the dike and drift walls on the flow and assume that, aside from waste packages, the drifts are empty. Similar to Bokhove and Woods (in preparation), the cross-sectional flow area is assumed to be that of the drift due to the relative diameters of the waste packages (1.8 m [5.9 ft]) and the drift (approximately 5 m [16 ft]). The three alternative scenarios postulated in Woods et al. (in preparation) are predicated on the assumptions that:

- Tangential and thermal stresses around the drift do not prevent dike intersection with the drifts
- The drifts are not backfilled with sufficient material to impede flow
- Following intersection of the dike with the drift, the magma will be diverted into the drift because the drift provides the path of least resistance
- Interactions with other engineered components, such as ventilation shafts or drift support, have minor effect on magma flow processes.

Though not specifically stated by the authors, inherent in the calculations are the assumptions that the dike does not continue to the surface between drifts, explosive decompression and propagation of supersonic shockwaves occurs in the drifts, the drifts are inundated by pyroclastic flow, and repressurization of the drift allows the dike to reestablish flow at points remote from the location of initial intersection.

Woods et al. (in preparation) use their model to calculate pressure conditions and found that “a region of very high overpressure, 10–20 MPa, develops between the end of the drift and the shock,” suggesting that if the dike intersects the drift 200 to 300 m (660 to 1,000 ft) from the end of a closed drift, then the pressure will build up to the level along the whole drift, within about 10 seconds. Additionally, the authors state that the calculated estimates of the fluid pressure required to initiate a vertical fracture range from 2 to 6 MPa, depending upon the fracture orientation. They also state that the precise location of the preferred magma pathways from the drift to the surface will depend on many factors, including any heterogeneity of fractures in the overlying rock strata, proximity of the drift to the surface, and any damage to the rock prior to intersection of the dike and the drift.

Based on these findings, Woods et al. (in preparation) postulate three different cases "which might bound the range of possibilities." The three cases include "(Case 1) that the deep dike path continues to the surface without any major perturbation by the repository system, (Case 2) that the pathway to the surface is shifted to a new position, 500 m along a drift with an area of 20 m^2 and (Case 3) that the magma uses the main access drift to the repository for flow to the surface." The authors extend the flow model calculations to include a conduit from the drift to the surface and then calculate flow speeds for each case. The results for each indicate eruption speeds on the order of 90 m/ s (300 ft/s). The authors then calculate drag forces on the waste packages for Cases 2 and 3 and suggest that, based on the calculations, the waste packages may be displaced down the drifts, although flow is much too weak to keep the waste packages in suspension and waste package motion is likely to be slow. The authors also calculate the time required for the walls of the waste packages to reach temperatures above the likely deformation temperature. Based on that calculation, the authors indicate that waste package failure is anticipated.

In discussing their findings, Woods et al. (in preparation) state, "although our models are a considerable simplification of the complex processes involved with magma-repository interaction, the models are consistent with general observations of explosive basaltic eruptions and current knowledge of the underlying physics." Additionally, the authors acknowledge that there are large uncertainties inherent in these conceptual models and suggest that the risk significance of these models should be determined for a potential subsurface repository at Yucca Mountain. In particular, the authors state that the assessments suggest a greater number of waste packages may be adversely affected than previously recognized. Woods et al. (in preparation) also suggest the following:

- That intersected drifts will be quickly filled by magma at an early stage in an eruption
- Repository drifts may provide a potential flow path to the surface
- Magma injection into drifts can potentially affect a large number of waste packages in a repository
- Heating of the waste packages may lead to their failure
- Magma flow through the repository may provide a mechanism to transport contaminants to the earth's surface.

These two papers have been submitted for publication in professional journals but are currently unpublished. The significance of the Bokhove and Woods (in preparation) work is that it represents an initial attempt to mathematically model in more detail the dike–drift interaction process. The significance of Woods et al. (in preparation) is that it represents an potential idealized conceptual model for further evaluating igneous consequences of dike–drift interactions. Potential implications of the CNRWA-sponsored work are discussed in Section 4.1.

3.2 ADDITIONAL AEROMAGNETIC DATA AND INTERPRETATION

To estimate the probability of a future volcanic event in time and space, the number and locations of previous eruption sites are needed. Determination of the Plio-Pleistocene volcano inventory was, therefore, one of the interpretations made by experts included as part of the *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996). The analysis used USGS aeromagnetic survey data (Langenheim et al. 1993) to identify a number of anomalies as representing buried volcanic centers. Drilling has penetrated one of these suspected buried volcanic centers (Carr et al. 1995).

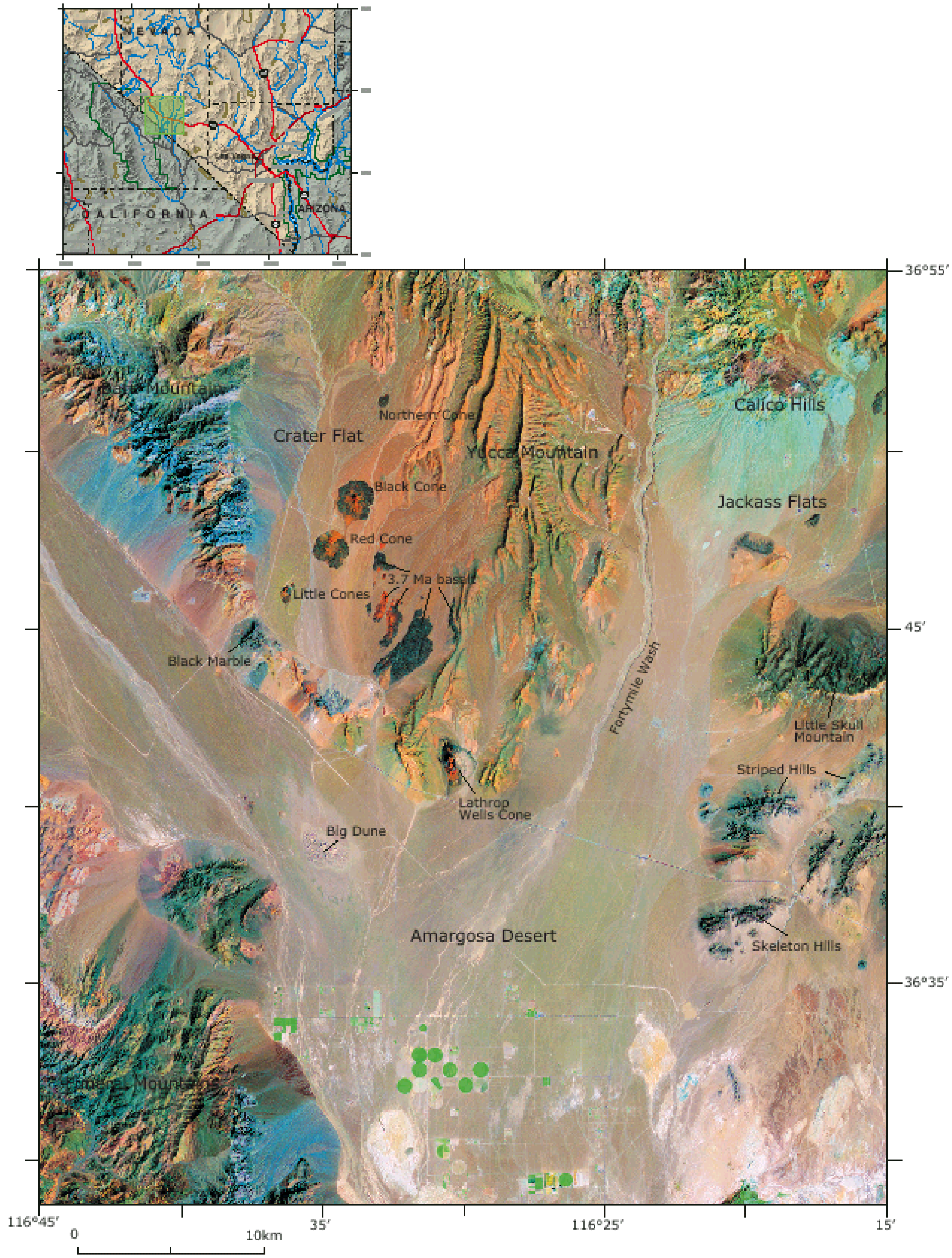
These and other subtle anomalies were more clearly delineated by a high-resolution aeromagnetic survey of the Amargosa Desert collected by the USGS in cooperation with Nye County in 1999 (Blakely et al. 2000). These additional data are being analyzed to determine if they have any impact on the results of the probabilistic volcanic hazard analysis. This report summarizes an evaluation of the magnetic anomalies observed in the 1999 USGS aeromagnetic data to determine whether they can be interpreted to represent buried basaltic volcanic centers in Crater Flat and in Amargosa Valley near Yucca Mountain. The goal is to determine whether the additional data are consistent with expert interpretations made as part of the probabilistic volcanic hazard analysis. As part of the probabilistic volcanic hazard analysis process, the experts interpreted the available data to identify the number of basaltic volcanic centers, including estimates of those that might exist but were not yet recognized ("hidden event factor").

The results of this evaluation are currently in draft form and have not yet been reviewed in accordance with controlling quality assurance procedures. Thus, while the scientists who carried out the evaluation have confidence in the interpretations, the results are considered to be preliminary. This section summarizes the preliminary results of the study. The scope of the investigation is discussed in Section 3.2.1, the results and interpretations are discussed in Section 3.2.2, and the implications of the interpretations are discussed in Section 4.2.

3.2.1 Scope of Aeromagnetic Data and Interpretation

The USGS is currently preparing an evaluation and interpretation of magnetic anomalies observed in the 1999 USGS aeromagnetic data and is focused on volcanic centers in Crater Flat and in Amargosa Valley near Yucca Mountain (Figure 1). The study addresses the question of what these buried volcanoes might look like and how deeply they are buried but does not directly address the issue of probability of volcanic activity. The implications on probability will be discussed in Section 4.

The study builds from and references previous modeling and survey efforts. In the study, physical sources of the magnetic anomalies are modeled by bodies having volumes, forms, and magnetic susceptibilities comparable to those of the basaltic volcanoes exposed in the vicinity of Yucca Mountain. The modeled bodies are given source depths and placements compatible with the anomalies shown in the aeromagnetic data, such that the calculated magnetic intensity mimics the observed intensity profile.



Note: Area covered corresponds to aeromagnetic map data. Map inset shows regional setting of study area (green rectangle). Image created by J. Dohrenwend for USGS.

Figure 1. False Color Landsat Image Showing Local Geographic Features and Plio-Pleistocene Volcanic Centers near Yucca Mountain

The goal of the study was to use magnetic and gravity data to constrain the three-dimensional shapes of buried volcanoes that are presumed to lie beneath selected aeromagnetic anomalies in Crater Flat and the northern Amargosa Desert. The target anomalies were selected primarily on the basis of the strong magnetic contrast inferred to exist between volcanic rocks and surrounding alluvium. Models of the magnetic source bodies were constructed with a commercially available program that facilitates both forward and inverse calculations. The models are based on linear profiles across the anomalies and assume that the bodies are two-dimensional in shape but finite in length perpendicular to each profile. In some cases, models are based on multiple profiles in order to constrain the three-dimensional shape of the bodies.

The models are based primarily on forward calculations, where body shapes are determined by obtaining reasonable fits between observed and calculated profiles via trial-and-error iterations. An inverse method (Webring 1985) was also used to assist the trial-and-error procedure. The inverse method requires an initial estimate of model parameters and varies them to reduce the weighted root-mean-square error between observed and calculated gravity and magnetic values along the profile. The solutions are not unique because an infinite number of geometric models will have an associated magnetic or gravity field that closely matches the measured field. No detailed gravity surveys have been conducted in the vicinity of the magnetic anomalies investigated here, and variations in the regional data (Ponce et al. 1999) mainly reflect trends in pre-Tertiary basement. For an additional constraint on the models, the study used the pre-Tertiary basement surface derived by Hildenbrand et al. (1999), which was based on an inversion of regional gravity data.

3.2.2 Results of Aeromagnetic Data and Interpretation

Specific anomalies discussed in the text and shown in the figures are labeled with letters A through T; Table 1 cross-references the USGS labels with those of previous studies.

From previous studies, probabilistic volcanic hazard analysis experts were provided data (CRWMS M&O 1996, Figure 1-1) that showed a buried aeromagnetic anomaly (A) located 2 km south of Little Cones in Crater Flat and six buried aeromagnetic anomalies (B-G) in Amargosa Valley south of Yucca Mountain (Table 1, Figures 2 and 3). Anomalies A through G were previously considered by the panel of experts as part of their determining the probabilistic volcanic hazard and are discussed here for completeness.

Despite the proximity of anomaly A to Little Cones, most of the probabilistic volcanic hazard analysis experts discounted the anomaly; their interest was whether all the exposed cones of the 1.0 Ma volcanic alignment represent a single event, and five of the ten experts favored a collective single event interpretation for the four cones. Because the source body of anomaly A possesses a normal magnetic polarity in contrast to the reversely magnetized cones of the 1.0 Ma volcanic alignment, a significant age difference must exist between the events.

Table 1. Labels and Features of Magnetic Anomalies in Crater Flat and Amargosa Desert Area, Nevada

Anomaly Label/Source				Location		
USGS 2001	PVHA	Connor et al. 2000	Langenheim 1995	Latitude (North) Degree, Minutes	Longitude (West) Degree, Minutes	Polarization
A	A	A	F	36 45.27	116 36.48	+
B	B	AAB	B	36 36.71	116 24.14	-
C	C	AAC	C	36 31.82	116 28.27	-
D	D	AAD	D	36 30.02	116 26.94	+
E	E	AAE	E	36 34.06	116 34.03	+
F	F	AAA	A	36 37.36	116 29.20	-
G	G	AAA	A	36 38.23	116 29.00	-
H		AAA		36 36.56	116 30.06	-
I				36 39.52	116 29.78	+
J				36 37.32	116 33.15	+
K				36 31.97	116 34.50	+
L				36 41.09	116 38.87	+
M				36 41.26	116 38.27	+
N				36 41.98	116 37.71	+
O				36 42.60	116 37.24	+
P				36 50.22	116 33.41	-
Q		C		36 50.76	116 34.31	-
R				36 51.98	116 35.16	-
S				36 53.43	116 32.81	-
T	(Position approximated from drawing)			36 47.50	116 35.40	-

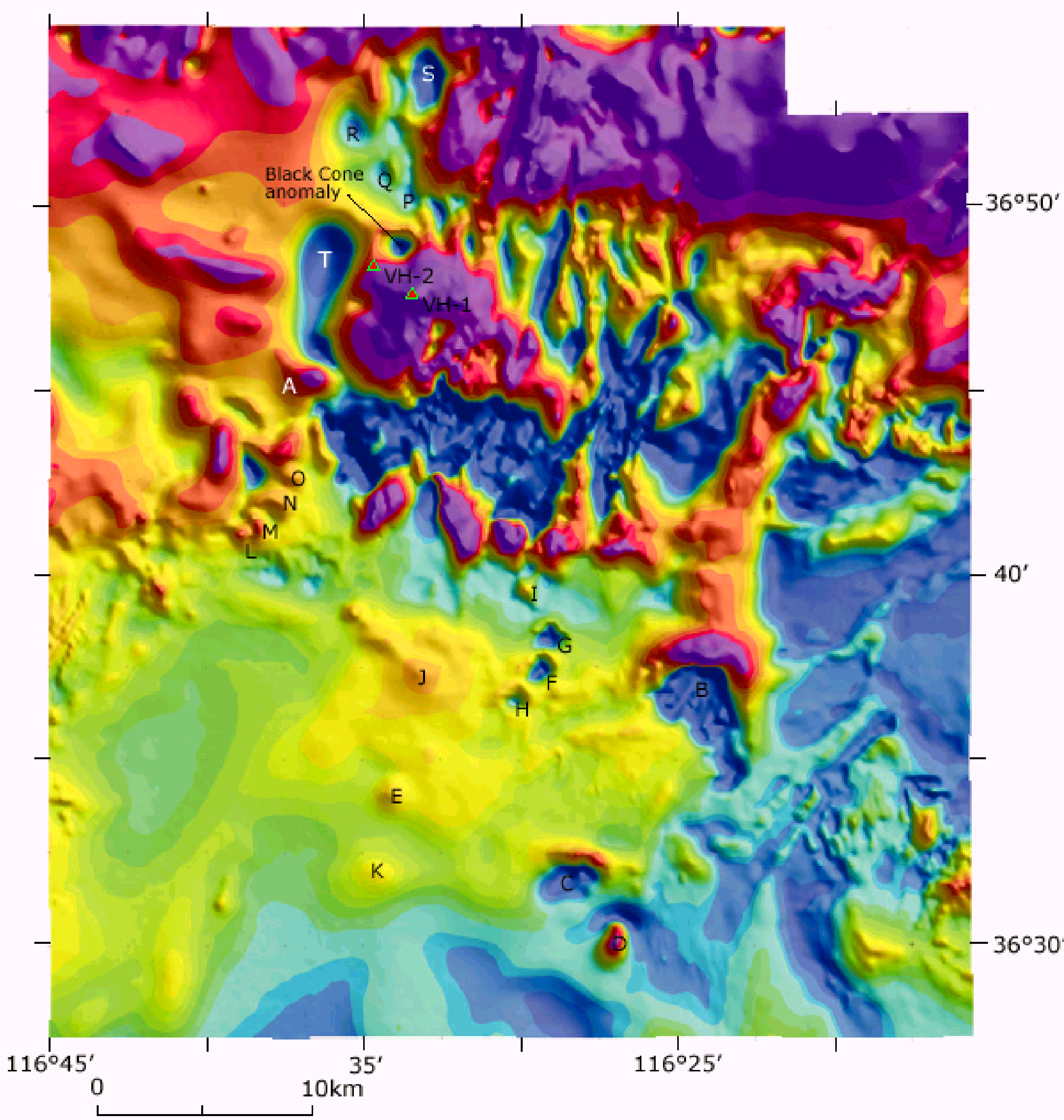
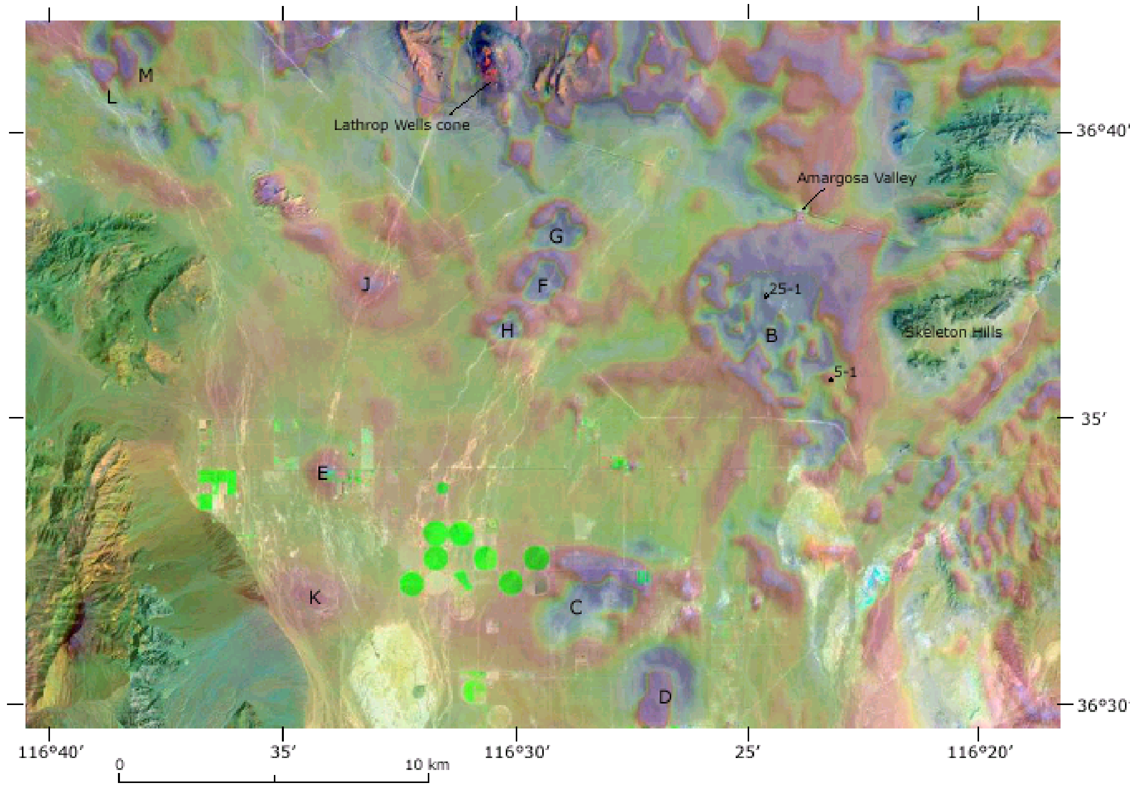


Figure 2. Magnetic Anomalies Near Yucca Mountain and the Northern Amargosa Desert, Nevada



Note: Landsat image overprint shows outcrops and drainage features of the northern Amargosa Desert. Locations of drill holes Felderhoff Federal 25-1 and 5-1 (Carr et al. 1995) are shown in relation to anomaly B.

Figure 3. Landsat Image Overlain on Residual Magnetic Anomalies of Possible Plio-Pliestocene Basaltic Origin

Of the six aeromagnetic anomalies (B-G) located in Amargosa Valley (CRWMS M&O 1996, Figure 1-1), anomaly B was unanimously counted as a volcanic center/event because drilling had obtained samples dated at about 4.0 Ma (Crowe et al. 1995). Anomaly D was also accepted as drilling nearby had obtained basalt fragments (Walker and Eakin 1963) presumably derived from the anomaly source. Anomalies C and E were considered individual cones or centers (except by Walker who discounted E). Anomalies F and G were either lumped as a single center (McBirney, Walker, Sheridan) or were suspected as possibly nonvolcanic (Walker, Crowe, Carlson). On the basis of the exposed volcanic centers, including individual vents and the anomalies A and C, eight volcanic centers were counted in Crater Flat.

Anomalies B, C, D, F, G and H, in Amargosa Desert (Figures 3) were modeled or detailed by others using ground survey data. The largest of the anomalies (B) covers an area of about 20 km^2 (7.7 mi^2). A “dike swarm” model (raised dike segments on a tabular body) provides a good fit between the observed and calculated magnetic profiles (Langenheim et al. 1993, pp. 1843 to 1844). Anomaly C was modeled by Langenheim and Ponce (1995). Given that the estimated top to the source is about 200 m (660 ft) (Langenheim and Ponce 1995, p. 9) and the depth to basement in this area is about 700 m (2,300 ft), the source body is probably a Pliocene basalt mass embedded in alluvium (Langenheim and Ponce 1995, p. 11). Anomaly D is also a double-peaked feature that has little or no gravity expression. The peaks suggest two vent edifices spaced about 700 m (2,300 ft) apart (Langenheim and Ponce 1995). The thickness of the source body embedded in alluvium at a depth of about 180 m (590 ft) is estimated to be about 70 m (230 ft) (Langenheim and Ponce 1995).

Ground magnetic surveys in Amargosa Valley reported by Connor et al. (1997) showed that anomalies F and G (designated as A in Connor et al. 1997, p. 74; and AAA in Connor et al. 2000, p. 424, Table 1) comprise three distinct cones that form a NE-oriented alignment 4.5 km (2.8 mi) long. The individual anomalies feature pronounced northeast-oriented forms (Connor et al. 1997, p. 74) that suggest en echelon structure. Use of Peters' method (Peters 1949; Blakely 1995) indicates depths of 300 m (1,000 ft) and 250 m (820 ft) to the sources of anomalies F and G, respectively. The observed magnetization along this profile proved more difficult to match than others described in this report. The mismatch at the south end of the profile, however, obviously is due in part to the influence of anomaly H and other, more subtle anomalies in this area. Although the relative shapes of the anomalies can be matched, considerable discrepancy remains. Anomaly G has a distinct dipole signature and is reasonably modeled as a basalt body about 250 m (820 ft) below ground surface. Anomaly F shows conspicuous NE-trending linear characteristics (Connor et al. 1997, p. 75). It may be part of an aligned group of volcanic centers (anomalies H, F, G). Connor et al. (2000) also pointed out the "AAA alignment" through anomalies H, F, and G (Figure 3). Vents that cluster in close proximity often share the same paleomagnetic direction, suggesting that they erupted in a single volcanic episode. The 1.0 Ma volcanic centers in Crater Flat, for example, all share the same paleomagnetic direction (Champion 1995), suggesting that little time elapsed between eruptions. Sources for anomalies F and G, although both reversely magnetized, may have significantly different remnant magnetization directions. If true, these bodies must have erupted at times separated by some tens, if not hundreds, of years based on normal rates of geomagnetic secular variation (see, for example, Hagstrum and Champion 1995; Hagstrum and Champion [in press]). Such small time intervals are unlikely to be resolved with radiometric techniques. Although part of the same volcanic episode, the eruptions need not have been simultaneous.

Evaluation of the 1999 USGS aeromagnetic data identified eight new positive magnetic anomalies in the Amargosa Desert that may be of basaltic volcano origin (labeled as anomalies K, E, J, I, L, M, N, and O). As discussed below, these anomalies can be modeled with varying degrees of success as buried basaltic centers. Some anomalies are also consistent with alternative interpretations. It should be noted that interpretations and models of the potential field data are not unique; multiple geometric models can produce similar fits to the observed data. In addition, any buried basaltic deposits that do not generate an aeromagnetic anomaly because they are too small or too thin are not addressed by the current evaluation.

The anomalies K, E, and J, are questionable features; K and E are the most likely candidates for volcanic origin as their circular shapes and NNE alignment are indicative, but the basalts are likely old and deeply buried. Anomaly J may also have a deeply buried volcanic source, but its association with an irregular, northwest oriented cluster of positive anomalies suggests it is part of a basement feature. Anomaly I was also successfully modeled as a small, relatively shallow basaltic source body.

Anomalies L, M, N, and O were also modeled as volcanic sources. The NNE alignment of anomalies L, M, N and O and the fact that they are on strike with exposed volcanoes in Crater Flat are suggestive of volcanic origins. It is interesting to note that depths to most of the sources are approximately the same, suggesting that, if they are volcanic centers, they were erupted onto a common paleosurface. For anomalies O, N, M, and L, paleosurface is interpreted to be the eroded Topopah Spring Tuff. Groups of closely spaced vents/volcanic centers in the area may have been localized along faults (Connor et al. 2000). Anomalies O, N, M, and L are particularly interesting in this respect because they are approximately parallel to the Crater Flat alignment of Connor et al. (2000). A fault, 5 km (3 mi) or more in length, may have provided access through the Topopah Spring Tuff. The normal polarity rocks could date from the Brunhes Normal Polarity Chron (780 ka to present), possibly one of the longer subchrons (Jaramillo or Olduvai) of the Matuyama Chron, or any of the post-middle Miocene periods of normal magnetic polarity. If the positive anomalies L, M, N, and O are of volcanic origin they are likely of late Miocene age, as they are aligned along the late Miocene structural trend.

Alternately, the alignment may reflect uplifted blocks of magnetic tuff caught between NNW- and WNW-striking faults. The irregular shapes of the anomalies (L is circular, M and N are crescent-shaped, O is lozenge-shaped), their association with the inferred Carrara fault and perhaps older basalt bodies (Connor et al. 2000), all suggest the source bodies could be bedrock rather than Plio-Pleistocene volcanic features. In any case, the sources of anomalies L, M, N, and O appear to be aligned by structural control and have relatively shallow source depths.

Based on ground survey data, Connor et al. (2000, p. 424) reported a buried anomaly located 2.5 km (1.6 mi) southwest of Northern Cone (identified as Q in Table 1 and Figure 2 and labeled as C in Connor et al. 2000) and identified it as a possible volcanic source (Connor et al. 2000, p. 423). Based on a positive anomaly, they inferred that this anomaly represented an event likely older than the 1.0 Ma basalt. This anomaly does have a peripheral positive peak; if the peak is a dipole effect of volcanic origin the body has been rotated clockwise about 58° (Connor et al. 2000, p. 424). But clockwise rotation of this magnitude for the source of anomaly Q seems unlikely; tectonic rotation at this latitude in Crater Flat basin has been less than 30° (Minor et al. 1997, p. 18), and tectonic rotation associated with extension in post-Miocene time has been negligible (Fridrich et al. 1999, p. 210). The inferred dipole effect is most likely an edge effect either representing Yucca Mountain faulting or a zone of relatively low magnetization of anomalous direction. Large, abrupt changes in magnetic intensity, both laterally and vertically, are known to occur also within the tuff layers of Yucca Mountain, attaining amplitudes as great as 450 nT (Bath and Jahren 1985, p. 11, 13). Given their setting and the character of the anomalies, it is unlikely that three negative anomalies P, Q, and R represent Plio-Pleistocene volcanic centers (Figure 2). However, there is a possibility that these anomalies, along with anomaly S could represent bodies of 10.5 Ma basalt, separated from the larger body of pre-Pleistocene basalts (anomaly T) to the south.

A large north–south elongated negative anomaly (anomaly T, Figure 2) occupies the western part of Crater Flat basin. Drill hole VH-2, at the east side of this anomaly (Carr and Parrish 1985, Figure 3), penetrated 30 m (98 ft) of basalt lava flows, breccia, and scoria at a depth of 360 m (1,181 ft). The basalt unit lies directly on 11.45 Ma Ammonia Tanks Tuff, has a strong reverse magnetism, and is dated at 11.3±0.1 Ma (Carr and Parrish 1985, p. 30). This large negative anomaly most likely represents the extent of the late Miocene basalt (Langenheim and Ponce 1995, p. 7; Fridrich 1999, p. 189), which is interrupted only by anomaly A (CRWMS M&O 1996; referred to as Anomaly F in Langenheim and Ponce 1995, p. 7). The southern extent of the anomaly presumably is represented at the cuesta by outcropping basalt dated 10.5±0.1 Ma (Swadley and Carr 1987). These basalts are pre-Pleistocene and would not significantly affect the probability of igneous activity, which was evaluated primarily based on basalts dated at 5 Ma or more recent.

The implications of the interpretation of the aeromagnetic anomalies are discussed in Section 4.

3.3 COLLECTION OF GEOTECHNICAL DATA TO SUPPORT SEISMIC ANALYSES

Development of seismic inputs for use in design analyses for the site recommendation documentation to be considered by the Secretary was based on site characterization data available in 1999. Uncertainties were incorporated directly into the analysis, as appropriate, given the available data. Subsequent to the development of seismic inputs for site recommendation analyses, a program was initiated to expand the supporting geotechnical data set. This section summarizes the results of that program. The scope of the investigation is discussed in Section 3.3.1, the results and interpretations are discussed in Section 3.3.2, and the implications of the interpretations are discussed in Section 4.3.

Development of seismic inputs for design analysis is based on results of the probabilistic seismic hazard analysis for Yucca Mountain. Ground motion hazard results were determined for a hypothetical reference outcrop with properties found at a depth of 300 m (984 ft) beneath the site. Site-specific seismic inputs for design analyses must take into account the effect on ground motion of the upper 300 m (984 ft) or rock and soil. Key factors in determining this effect are the seismic velocity and dynamic properties of the upper 300 m (984 ft) of material.

Uncertainties were incorporated into the developed seismic inputs using a Monte Carlo approach. For each mean shear-wave velocity versus depth profile, 60 randomized profiles were generated reflecting the variability in layer velocity and thickness. The effect of the upper 300 m (984 ft) of rock and soil on ground motion was then determined for each profile. Based on these results a mean ground motion effect was computed and used to adjust the reference outcrop motions. For the repository block, in addition to the best-estimate velocity profile, the analysis was also carried out for lower- and upper-bound mean profiles and the results based on the three profiles were enveloped to arrive at the final ground motions. Uncertainties in dynamic rock and soil properties (shear modulus reduction and damping as a function of shear strain) were treated in a similar fashion.

Data and results reported in this document are preliminary. Data collection and analyses are being carried out in accordance with controlling quality assurance procedures. Review of the data, submittal to the Technical Data Management System, and documentation of data collection and analyses in a report have not yet been completed. While it is not expected that the results presented here will change significantly, they should be considered with the limitations noted.

3.3.1 Scope of the Geotechnical Investigations

To further characterize the site of the Waste Handling Building (WHB) and the repository block, a two-phase geotechnical, geological, and geophysical investigation program was conducted. The purpose of the program was to characterize the subsurface geology beneath the WHB site and the repository block in terms of S-wave and P-wave velocity structure and dynamic material properties for input into developing seismic design earthquake ground motion parameters. The first phase of field investigations began in June 2000 and focused on characterizing the WHB site. The second phase began in June 2001 and consisted of studies to characterize the 300-m

(984-ft)-thick geologic section between the crest of Yucca Mountain and the potential emplacement areas.

The investigation program collected the following additional data:

- Geologic data from seven new "deep" boreholes and eight new "shallow" boreholes in and around the WHB site. The new borings are designated UE-25 RF#14 through UE-25 RF#29.[1,2] The borehole depths were selected so that deep boreholes would extend approximately 30 m (100 ft) into bedrock with a shear wave velocity of at least 1,500 m/s (5,000 ft/s) and shallow boreholes would extend approximately 15 m (50 ft) into the densely welded Tiva Canyon Tuff. Geologic data acquired in the boreholes included depth below ground surface (bgs) of lithologic subunit contacts; depth bgs and dip of faults and other structural features; rock hardness, welding, and fracture density; percent core recovery, and Rock Quality Designator (RQD).

- Shear-wave and compression-wave velocity profiles based on arrival times from downhole seismic surveys at new boreholes RF#14 through RF#29 and existing borehole RF#13 at the WHB site.

- Shear wave-and compression-wave velocity profiles based on arrival times from downhole seismic surveys at existing boreholes UZ-N27, UZ-N33, UZ-N46, UZ-N64, UZ-N66, UZ-N71, UZ-N77, and UZ-N94 within the repository emplacement block.

- Shear-wave and compression-wave velocity profiles based on travel times from suspension seismic surveys at boreholes RF#14 through RF#29.

- Caliper and gamma-gamma wireline surveys in boreholes RF#16, RF#18, RF#20, RF#21, RF#22, RF#24 and RF#28.

- Shear-wave velocity profiles from spectral analysis of surface waves (SASW) surveys SASW-1 through SASW-37 at the WHB site.

- Shear-wave velocity profiles from SASW surveys SASW-D1 through D12 and SASW-S1 through S12 on the repository emplacement block.

- Resonant column and torsional shear test results for samples of bedrock, alluvium and engineered fill (includes density; water content; shear wave velocity (v_s), shear modulus (G_{max}) and material damping at low amplitude versus effective confining stress; and shear modulus (G) and material damping versus shear strain).

- Observations and logging of four test pits dug at the site for geotechnical purposes. These are not related to seismic studies and are not discussed further.

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[1] For brevity, the "UE-25" preface will be omitted from borehole designations in the rest of this white paper.

[2] Note that Borehole RF#27 was abandoned after setting a surface casing in favor of advancing a borehole at a different location, which is designated RF#29. Thus, when reference is made to RF#13 through RF#29 or RF#14 through RF#29, the reader should recall that there will be no data associated with RF#27.

The spatial distribution of the new boreholes, the existing boreholes in which downhole seismic logging was carried out, and the locations of the SASW survey lines are shown on Figure 4 for the WHB site and Figure 5 for the repository block. The results of the investigations are summarized in Figures 6 through 11.

3.3.2 Results of the Geotechnical Investigations

This section presents results of the geotechnical investigations. Results that support the development of seismic design inputs are emphasized. The investigations also provide results that characterize the subsurface materials for foundation design and analysis, but those are not reported in this document.

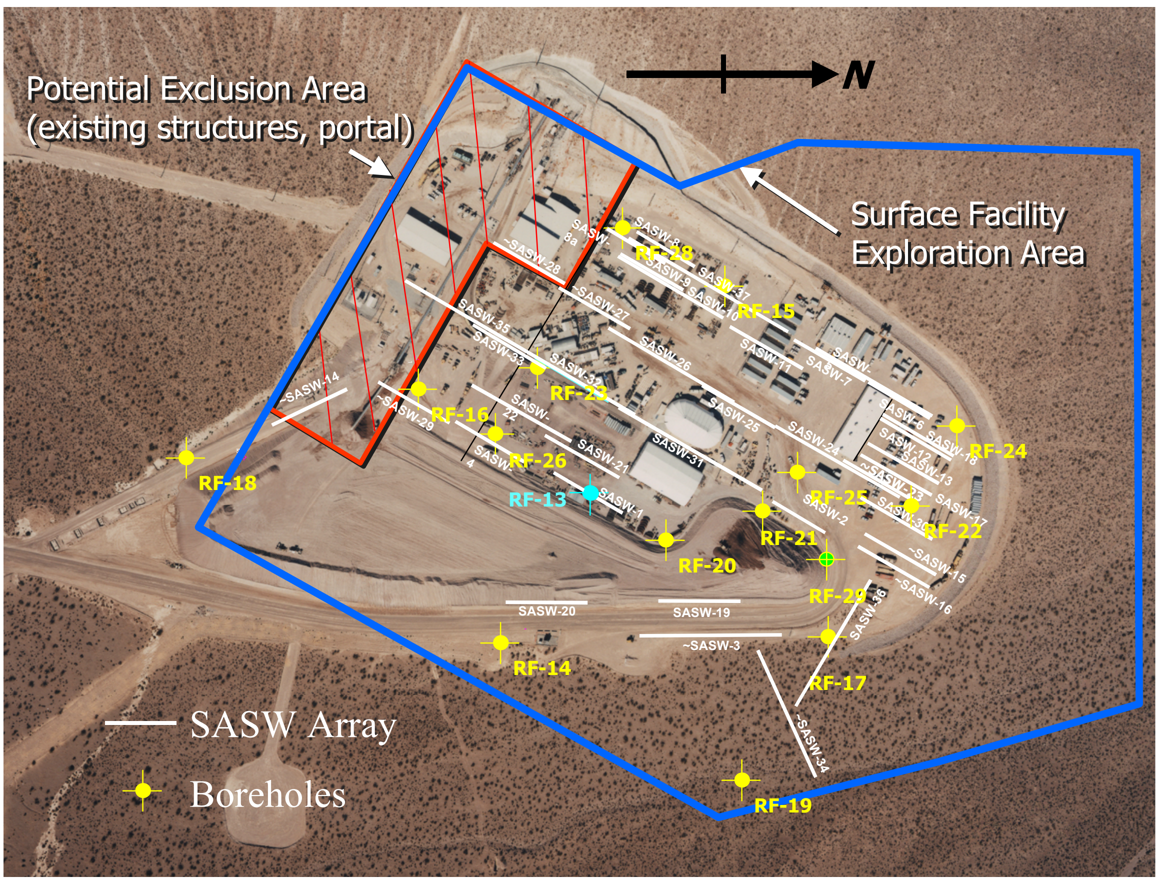

Figure 4. Location of Boreholes and SASW Survey Lines for Geotechnical Investigation of the WHB Site

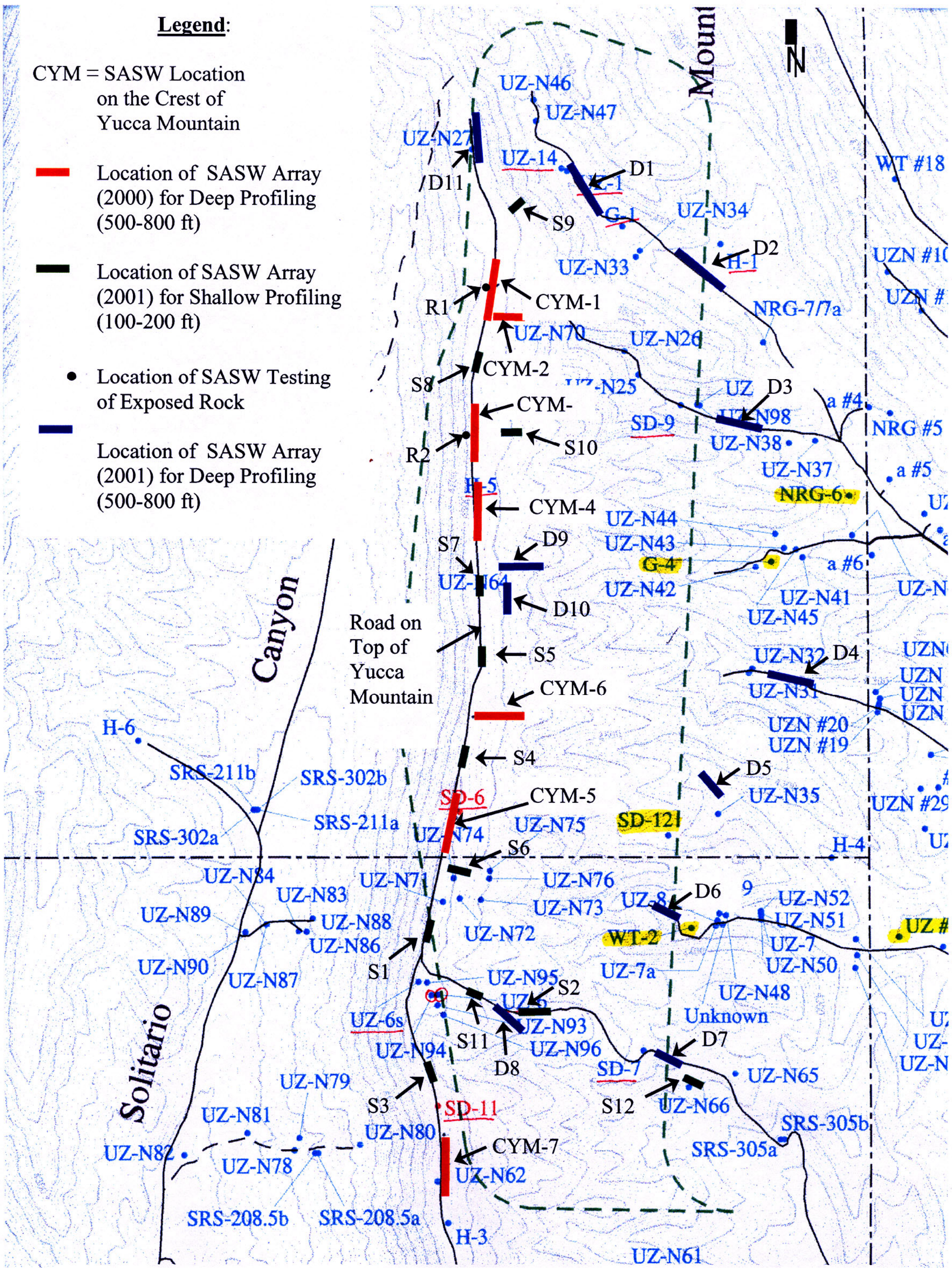

Figure 5. Location of Boreholes and SASW Survey Lines for Geotechnical Investigation of the Potential Repository Block

Subsurface Geology of the WHB Site—Recent investigations have revealed subsurface geology beneath the WHB site is very similar to that expected when the investigation program began. The site consists of faulted, gently dipping, pyroclastic and ash-fall volcanics overlain by interfingered colluvium and alluvium. Beneath the North Portal pad, the gravelly soils are generally well-cemented with pedogenic calcium carbonate. Farther east and away from the base of the Exile Hill slope, the soils become somewhat finer and are generally uncemented.

Information from the boreholes helped define the structure and stratigraphy of the rock beneath the site. Rocks of the pre-Rainier Mesa bedded tuffs, Comb Peak Ignimbrite (Tuff "X"), and Tiva Canyon Tuff were encountered in the WHB foundation area. Nine faults were defined based on information from the drilling. One of these faults is projected to have significant stratigraphic separation-approximately 100 m (328 ft). The fault is northwest striking (azimuth approximately 340°) and located beneath the northeast corner of the North Portal pad. The graben formed by this fault is partially filled with younger, nonwelded volcanic rocks, indicating that the majority of the offset occurred prior to deposition of the overlying soils. None of the faults are believed to offset any of the unconsolidated soils. Figure 6 shows a cross section of the site with the interpreted geologic structure and stratigraphy.

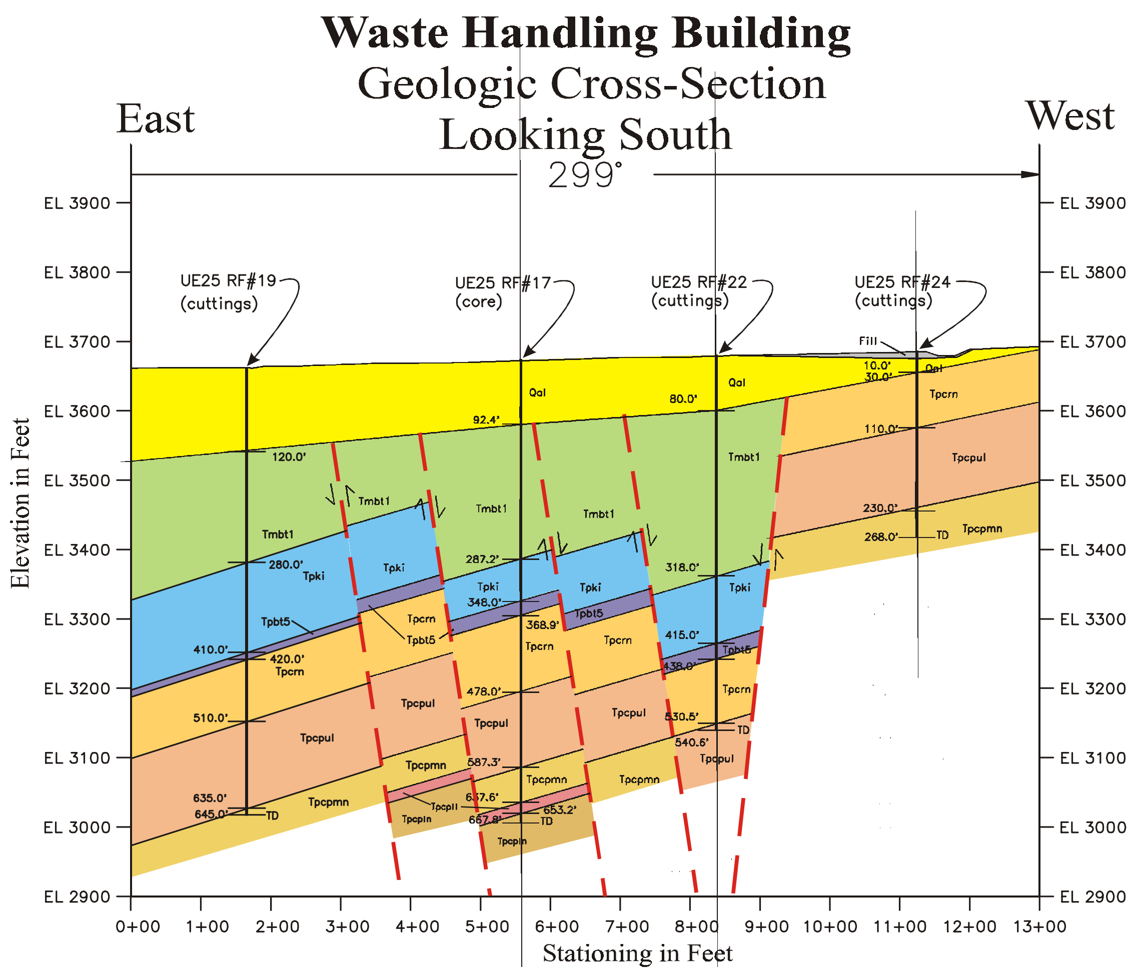

Figure 6. Geologic Cross Section of the WHB Site

Downhole Seismic Surveys—Data acquired through downhole seismic surveys support characterization of the seismic velocity model, and its variability, beneath the WHB site and for the repository emplacement block. The velocity profile derived from this model is a key input in developing seismic inputs for design analyses. Downhole seismic surveys are useful for evaluating the average seismic velocity of a layer with a relatively uniform seismic velocity.

Figure 7 shows the velocity data collected for the WHB site along with the profile used to develop seismic design inputs for site recommendation analyses. Figure 8 summarizes the additional data in terms of their mean and standard deviation as a function of depth. In general, the profile used for site recommendation analyses falls within one standard deviation of the mean for the expanded data set.

Figure 9 shows the velocity data collected for the potential repository block along with the upper, best-estimate, and lower bound mean profiles used for site recommendation analyses. The additional data are, in general, consistent with the mean profiles used previously.

SASW Seismic Surveys—Data acquired through SASW surveys supplement the data from the downhole seismic surveys to characterize the velocities beneath the WHB site and for the potential repository block. Downhole seismic data obtained from boreholes provide the average velocity at a given borehole location. The velocities determined from the SASW surveys represent average velocities over the length of the survey line.

The two methods, therefore, complement each other with the SASW data providing information on the area between boreholes. Longer SASW survey lines allow velocities from greater depths to be imaged.

Figure 10 shows the results for the SASW surveys carried out at the WHB site. The profile used for site recommendation analyses is, in general, consistent with the range of velocities determined from the SASW surveys.

Figure 11 shows the results for the SASW surveys carried out to characterize the shear-wave velocities of the potential emplacement block. Comparison to the best-estimate, lower, and upper bound mean profiles from the previous analysis suggest that the uncertainty incorporated into the previous analysis can be reduced. That is, below about 23 m (75 ft), most of the data lie between the best-estimate and lower-bound mean profiles.

Suspension Seismic Surveys—Suspension seismic survey data provide information on interval velocities within the surveyed boreholes. In general, the results of the suspension seismic surveys are consistent with the downhole seismic survey data. For determining velocity profiles to use in development of seismic design inputs, the downhole and SASW velocity data will be relied upon, with the suspension survey results providing corroborative information.

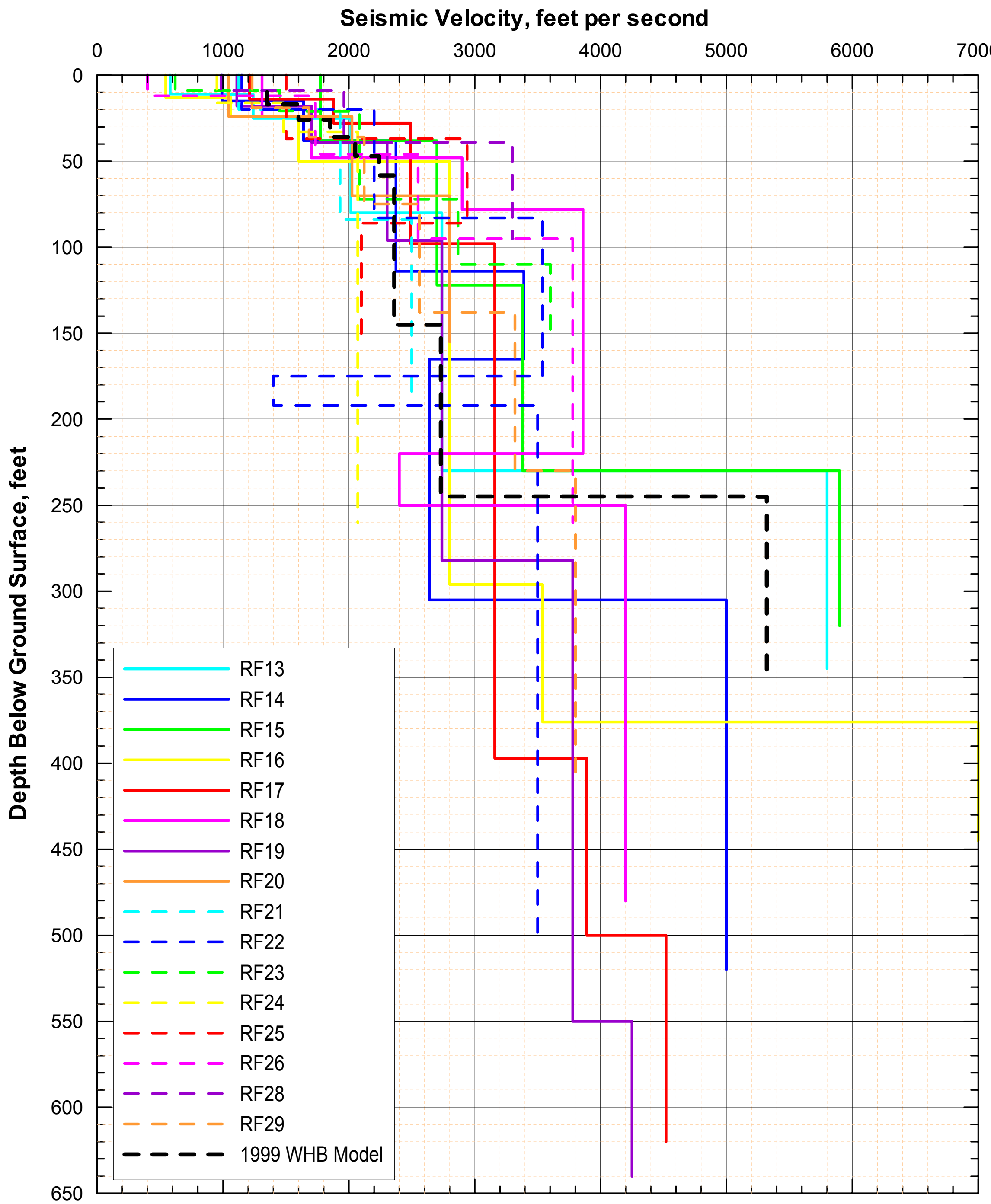

Figure 7. Downhole Seismic Survey Shear-Wave Velocity Results for the WHB Site Compared to Velocity Profile Used as Basis for Previous Analysis

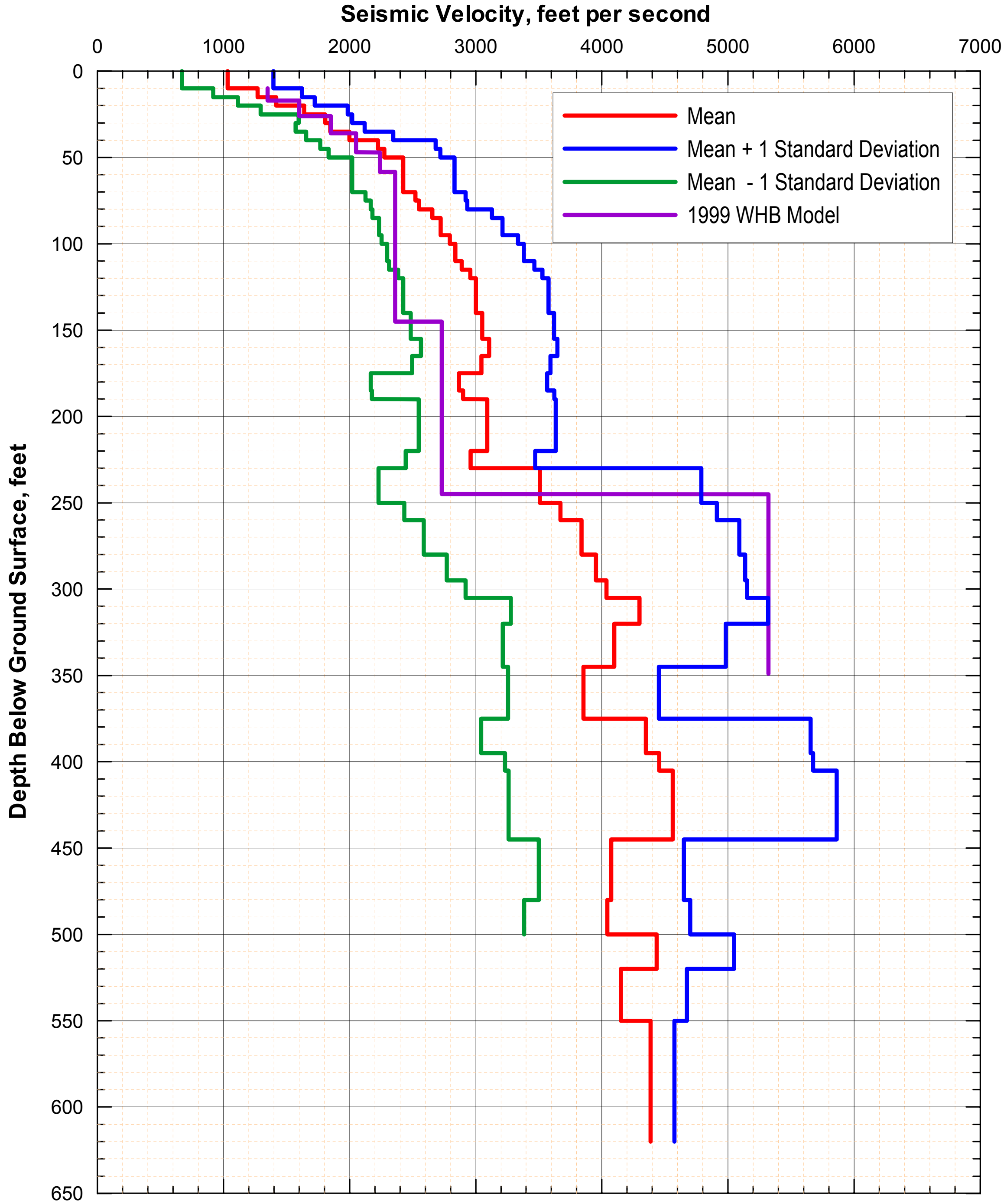

Figure 8. Mean and Standard Deviation of Downhole Seismic Survey Shear-Wave Velocity Results for the WHB Site Compared to Velocity Profile Used as Basis for Previous Analysis

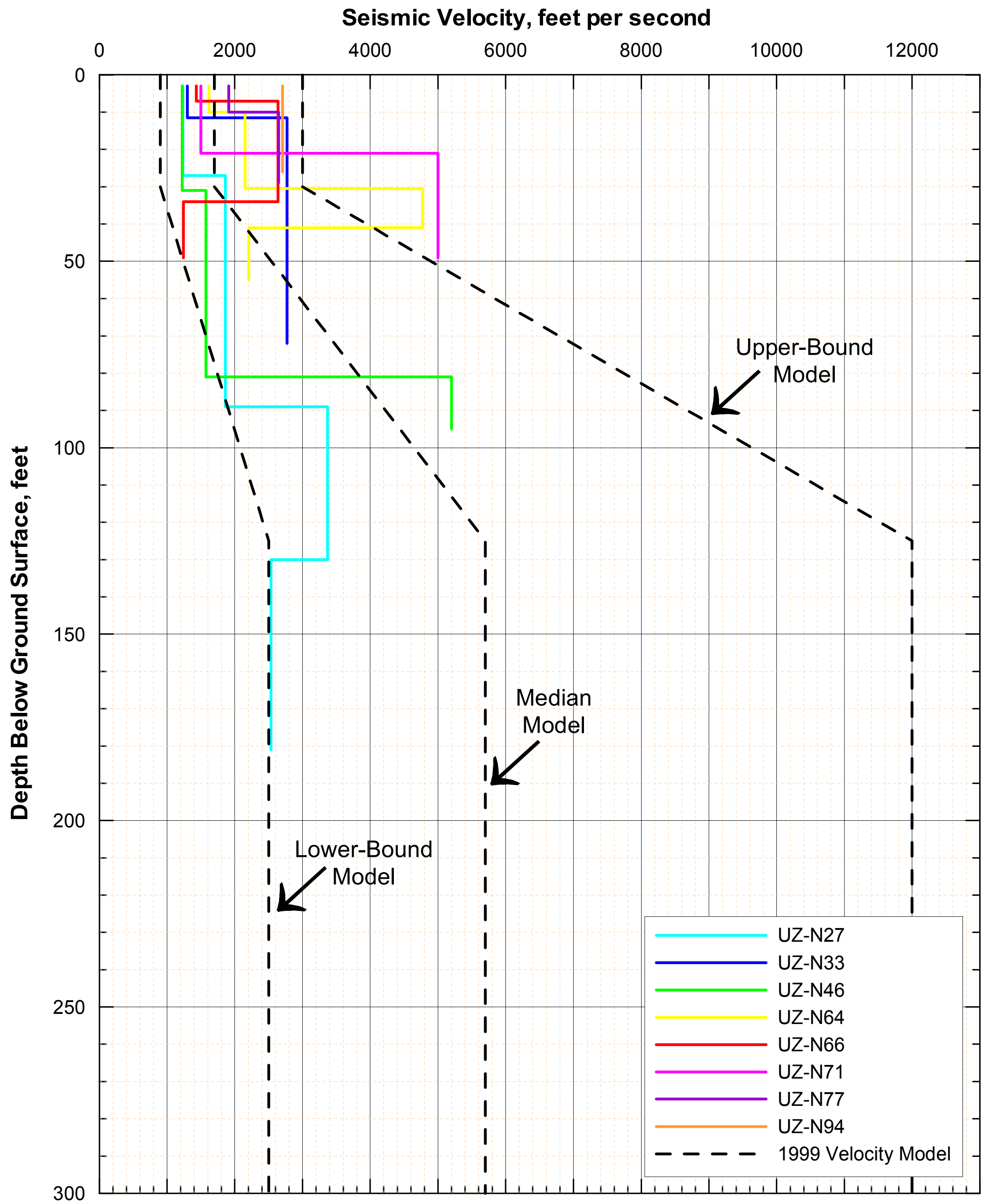

Figure 9. Downhole Seismic Survey Shear-Wave Velocity Results for the Potential Repository Block Compared to Velocity Profiles Used in Previous Analysis

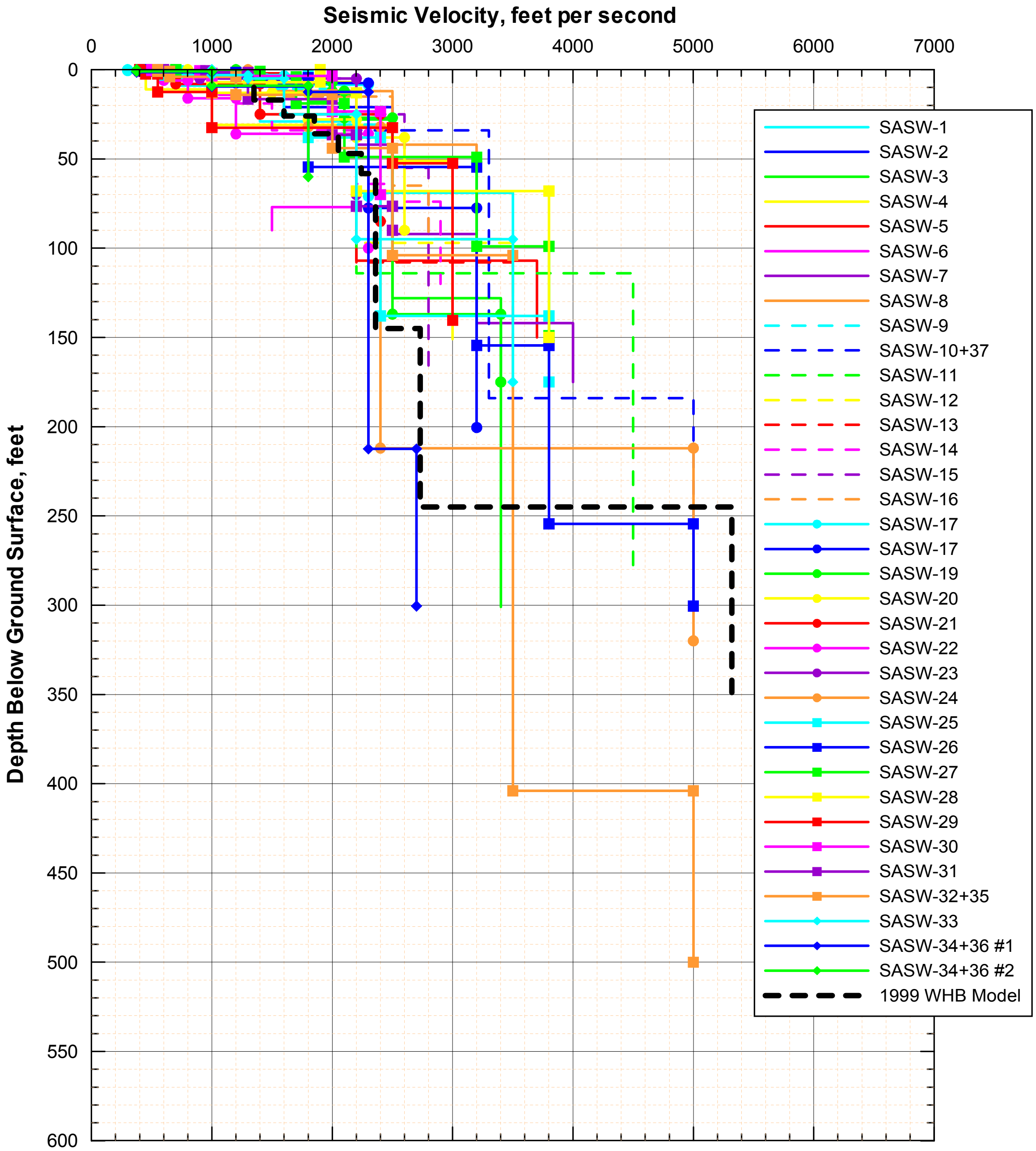

Figure 10. SASW Survey Shear-Wave Velocity Results for the WHB Site Compared to Velocity Profile Used in Previous Analysis

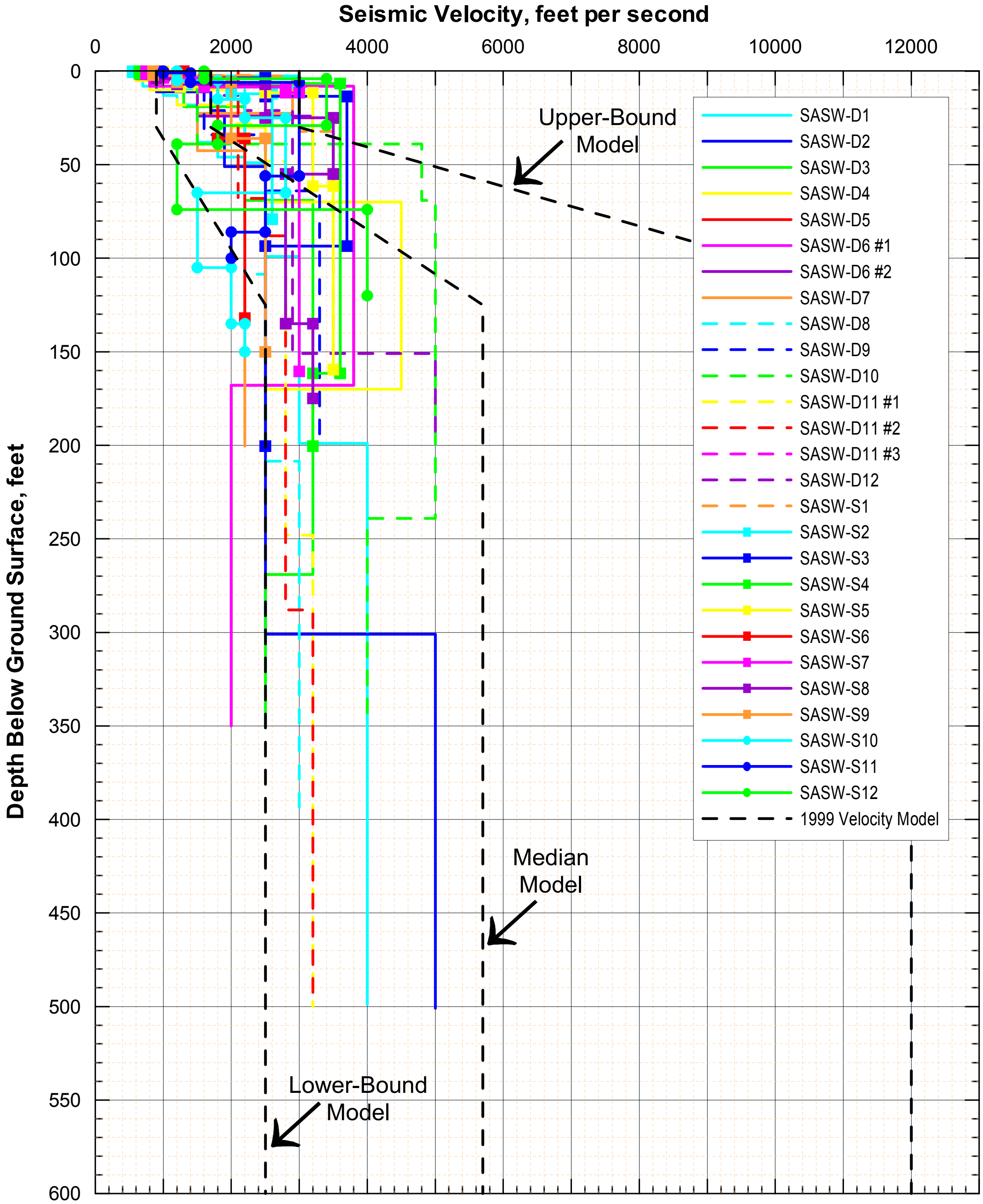

Figure 11. SASW Survey Shear-Wave Velocity Results for the Potential Repository Block Compared to Velocity Profiles Used in Previous Analysis

3.4 GEODETIC RESULTS FROM CONTINUOUS GLOBAL POSITIONING SYSTEM MEASUREMENTS

Wernicke et al. (1998) presented data from global positioning system (GPS) surveys that they interpreted as indicating a strain rate near Yucca Mountain three to four times the Basin and Range average. Based on this interpretation, they suggested that the volcano recurrence rate in the Yucca Mountain region might have been underestimated by an order of magnitude. It has been pointed out that this suggested order-of-magnitude increase in the recurrence rate is not consistent with the post-Miocene volcanic record of the Yucca Mountain region (CRWMS M&O 2000d, p. 55). An increased strain rate could also have implications for determining the seismic hazard. Recent geodetic measurements (Savage et al. 1999; Marks 2001, Enclosures 1 and 2)), however, indicate a much lower strain rate than that reported in Wernicke et al. (1998). The Blewitt (Marks 2001, Enclosure 1) and Wernicke and Davis (Marks 2001, Enclosure 2) strain rate results are based on approximately two years of continuous GPS measurements. A preliminary interpretation by Wernicke and Davis (Marks 2001, Enclosure 1), for the "discrepancy" between the high strain rates reported in Wernicke et al. (1998) and the "notably lower rate" based on the recent measurements, is that the earlier measurements were affected by a large postseismic transient from the 1992 Little Skull Mountain earthquake (M 5.6). The latest geodetic information is more consistent with the volcanic record in the Yucca Mountain region. Savage et al. (1999), after removing the coseismic effects of the 1992 earthquake from the data set, attributed about one-half of the strain rate of the Wernicke et al. (1998) reported rate to accumulation on the Death Valley–Furnace Creek and Hunter Mountain–Panamint Valley faults.

4. IMPLICATIONS OF RECENT TEST RESULTS AND OTHER ADDITIONAL INFORMATION

This section discusses the implications that the additional information as a whole has on the understanding of the disruptive events process model (including the underlying component models). It is limited to only the implications on the model or inputs and does not discuss potential impacts on the TSPA.

4.1 CNWRA-SPONSORED RESEARCH AND ANALYSES RELATED TO DIKE–DRIFT INTERACTIONS

The CNRWA-sponsored research and analyses described in Section 3.1 represent an initial attempt to mathematically model in more detail the dike–drift interaction process and present an idealized conceptual model for further evaluating igneous consequences of dike–drift interactions. In particular, Woods et al. (in preparation) state the assessments suggest a greater number of waste packages may be adversely affected than previously recognized.

With regard to the idealized conceptual models and potential implications, the TSPA-SR model and the supplemental TSPA model are based on the conceptual models discussed in *Dike Propagation Near Drifts* (CRWMS M&O 2000f), which was specifically developed to address the interactions of a hypothetical igneous dike with a repository drift or tunnel and with the drift contents. The results of that analysis, along with the results of the calculation *Number of Waste Packages Hit by Igneous Intrusion* (CRWMS M&O 2000g), were taken forward into *Igneous Consequence Modeling for the TSPA-SR* (CRWMS M&O 2000c), the results of which were used in the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b) and based on further consideration, updated in the *FY01 Supplemental Science and Performance Analyses* (BSC 2001a; BSC 2001b).

The concepts developed in the analysis model report (AMR) *Dike Propagation Near Drifts* (CRWMS M&O 2000f) are similar to the CNRWA-sponsored analyses in that the concept of explosive decompression, shock waves, and pyroclastic flow effects are considered, as is damage to the waste package. Also, they both assume that the components of the engineered barrier system are irrelevant to flow. The cases presented in Woods et al. (in preparation) are recognized in the AMR, but significant differences do exist in the resulting conceptual models. The AMR discusses the possible effects of fragmentation history on flow conditions, it considers the possibility of pyroclastic flow preferentially sealing the drift and allowing for continuation of dike propagation at or near the point of dike–drift intersection, as does consideration of pressure-loss conditions associated with high magma flow rates, and it considers the effect that displacement of the drip shields and displacement of waste containers might have on the flow conditions. Furthermore, the AMR also considers the possibility of varying damage states associated with different aspects of the intrusive event.

With regard to estimating the igneous consequence, the analysis requires definition of the probability of the given size and type of intrusive event (e.g., what is the probability of intersecting one or multiple drifts), the damage state of the containers, and the waste transport mechanism. The CNRWA-sponsored analyses were focused on the idealized conceptual models based on a single drift and did not specifically address the probability of the various cases occurring, the probability distribution of one or more drifts being intercepted, the quantification of the number of packages damaged, or the damage state of the packages. For the TSPA-SR model (CRWMS M&O 2000b) and supplemental TSPA model (BSC 2001a and 2001b), probabilities were developed in the various disruptive events AMRs. This includes consideration of the number of drifts intersected by various orientations and length of dikes, the number of conduits that could intersect drifts (1 to 13, with 1 being highly more probable and 2 being an approximate mean value), a range of possible conduit diameters (1 to 150 m [3.2 to 500 ft]), the number of waste packages directly intersected by a conduit (ranges from 1 to 51), and the number of waste packages damaged (either intercepted by the dike or otherwise damaged and ranging from 0 to 11,184) (CRWMS M&O 2000c).

For the sole purpose of evaluating the potential implication of the idealized conceptual models in the CNRWA-sponsored analyses, a very rough estimate of the increase in the mean number of waste packages that could potentially be affected using the idealized conceptual model can be scaled from the reference probability distributions provided in the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000b) and *FY01 Supplemental Science and Performance Analyses* (BSC 2001a and 2001b). For an eruptive release to occur, a conduit has to form somewhere along the dike and within the potential repository footprint. The distribution of the number of conduits can range from 1 to 13, with a mean of approximately 2 conduits per dike. In the idealized conceptual model, the dike intersects one or more drifts and then breaks out somewhere along an intersected drift, with the potential for the contents of all packages within the intersected drift to reach the surface via a conduit that has formed along the dike–drift path (this assumes no or minimal cross-connection between intersected drifts). This suggests that the mean number of packages that could be erupted is constrained by the number of packages per drift and the mean number of conduits formed (i.e., 219 packages per drift and a mean of 2 conduits per dike). This suggests that the mean number of packages involved in an eruptive release for the idealized conceptual model may be approximately 400 to 500 packages. The current mean for the distributions used in the TSPA-SR model and the supplemental TSPA model for the eruptive case is based on assuming 2 conduits of 50-m (160-ft) diameter each and centered on the drifts, or an equivalence of about 20 packages. The current mean number of packages is constrained by diameter of the conduits rather than the number of waste packages per drift as would be the case for the idealized conceptual model.

The current technical basis is sufficient to support the site suitability determination and to support the Secretary's considerations regarding a potential site recommendation. The work done to support site recommendation provides a defensible basis for the potential site recommendation (the low probability of an event and the robustness of the hazard estimate, the waning character of volcanism in the region, localization of igneous activity away from Yucca Mountain), and the analyses of igneous consequences are representative of a range of effects and the existing analyses appropriately demonstrate, within the framework of the work the Project has completed for site recommendation, the probabilistic risk to a potential receptor represented by a basaltic volcanic event intersecting the repository.

4.2 ADDITIONAL AEROMAGNETIC DATA AND INTERPRETATION

The approach to the volcanism analysis that supports the TSPA-SR is a probabilistic treatment of consequences with volcanic eruption release and igneous intrusion groundwater release analysis included in the TSPA-SR model. For both the eruptive and intrusive disruptive events, the corresponding risk is determined by weighting the (conditional) dose with the probability of the volcanic event occurring within the footprint of the potential repository at Yucca Mountain. To estimate the probability of a future volcanic event in time and space, the number, locations, and age of previous eruption sites are needed. Determination of the Plio-Pleistocene volcano inventory was, therefore, one of the interpretations made by experts included as part of the *Probabilistic Volcanic Hazard Analysis for Yucca Mountain, Nevada* (CRWMS M&O 1996). The analysis used USGS aeromagnetic survey data (Langenheim et al. 1993) to identify a number of anomalies as representing buried volcanic centers. These and other subtle anomalies were more clearly delineated by a high-resolution aeromagnetic survey of the Amargosa Desert collected by the USGS in cooperation with Nye County in 1999 (Blakely et al. 2000).

The recognition and the interpretation and modeling of these additional anomalies of possible volcanic origin constitutes additional information and implies that the probability of a volcanic event may need to be reviewed and/or updated.

The initial interpretation of the anomaly data presented above does not deal directly with the probability estimate, and the interpretations should be considered preliminary. The interpretations and models derived from potential-field data are reasonable but are not unique. An infinite number of geometric models will have an associated magnetic or gravity field that closely matches the measured field. If all the anomalies modeled as buried volcanoes are about 3.7 to 4.0 Ma or older, it would imply that the buried volcanic centers form a distinct volcanic field perhaps having its own tectonic controls and apparently extinct, judging from the alluvial burial. This conclusion would increase the recurrence interval for volcanism and thereby lower hazard estimates. However, if one or more of the buried volcanoes are Pleistocene in age, it could imply existence of a tectonic linkage between Amargosa Valley and Crater Flat basin, and a high rate of alluviation in Amargosa Valley relative to Crater Flat, and possibly suggest an increase in the probability of an igneous event.

The implication, either increasing or decreasing the probability estimates, is currently indeterminate but likely minimal because the probabilistic volcanic hazard analysis included consideration of a "hidden events factor," which allowed for additional undetected events not counted in the total Yucca Mountain region event counts that already included the Amargosa Valley event counts (CRWMS M&O 1996, Figures 3-62 and 3-63). This factor typically resulted in an increase of 10 to 50 percent in the rate of volcanic events over that computed from the observed volcanic events. The use of the factor may compensate for the presence of some limited number of additional igneous features, which suggests that, if needed, adjustments in the calculated probability may be minor. Furthermore, the TSPA-SR model sampled a probability distribution ranging to as high as 10^{-7}/yr, which would tend to further minimize the effect on any minor change in probability estimates.

4.3 GEOTECHNICAL INVESTIGATIONS SUPPORTING SEISMIC ANALYSES

The amount of uncertainty incorporated into the site-specific ground motions for the repository block based on limited velocity data available in 1999, appears to be more than is warranted on the basis of the additional data for the repository block. Higher ground motions resulting from uncertainty, therefore, should be reduced, although this effect may be compensated by other changes associated with the expanded data set.

4.4 GEODETIC RESULTS FROM CONTINUOUS GLOBAL POSITIONING SYSTEM MEASUREMENTS

The recent work by Blewitt (Marks 2001, Enclosure 1) and Wernicke and Davis (Marks 2001, Enclosure 2) confirms the work by Savage et al. (1999) and strengthens the arguments against consideration of a higher strain rate and its effects on volcanism and tectonic activity as discussed in *Characterize Framework for Igneous Activity* (CRWMS M&O 2000d, p. 55) and in *Features, Events, and Processes: Disruptive Events* (CRWMS M&O 2000h, p. 37). There is, therefore, no implication on reference disruptive events models.

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